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Automated Diagnostics Scoping Study

Final Report

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EXECUTIVE SUMMARY

The objective of the Automated Diagnostics Scoping Study was to investigate the needs for diagnostics in building operation and to examine some of the current technologies in automated diagnostics that can address these needs. The study was conducted in two parts. In the *needs analysis*, we interviewed facility managers and engineers at five building sites. In the *technology survey*, we collected published information on automated diagnostic technologies in commercial and military applications as well as on technologies currently under research. The results of both investigations are presented with the following caveat: the small sample of buildings and technologies is not necessarily representative of all types of facilities or diagnostic technologies and a broader study is recommended. The results do, however, provide a basis for discussion about diagnostic needs, and suggest opportunities for new technologies to meet those needs. The following describe key areas that we identify for the research, development, and deployment of automated diagnostic technologies.

- Tools and techniques to aid diagnosis during building commissioning, especially those that address issues arising from integrating building systems and diagnosing multiple simultaneous faults.
- Technologies to aid diagnosis for systems and components that are unmonitored or unalarmed.
- Automated capabilities to assist cause-and-effect exploration during diagnosis.
- Inexpensive, reliable sensors, especially those that expand the current range of sensory input.
- Technologies that aid "predictive" diagnosis through trend analysis.
- Integration of simulation and optimization tools with building automation systems to optimize control strategies and energy performance.
- Integration of diagnostic, control, and preventive maintenance technologies.

By relating existing technologies to perceived and actual needs, we reached some conclusions about the opportunities for automated diagnostics in building operation. Some of a building operator's needs can be satisfied by off-the-shelf hardware and software. Other needs are not so easily satisfied, suggesting directions for future research. Our conclusions and suggestions are offered in the final section of this study.

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Section 1

INTRODUCTION

The observations of building energy auditors and field researchers, as well as analysis of field-performance data, tend to show that almost every building has faulty or degraded equipment and operation practices that could be improved.

One of the keys to identifying and correcting these problems is the ability to detect and diagnose problems before or when they occur. Because of the large number of distributed components in commercial buildings, automating the detection and diagnostic processes could improve the ability to accomplish this while reducing overall operating costs.

A basic premise of this Automated Diagnostics Scoping Study was that automated diagnostics can improve building energy performance by identifying components and systems that waste energy because of defective operation. Automated diagnostic systems can also explain why the faults occurred and offer suggestions for repairing and preventing future occurrences of the faults. Because of this, automated diagnosis provides other economic benefits, such as decreased labor hours for tracking down equipment problems and decreased costs of obtaining repair expertise.

STUDY OBJECTIVES

The objectives of this study were to investigate the needs for diagnostics in building operation and to examine current technologies and capabilities in automated diagnostics that can address these needs.

STUDY SCOPE

The study was conducted in two parts. In the *needs analysis*, we interviewed five facility managers and engineers at building sites. In the *technology survey*, we collected information from publications and experts on automated diagnostics in commercial and military applications. We also investigated automated diagnostic technologies currently under research.

REPORT ORGANIZATION

The needs analysis is presented in Section 2, where we describe our methods, case studies of five buildings, and summary of needs for diagnostics in building operation. In Section 3, we present brief descriptions of the various diagnostic technologies surveyed (additional detail about these technologies can be found in Appendix A). Finally, in Section 4, we suggest how existing technologies could meet the

diagnostic needs of building operators and offer recommendations for research in automated diagnostics in anticipation of future building operation needs.

IMPORTANT DEFINITIONS

Webster defines *diagnosis* as "an analysis of the cause or nature of a condition, situation, or problem" (Mish 1991). For the purposes of this study, we characterize the practice of diagnosis, i.e., *diagnostics*, by the following key elements:

- Observation of the actual performance of a device or system.
- Knowledge of the expected performance of the device or system.
- Comparison between actual and expected performance.
- Explanation of the result of this comparison. It is important to note that this "explanation" itself may require additional analysis and that the process of diagnosis must be applied recursively until an adequate explanation can be provided.

Other elements are sometimes considered part of diagnosis, but we do not include them in our definition. Examples of these are modifications to a device or system to close the gap between actual and expected performance (i.e., repair), or actions intended to prevent discrepancies between expected and future performance (i.e., preventive maintenance).

Automated diagnostics is the practice of diagnosis by a machine. Some devices are capable of recognizing and explaining "abnormal"¹ behavior without human assistance. Some modern photocopiers, for example, integrate all four elements described above:

- The photocopier monitors the contrast of the copies that it produces.
- The photocopier knows the expected contrast levels.
- The photocopier recognizes when actual contrast levels differ significantly from expected contrast levels. It may use a flashing red icon on the control panel to indicate this discrepancy.
- The photocopier explains the discrepancy by displaying a message on the control panel such as "Toner is low — replace cartridge."

¹"Abnormal" in this context is defined as the condition in which actual performance differs significantly from expected performance.

In this example, the machine's diagnosis of the problem is "fully automated"; human assistance is not required to analyze the nature of the situation. Not all machines have a fully automated diagnostic process—some automate only part of the process, like the warning light on an automobile dashboard that reads "Check Engine." In this example, a computer in the automobile has identified a performance discrepancy (involving the first three elements of diagnosis, as described above) but requires a human (or another machine) to provide an explanation (the fourth element of diagnosis). As noted earlier, further analysis may be required to determine this explanation, implying that the diagnostic process is performed recursively at increasingly finer levels of detail. At the other end of the spectrum are those machines that simply monitor performance (the first element of diagnosis—observation), but are unable to recognize when that performance varies from expected parameters and explain why this may occur (the remaining three elements of diagnosis). A boiler to which a temperature gauge has been connected is an example of such a machine. The gauge measures internal temperatures but neither has knowledge of acceptable temperature limits nor can it explain why the temperature may exceed those limits. Devices with this type of diagnostic capability are considered "partially automated" and require human assistance to complete the diagnosis.

We investigated a range of partially to fully automated diagnostic technologies that are used to analyze building operation. In this study, we use the term *building operation* to refer to the operation of the mechanical and electrical equipment and systems that support a building's lighting, security, transport (e.g., elevators and escalators), communications, hot/cold water, heating, ventilation, and air-conditioning (HVAC), and waste disposal systems. *Operation*, in this context, includes controlling, monitoring, diagnosing, repairing, and maintaining such systems. These functions are defined as follows:

- *Controlling*: turning the device on or off, or setting it to a specific mode of operation.
- *Monitoring*: observing actual performance.
- *Diagnosing*: analyzing the cause or nature of a condition, situation, or problem (as defined above).
- *Repairing*: modifying the device to correct abnormal performance.
- *Maintaining*: modifying the device to prevent future occurrences of abnormal performance.

Large facilities require a sizable amount of equipment to maintain interior air temperatures, light levels, security, and other amenities. The number of individual components (e.g., pumps, fans, motors, compressors) can easily run into the hundreds, sometimes into the thousands. In some facilities where many such devices are in operation, building engineers have integrated and centralized automatic control

and monitoring functions through a *building automation system* (BAS).² A BAS allows the engineer to control and monitor building equipment either manually or automatically from a remote location. In the buildings that we visited, we found that the BAS is often used for diagnosing problems, although we know of no commercial BASs that could be considered “fully automated” in their diagnostic capability.

²Also referred to as an *energy management and control system* (EMCS).

Section 2

NEEDS ANALYSIS

The objectives of the needs analysis were to understand building operation activities, determine the type and complexity of current methods of diagnosis, and assess the desire, need, and potential for automated diagnostics. To achieve these objectives, we interviewed the chief building engineers at five commercial sites: two medical complexes, two office buildings, and one hotel.

The needs analysis is presented with one caveat: the small sample of five buildings is not necessarily representative of hospitals, office buildings, hotels, or all commercial buildings. Our investigation simply provides an indicator of some of the diagnostic needs of these types of facilities and should be interpreted accordingly. A broader study of such needs to verify and supplement our findings would be necessary to understand the needs and opportunities for diagnostics in the commercial building stock and is recommended as a future activity.

In addition, our findings are limited to the opinions and experiences of the building engineers who we interviewed. Many problems and opportunities to improve energy performance may exist of which the building engineers are unaware. These would remain undetected in this study. Nonetheless, the results are useful as a first step in understanding the needs and opportunities to use automated diagnostics in commercial buildings.

METHODOLOGY

We conducted on-site interviews with the chief building engineers of five facilities. During these interviews, we sought information in the following categories: building description, building automation system, energy management, diagnostics, and preventive maintenance. Sample questions from each of these categories are presented here.

Building Description

- What is the occupied area of the building?
- How many stories does it contain?
- Describe the systems that you operate for the building (e.g., HVAC, lighting, transport, security).
- How many people are on the building engineering staff? What are their backgrounds? What are their responsibilities?

Building Automation System

- What kind of BAS is in use?
- How long has it been in use?
- What equipment is connected to it?
- What information does it supply? How often? At what level of detail?
- How many of the building engineering staff are qualified to operate the BAS? At what level of expertise?

Energy Management

- Do energy concerns affect the operation of the building? If so, how?
- What rate structure is the facility on? Has facilities management ever considered real-time pricing (RTP)?
- What knowledge is required to operate the building equipment in a more energy-efficient manner? How is that knowledge stored and transferred to others?

Diagnostics

- How do building engineers know what is the expected performance and behavior of building equipment?
- How do building engineers determine discrepancies between actual and expected performance? Are there alarms or other notification?
- How do building engineers analyze and explain such discrepancies? What specific actions are taken to perform this analysis?
- What are the most critical problems to be diagnosed?

Preventive Maintenance

- How does the building engineer identify devices that require maintenance?
- How is maintenance for these devices scheduled?
- How is the maintenance recorded? Are these records used in diagnostics?

CASE STUDIES

Our case studies consisted of five large facilities of various types: two medical facilities, two office buildings, and one hotel. All had relatively sophisticated building automation systems installed after 1986.

While our sample was biased toward high technology, we selected these facilities for two reasons. First, they represent the state of the art in building automation—we were unlikely to find better opportunities to observe how technology is used in the diagnostic process. Second, the building engineers at these sites had high levels of technical expertise, and their familiarity with BASs provided invaluable insights into the current capabilities and future needs of automated diagnostics.

The drawback of using such a sample, however, is that we did not gain any insights into how diagnostics are performed at the large majority of facilities without building automation systems or a sophisticated engineering staff. The operation staff at these facilities probably have different needs than the engineers we interviewed. Furthermore, we speculate that these staff might view and use automated diagnostic technologies differently from their “high-tech” counterparts.

The five buildings studied were simply identified as

- Office Building A; Portland, Oregon.
- Office Building B; San Francisco, California.
- Medical Facility A; Oakland, California.
- Medical Facility B; South San Francisco, California.
- Hotel A; San Francisco, California.

In the following sections, we describe each of these buildings in the five categories identified in our methodology.

Office Building A, Portland, Oregon

Building Description. This building is a 16-story office tower with 350,000 ft² of occupied space. The original structure was built in the late 1970s. In late 1989, the building was retrofitted with a direct digital control (DDC) energy management system funded by Pacific Power and managed by MicroGrid, Inc. The basic HVAC system includes a terminally-regulated air volume (TRAV) system with reheat. A chief engineer (who also manages all of the building owners' facilities) and a full-time technician comprise the building operations staff.

Building Automation System. After evaluating several BASs, the building engineer chose Delta Systems' INTELLE-SYS. The choice was based on the system's programmability, potential for upgrades, communication network speed, and well-designed user interface.

Installed by NW-AIR, the BAS is designed around the building's TRAV system. Every two variable-air-volume (VAV) boxes share a single local control module with eight data ports. The BAS monitors building occupancy based on lighting. Component operation is then automatically adjusted to meet only the demand resulting from the building's occupancy level.

Software downloaded to a central control module controls the BAS operation. However, the building engineer interacts with the system using windows-based software. The interface allows the engineer to use elaborate, three-dimensional graphics of the building and components to monitor and adjust all control and sensor information. A zone/building map displayed on a monitor screen allows the engineer to "see" all temperature and humidity information for each thermal zone overlain on the floor plan. Any one of the individual VAV boxes can be viewed to investigate damper position, flow rate, or supply air temperature. The engineer can also vary these parameters using the graphical interface.

The central plant is also automated and monitored, but the system only provides information on operational status (on/off) and a few select temperatures. Because the plant is more reliable than the VAV boxes, the building engineer feels these data are sufficient for monitoring and diagnosing central plant performance. Selected sensor information can be tagged with audio and visual alarms to warn the engineer of abnormal conditions. The engineer predefines these conditions based on maximum and minimum performance specifications. The BAS includes a separate disk for storing data histories, as well as a modem for operating the building remotely.

Energy Management. After the installation of the BAS, building energy use declined significantly.

The building engineer credits the BAS and TRAV system control, which uses the following strategies:

- HVAC system operation is based on the building's actual level of occupancy.
- Occupancy is determined by active lighting levels throughout the facility.
- The BAS adjusts fan speed and damper positions to supply air only to occupied spaces.

Diagnostics. Problem diagnosis usually occurs only after a tenant complaint or a BAS alarm. The engineer first attempts to locate the problem using the BAS graphical interface. Next, values of relevant parameters are traced backward through the HVAC system until the problem is found. Of these complaints or alarms, the building engineer claims that about 90% are "obvious" and easily located with the graphical interface. The more difficult problems not found using this strategy are diagnosed manually. The engineer uses practical experience, hard-copy troubleshooting guides, and live investigation. Although trend information about various system parameters is stored for up to a year on a backup disk, this information is rarely used for problem diagnosis because of "lack of time."

The engineer stated that the most critical piece of diagnostic information is the supply air temperature to various spaces. Because it is the final product of the air-conditioning process, the building engineer uses the supply air temperature as the first step in tracing backwards through the system to investigate cause-and-effect relationships.

Preventive Maintenance. The BAS is not used to inform the preventive maintenance process. Although the BAS logs hours of equipment use, maintenance on the equipment is performed quarterly regardless of actual operation time. The engineer uses manuals to help troubleshoot maintenance problems; equipment maintenance histories are stored in files. The engineer has found that most problems are caused by equipment age, so equipment maintenance plays a major role in maintaining a correctly operating system and preventing difficult problem diagnosis.

Summary. Office Building A was one of the most advanced cases we studied. It has won several awards for energy management and automation. The engineer indicated interest in having a rule-based-learning diagnostic system, but only for equipment problems that were not immediately obvious. The engineer stated that more software tends to create more problems than it solves because of software maintenance and performance issues. However, the engineer did say that a software program that could display equipment condition on a daily basis would be extremely useful in dealing with preventive maintenance issues.

Office Building B, San Francisco, California

Building Description. Office Building B is a 45-story building located in downtown San Francisco. The building contains 1 million ft² of occupied space, of which 70% is offices, 25% is retail, and 5% is parking. The building uses curtain-wall construction with double-glazed windows. A VAV system with an outside air economizer supplies the air. The central plant includes three chillers containing 2000 tons of total capacity and two low-pressure boilers. Staffing the building are eight engineers, one apprentice, and one man who handles lighting.

Building Automation System. The BAS, installed by Barrington in 1986, is used primarily to report equipment status (on/off and tonnage), critical temperatures, and flow rates, and to operate lighting. The system combines pneumatic and direct digital controllers and contains between two and six local processing units per floor. The local processing units are used primarily for lighting control. The data ports not used to control lighting are allocated to monitor temperatures, flow rates, and other parameters. The major mechanical systems (chillers, boilers) are still manually controlled.

Energy Management. Because these are "high rent" retail spaces, the tenant requests and input drive the building operation. Although the facility's rate structure is on real-time pricing (RTP), the RTP signals rarely alter operation because of tenant satisfaction concerns.

Global, real-time optimization is being implemented on a separate computer system that will be integrated with the current BAS. While these global energy optimization strategies are currently under discussion, small inconspicuous changes to standard operation, such as reduced lighting in common areas and garages, are already being made.

Diagnostics. Problem diagnoses are handled using a combination of the BAS and the building engineer's knowledge. The engineer typically becomes aware of a problem because of an alarm from the BAS or, in most cases, a tenant complaint. Most complaints stem from personal preference and not equipment failure. For obvious reasons, diagnosing "problems" not caused by equipment failure is difficult for the BAS.

When actual breakdowns occur, the BAS alarms the engineer visually and audibly, and the engineer typically uses the BAS to scan system variables. The engineer uses his own background and reasoning abilities to interpret the data. Because of inaccuracies with the pneumatic system, not all system variables can be monitored reliably. The only reliable system variables are temperatures and some flow rates. Trend information is recorded and reviewed to alter DDC control strategies, but not to predict potential equipment failures.

Most difficult diagnostic problems are investigated manually because accurate sensory information is absent. The engineer suggested that the most useful diagnostic aid would be a BAS that could display all relevant system information when a complaint is logged or an alarm is triggered. With this type of information, building engineers with different levels of experience could quickly locate the problem.

Preventive Maintenance. The building engineering staff spends more than 80% of the operational hours responding to tenant needs such as air, lighting, plumbing, and logistics. For this reason, preventive maintenance is scheduled during weekends and nights when the building is unoccupied. The engineers frequently use an unscheduled maintenance log to aid in problem diagnosis. The building engineer suggested that an ideal automation system could check critical system functions in the off-hours and report abnormal conditions to the engineer each morning.

Summary. In Office Building B, we found that the engineer's first priority is to resolve tenant concerns effectively and efficiently. The ability for the automation system to aid the engineer in this task would be extremely beneficial. To be effective in this type of facility, the BAS should be tailored not only to help diagnose actual equipment problems, but also to understand personal comfort preferences.

Medical Facility A; Oakland, California

Building Description. Medical Facility A is a large health-care facility located in 13 buildings containing 1.8 million ft² of floor space, of which 1 million ft² are inpatient facilities. Another 150,000 ft² of new medical office space are under construction. The main building contains a central tower built upon a low-rise base. The central tower contains 348 beds and is served by seven air-handling units. These units are constant volume systems circulating 100% outside air. Cooling is provided by chilled water coils, and heating is obtained using hot water reheat. The low-rise portion of the facility has two VAV systems with reheat, variable-speed drives, and indoor air circulation capabilities.

In early 1991, Carrier Corporation managed the installation of a \$7.5 million central plant and control system. PG&E provided a \$50,000 rebate from its demand-side management (DSM) program. The central plant includes two oversized 35-MBtu boilers and four chillers ranging from 300 to 400 tons each. All pumps in the plant have variable-frequency drives. The central plant contains a steam plant that consist of six small "California Special" boilers. The prospect of implementing a 240-kW cogeneration plant is currently under review. The building engineering staff has 36 people, 10 of whom are familiar with the BAS and have access at different levels. Only two engineers have access to the highest levels of the BAS and are able to actually reprogram control strategies.

Building Automation System. The BAS was installed with the new central plant upgrade. The system is a Barber-Coleman Network 8000 consisting of four global control modules and nine local control modules. All are connected by a simple, single-line network run. The system control strategy was programmed in-house with the aid of a Barber-Coleman representative.

The BAS is designed to monitor and control the central plant very closely; most of the sensors are located in the plant. Other sensor points are located sporadically throughout the building. The BAS allows the building engineer to define coil set-points, pump operation, and VAV operation strategies that are energy-efficient and tailored to each specific building. The BAS generates a detailed graphic of the different central plant components and allows the engineer to remotely control and visually monitor the system.

Alarms are triggered when a sensor point exceeds a preset limit defined by the building engineer. The three main types of alarming used are visual, audible, and printed. The system can also have the building engineer paged. This BAS is unique from those in our other case studies in that each individual control module is fully programmable. The BAS is being upgraded to include other buildings and components.

Energy Management. Using the BAS to optimize energy use is not a high priority. Health-care facility regulations require stringent building control, so operational flexibility is somewhat constrained. The engineers do however respond to PG&E's seasonal rate structures and will sometimes reduce the peak by using backup generators.

To explore energy-efficient operational strategies, an energy engineer will be hired to examine and optimize operational strategies. One tool that might help would be a statistical model of the system to explore optimal control strategies and equipment operation for various building and environmental conditions. Such a tool would allow the engineer to explore optimization without having to wait for certain environmental conditions to occur, and without having to test strategies with the actual equipment.

Diagnostics. When abnormal conditions occur, alarms alert the engineering staff. The BAS is used to work back through its graphics and sensor data until a reason for the alarm is found. If the alarm cause is not found, a walk-through is performed to locate the problem. Ideally, the building engineer would like an intelligent system to trace back through the system and possibly locate and even fix the condition automatically. Almost all equipment problems are "obvious" to the senior engineers. Less experienced staff could possibly use automated diagnostics to help solve problems, but for senior staff it is generally easy enough to simply use the BAS to locate suspicious components.

According to the building engineer, the most difficult diagnostics problems occurred during initial start-up of the system. The BAS records trend information, but that data is never used to diagnose difficult problems. The DDC system itself very rarely has problems.

Preventive Maintenance. Preventive maintenance is handled by the Hospital Engineering Maintenance System (HEMS), an automated maintenance system designed at the University of Vermont. Scheduled and unscheduled maintenance, repairs, and action taken on errors are reported in HEMS. HEMS is never used to explain abnormal conditions to predict future problems. However, the building engineer may use HEMS occasionally to review trends in equipment repair and decide if replacements are necessary.

Preventive maintenance occupies most of the staff's time. Only two people are available for other service calls because of preventive maintenance needs.

Summary. Medical Facility A was one of the more modern BASs investigated. Its distributed programmability and multiple sensor points allowed the engineer very effective control of the entire system from a single location. A statistical model of the system to determine optimal operation would be of great use to this facility; building engineering staff are extremely limited in how much they can vary actual equipment performance because of restrictive performance regulations. A statistical model would allow the engineers to determine optimal strategies without affecting building conditions.

The staff indicated that automated diagnostics to locate problems would be beneficial for junior staff and extremely difficult problems. The ability for the automation system to use equipment histories and trend information to predict problems would be very valuable.

Medical Facility B, South San Francisco, California

Building Description. Medical Facility B is a 318,000 ft² facility built in five stages. The hospital has 16 air-handlers. Fourteen are simple rooftop, constant-volume systems, and the other two are VAV systems. In an upcoming upgrade, two new variable-frequency-drive (VFD) pumps will be added to the system. The building staff consists of 12 people, two of whom are proficient with the BAS.

Building Automation System. The BAS was installed in stages. The first stage, installed in 1986 by Landis and Gyr Powers, Inc., included a base system with limited capabilities. Its main purpose was to relieve overwhelmed pneumatic relays. The second stage was implemented in 1991, adding two standalone programmable control interfaces.

The BAS controls approximately 50% of the building's systems. It monitors problems with equipment, provides accurate equipment control, and monitors critical temperatures. The system includes standard alarming capability, trend data storage, and limited programmability.

Energy Management. The hospital's HVAC operational requirements are extremely stringent; certain levels of performance must be provided, regardless of cost. Consequently, this facility does not respond to changes in the rate structure, and energy cost savings are a lower priority than meeting the satisfying the operating requirements.

Energy management concerns do not affect the hospital's daily operation. The only potential energy management strategy involves the timing of chiller operation. The operation of a small, energy-efficient chiller and a large, less-efficient chiller is manually controlled. During startup, the small chiller operates until the load exceeds its capacity, after which the large chiller is brought on-line. When the load approaches the capacity of the large chiller, both chillers are put on-line. The chiller control could possibly be handled by the BAS but currently is not because of a lack of control modules.

Diagnostics. Problem diagnosis is handled in two distinct ways. In the first, the engineering staff performs "morning rounds" of the equipment. This procedure allows the engineers to see, hear, and smell the equipment and diagnose problems based on personal knowledge of how the equipment normally operates.

The second procedure involves diagnosing system breakdowns using the BAS. The BAS is configured to audibly and visually alarm when an abnormal condition occurs. The engineer's first step is to use the BAS graphical interface to trace the problem. Once the problem is located, the engineer then investigates personally. The ability to conduct manual inspections is considered to be very important because of the inability of sensors to provide complete sensory information.

A database of equipment histories is not used to aid in problem diagnosis. Instead, a crude but effective system is used. Next to the BAS, a schematic of the building is reprinted on a corkboard. The board contains colored pins at various locations. The pins represent reported problems in the respective areas; the color represents the month of the occurrence. When an operator diagnoses a problem, both the BAS and the corkboard schematic are used.

Preventive Maintenance. Preventive maintenance is handled separately from the BAS. Work orders are logged on a different database. Preventive maintenance actions are scheduled based on a predefined timeframe, independent of equipment run times. Trending analysis and equipment histories are rarely used for preventive maintenance because of a lack of time and information.

Summary. Medical Facility B was one of the least sophisticated HVAC systems we studied, although its BAS was above average. The BAS was an extremely useful system for the building engineer, but it controlled less than 50% of the equipment and had access to only extremely critical points. The level of automated control is being increased, but cost is the limiting factor.

Hotel A, San Francisco, California

Building Description. Hotel A is located in downtown San Francisco. The hotel contains 1,500 rooms, 134 suites, 43 floors, and 98 concierge rooms. The central plant and air-handlers serve approximately 1.5 million ft². The rooms are controlled by four-pipe fan coil units, and most of the other community areas are constant-volume systems. The meeting and ballrooms have a combination of VAV and constant-volume systems. The hotel opened in 1989 and embodies system specifications laid out in 1986.

Building Automation System. The BAS was installed by Honeywell and Energy Control Systems (ECS). The Honeywell system is a basic DDC package that runs building equipment. The ECS software contains 12 energy management and optimization programs used by the Honeywell system. The current configuration uses only the time clock function from the ECS software because of communication time lags between the systems and the fact that the ECS software cannot be tailored to the hotel's needs. The Honeywell system does not incorporate graphical representation of data and system performance. Instead, performance is represented using formatted data dumps to the terminal and a line printer. Critical data points are alarmed with audible and visible indicators.

Honeywell provided an interactive tutorial program to explain how its system works, but that program is used for training and not daily operation. The current system is being upgraded to incorporate a lighting and fire protection system. It also will have a more robust user interface.

Energy Management. Energy management is a high priority at the hotel when savings can be obtained without sacrificing user comfort. The ability to effectively manage common areas is of the greatest importance and has the most potential for energy savings. However, the equipment optimization programs supplied by ECS are not used for energy management because they could not be tailored to suit the hotel's needs.

Instead, equipment operation is based on occupancy schedules and RTP. Each day, the building engineer receives a hard-copy printout of the common areas scheduled to be occupied, along with the RTP rate structure. This information is then used as the basis for manually setting equipment controls to maximize occupant comfort and reduce energy cost.

Diagnostics. The most critical diagnostic problem is the temperature of the discharge air, and this is the main parameter that the BAS alarms. However, diagnostic strategies are completely manual. If the discharge air temperature sets off an alarm, the building engineers personally examine equipment

affecting the air temperature until a problem is found. Typically, the staff uses laptop computers to interface with control panels in the plant to locate equipment problems. The BAS central terminal is used to examine some variables, but its "unfriendly" interface makes using it as a diagnostic tool somewhat cumbersome. Trending information is never used to aid in diagnostics before an actual breakdown occurs, and abnormal, unalarmed conditions are difficult to discover.

The engineer indicated that a rule-based diagnostic capability with programmability would be a desired adjunct to the BAS. This feature would be more beneficial to the engineer than elaborate three-dimensional graphics.

Preventive Maintenance. Preventive maintenance schedules were originally generated by the BAS system based on hours of equipment use. The engineers found that the amount of paperwork involved in using this system was not effective and consequently implemented a separate PM system independent from the BAS. The new preventive maintenance schedules are based on an absolute time (every 3 months) instead of operational time. However, depending on the engineers' experience with the equipment, the schedules are sometimes varied. Equipment histories are logged but rarely used for diagnostics.

Summary. Hotel A's BAS was one of the oldest we studied. We found that operational and diagnostic functions were handled by the engineering staff based upon their experience and rules of thumb. The building itself was extremely complex, but the building engineer appeared to have an extremely good grasp of the complicated dynamics. Significant effort was put into efficient operation; however, little of it was automated. Although a system upgrade will automate some of the current process, it appears unlikely that the new system will greatly affect the facility's daily operation.

FINDINGS

Despite their functional differences, the buildings in our sample shared some common features. All were large facilities and were managed by knowledgeable building engineering staff. Each building had a relatively sophisticated BAS, although not all of the building's equipment was connected to the BAS. None of the systems had "fully automated" diagnostic capabilities: most provided only the first of the four diagnostic activities—observation of actual conditions (see p. 1-2). We found one facility (Medical Facility A) in which the BAS identified potential faults in the equipment and the remainder of the diagnostic procedure was written on paper and taped to the wall.

In general, two kinds of diagnostic activities were apparent. One occurs during commissioning when the equipment and BAS are brought on-line. The other occurs on a daily basis as part of routine building operation.

During building/system commissioning, engineers had some difficulty in diagnosing problems in both the building equipment as well as in the BAS. This difficulty stems from the fact that multiple interdependent parameters require adjustment and balancing, and multiple simultaneous faults are more likely to occur. The commissioning process often required the assistance of the representatives from the controls companies or from the building equipment manufacturers to troubleshoot startup problems.

Diagnostics during daily operations, on the other hand, appear to be easy by comparison. The building engineers we interviewed estimated that the diagnosis of 85% to 90% of observed faults are "obvious"—only 10% to 15% of these problems required a detailed investigation. Typically the diagnosis process begins when the BAS signals an alarm that one of the monitored parameters (e.g., space temperatures, steam pressure, service hot water temperatures, generator activity) has exceeded prespecified limits. The alarm is usually displayed on a line printer in the building control room, although in some cases, the BAS will use a PBX system to page the building engineer directly. Although the BAS can monitor a large set of parameters, building engineers are interested primarily in the end product: temperature of discharge air from the system. When an alarm indicates that discharge air temperatures are out of range, engineers typically work backward to determine what components may contribute to the discharge air temperature problem. The engineers also use the BAS to quickly determine the current values of related parameters, then usually go to the equipment location to personally inspect the problem. The analysis of the situation is usually immediately clear based on visual inspection. Building engineers admit, however, that it is difficult to track down problems in components that are not monitored and subsequently have no alarms.

We term this kind of activity as "breakdown" diagnosis: it is an effort to explain the condition or situation after a failure has already occurred. For failures detected by the building engineer, the diagnosis is usually easy to make and repair is straightforward. What is often not detected are the small variations in equipment performance over time. Observation of these variations would allow the building engineer to engage in "predictive" diagnosis, in which a situation is assessed to predict future equipment failures.

The engineers claimed that the reliability of the BAS itself is inconsistent. The information gained from temperature and lighting sensors is generally reliable, but sensors for other functions (e.g., flow rates, chiller tonnage) cannot be designed and fabricated to the same level of accuracy, and are more likely to

malfunction in the field. Some of the building engineers still rely on visual/auditory inspections made during "morning rounds" instead of relying completely on the BAS. The engineers claim that even perfect reliability is not adequate because today's sensors are not sophisticated enough to discriminate nuances of sound, smell, and touch; and that this information is necessary to detect failures in the components and systems.

An interesting observation is that "trend" data is rarely used during the diagnostic process. Most BASs record the values of data points over time, establishing historical trends of information. Trends could be used, for example, to monitor equipment performance that slowly degrades over time. In some cases, however, this becomes difficult because of the number of confounding variables. Nevertheless, building engineers rarely consult the trend data to help diagnose existing problems.

Trend information is used to help the engineers decide if component replacements are necessary. The building engineer in the South San Francisco facility, for example, uses a corkboard with multicolored pins to track component failures over time. A collection of pins in a single location over a period of months suggests that a replacement may be necessary. Trend information is also examined occasionally to determine if control blocks within the BAS need to be reprogrammed.

Although it would appear that BAS trend information could be used to schedule preventive maintenance, we found that this was not the case in the facilities we examined. PM's were scheduled on a regular basis regardless of hours of equipment usage. One explanation is that the building engineer used two independent systems for the control and maintenance functions (e.g., the HEMS system and the Barrington system in Medical Facility A). Interfaces between such systems had not been established, and the benefits of integration were not perceived to outweigh the estimated costs. Another interesting observation is that the building engineers rarely used the preventive maintenance logs to assist with diagnosis. Most found that they could easily accomplish the diagnosis without examining these logs.

With respect to building operation, we found that energy conservation was not as high a priority as occupant comfort. However some engineers believed they could accomplish both with clever operational strategies. A BAS could be a very useful tool in exploring some of these strategies if it were capable of simulating various operational scenarios and optimizing control parameters for both energy-efficient and comfortable operation. We believe that optimization tools would be especially useful to help develop and implement efficient energy use strategies for buildings that employ dynamic rate structures (e.g., real-time pricing).

In summary, we observed that the diagnostic needs of building operators are in the following areas:

- Ability to assist diagnosis during commissioning, during which multiple fault problems abound.
- Ability to compensate for unmonitored and unalarmed components.
- Ability to assist the "backward-chaining" investigation of cause and effect during diagnosis.
- Ability to overcome problems associated with unreliable sensors.
- Ability to employ sensors that measure sound, smell, and feel.
- Ability to simulate performance on-line and offer suggestions to optimize operation strategies for energy use, comfort, or other objectives.

Although the following items were not expressed as "needs," we believe these capabilities can also assist diagnostic processes.

- Ability to use trend information for monitoring equipment performance degradation, providing preventive diagnoses, and reducing the need to (re)program BAS control blocks.
- Ability to connect BAS functions with preventive maintenance systems.

Section 3

TECHNOLOGY SURVEY

The objective of the technology survey was to gather and organize information about existing automated diagnostic technologies.

It is important to note that the same caveat holds true for this investigation as it did for the needs analysis: the survey is merely a sampling of some of the available technologies and is not to be construed as a comprehensive analysis of these technologies. We believe that further investigation of these and other technologies is warranted to better understand the state of the art in automated diagnostics.

METHODOLOGY

We obtained the information for the technology survey through a literature review, expert contacts, the needs analysis, and from published advertisements. We classified the data according to three features: *diagnostic level, information source, and application.*

Diagnostic Level

The diagnostic level of a technology is its location within the spectrum of partially automated to fully automated diagnostic capability. We rated each technology on a scale from 1 to 5, where Level 1 describes partially automated capability at the most minimal level, and Level 5 describes fully automated capability.

- Level 1—data acquisition, no automation
- Level 2—marginally automated diagnostics using simple alarming
- Level 3—partially automated diagnostics using data acquisition, graphical displays, and multiple level alarming
- Level 4—mostly automated diagnostics using a simplified rule base or database
- Level 5—fully automated diagnostics using artificial intelligence, such as an expert system

Information Source

The origin of the technologies and, to some degree, their maturity are reflected in the information source category. Technologies were either used in *commercial* or *military* applications, or were under development at *research* facilities. The commercial technologies review was undertaken to assess the state-of-the-art technologies that are commercially available to building engineers. These technologies

are not building/HVAC specific but include any commercially available diagnostic technology. Commercial technologies were gathered through a combination of expert contacts and literature review.

The military technologies review was included to cover "high-tech" diagnostic capabilities being developed by military sources (e.g., the U.S. Army Construction Engineering Research Laboratory and the Navy Artificial Intelligence Laboratory) and used in military applications (e.g., F-16 diagnostics). Most information about military technologies was gathered from expert contacts.

Finally, technologies under research were investigated to determine how these technologies meet current and future needs. Research efforts were gathered from a literature review.

Application

This feature describes how the technologies have been applied. Technologies are classified either at the *component* level (e.g., individual fans and motors), at the *system* level (e.g., domestic hot water system), or at the *building* level (e.g., building automation systems). Entries are identified corresponding to these three applications. This feature was used to determine the overall scope and impact that a diagnostic technology has.

Automated diagnostic technologies at the component level only "see" one element of the system, and are not affected by any other component. An example is a fan on-off LED display that shows the component (fan) in the system. At the system level, technologies have the ability to diagnose problems with component interactions as well as most components within a system. Example systems include HVAC, heat pump, boiler control, and fire protection systems. The broadest impacts are made by those technologies at the building level. Diagnostic technologies at this level understand system interactions and allow control and diagnostics of the entire facility.

AUTOMATED DIAGNOSTIC TECHNOLOGIES

We use diagnostic level as our primary means of classifying the surveyed technologies. Most of the 56 diagnostic technologies we investigated were classified as Level 3. A frequency distribution of all surveyed technologies is presented in Figure 3-1.

The sample in Figure 3-1 is not representative of the entire population of all available technologies. In fact, far more technologies than shown would be given a Level 1 or Level 2 rating. Because the technologies in these categories did not contribute significantly to our understanding of *automated* diagnostics, only a

Figure 3-1. Frequency distributions of diagnostic technologies surveyed.

few entries appear at these levels to provide a sampling of this level of capability. Levels 3 through 5, on the other hand, were more thoroughly investigated. Descriptions of the levels and summaries of the survey results follow.

Level 5: Automated Diagnostics Using Artificial Intelligence

This is the highest level of complexity found in the technology survey. Technologies categorized as Level 5 use artificial intelligence technologies and are capable of fully automated diagnostics. These technologies typically use model-based reasoning, complex rule-based reasoning, fuzzy logic, and/or neural networks to diagnose systems and components. The Level 5 technologies we investigated are listed in Table 3-1. More detailed descriptions of each are included in Appendix A.

Table 3-1

Fully Automated Diagnostics Using Artificial Intelligence

Technology Description	Company	Category	Level
A Failure Diagnosis System Based on a Neural Network Classifier for the Space Shuttle Main Engine	NASA ^a	Research	System
A Real-Time Simulation Evaluation of an Advanced Detection, Isolation, and Accommodation Algorithm for Sensor Failures in Turbine Engines	NASA	Research	System
A Distributed Fault-Detection and Diagnosis System Using On-Line Parameter Estimation	NASA	Research	System
Embedded Expert System Development for Monitoring Packaged HVAC Equipment	Woolery Corporation	Research	System
Fault Detection and Load Monitoring in Ventilation Systems	MIT ^b	Research	System

^aNational Aeronautics and Space Administration.

^bMassachusetts Institute of Technology.

All the Level 5 technologies we surveyed were still in the research phase. Most of these technologies are fairly advanced, but focus on a specific critical subsystem of a larger, more complex system.

Level 4: Mostly Automated Diagnostics Using a Simplified Rule Base or Database

Level 4 contains the second highest level of complexity found in the technology survey. Technologies grouped in this category have the ability to provide some reasoning for diagnostic purposes but lack the explanation facility of more robust AI systems. Level 4 technologies use simple rule-based algorithms for predefined problems or incorporate large linkable informational databases to compare actual conditions to previous or expected conditions. The main difference between Level 4 and Level 5 is that technologies in Level 4 have less domain knowledge and reasoning capability, and require a greater degree of human assistance to make diagnostic decisions. Table 3-2 lists surveyed technologies in this category. More detailed descriptions of each are included in Appendix A.

The first commercial technologies appear in Level 4. Most Level 4 technologies are on the component or small system level but are more generic than Level 5 technologies. One highlight of this category is ViewPort, a BAS designed by Sems. This was the only BAS found that actually incorporates some type of expert system.

Table 3-2**Mostly Automated Diagnostics Using a Simplified Rule Base or Database**

Technology	Description	Company	Category	Level
Knowledge-Based Software Aids in Decision Making	POMIS	Komatsu and Ford Motor Company	Commercial	Component
		Battelle, Pacific Northwest Laboratories	Research	System
HOTice		Rosemount	Military	System
TRAV Software		The Hartman Company	Commercial	Component
SmartPipe Software		Brown & Root, Inc.	Commercial	System
TrapMan		Control Specialists, Inc.	Commercial	Component
Chiller Acoustical Diagnostics		Johnson Controls	Research	Component
Motor Diagnostics		MIT	Research	Component
Local Area Network Scanners		Microtest	Commercial	System
Energy Analyzer		PSI	Commercial	Building
ViewPort		Sems	Commercial	Building

Unfortunately, much of the diagnostic software in Level 4 is restricted by hardware limitations. The TRAV Software, for example, is used in BASs to provide complete diagnoses of VAV air boxes. Although this software can handle many other components in addition to VAV boxes, it cannot be extended to other parts of the system because of insufficient processing hardware and sensory input.

Level 3: Partially Automated Diagnostics Using Data Acquisition, Graphical Displays, and Multiple Level Alarming

Level 3 includes most commercially available building automation systems and programmable control systems linked with components. The main difference between Levels 3 and 4 is that Level 4 technologies aid the individual by making diagnostic suggestions and Level 3 technologies simply provide the information needed to explain the discrepancy between actual and expected performance without actually performing an analysis. Technologies in this category generally have set-point programmable alarming, graphical trend and real-time displays, and multiple visual aids for manual diagnostics, but are not generally "intelligent." Although most BASs in this category may include some diagnostic logic, they offer very limited programmable memory and slow network speeds. These factors, plus the lack of some sensory information, make automated diagnostics impractical. Some diagnostic software for DDC systems is listed as Level 4, but the BAS itself is rated Level 3. Surveyed technologies in this category are presented in Table 3-3. Appendix A contains more detailed descriptions.

Table 3-3**Partially Automated Diagnostics Using Data Acquisition, Graphical Displays, and Multiple-Level Alarming**

Technology Description	Company	Category	Level
INFINITY	Andover Controls	Commercial	Building
AI2100 Building Brains	AutoMatrix	Commercial	Building
INTELLE-SYS	Delta-Controls	Commercial	Building
KMDigital	Kreuter Manufacturing	Commercial	Building
IMS 2000	Rosemount Boilers	Commercial	System
System 20/20	Automated Logic	Commercial	Building
CCN Building Supervisor	Carrier	Commercial	Building
MAX1000	Leeds & Northrup	Commercial	System
Micromax2	Leeds & Northrup	Commercial	System
Trane Clinic (a manual method)	The Trane Co.	Commercial	Building
Metasys	Johnson Controls	Commercial	Building
Service Net	Honeywell	Commercial	Building
Deltanet	Honeywell	Commercial	Building
Mobile Link	Ecolochem	Commercial	System
UNITY	Electronic Systems	Commercial	Building
INTEGRATOR	Teletrol	Commercial	Building
I/NET 7700	CSI	Commercial	Building
System 600	Landis & Gyr Powers, Inc.	Commercial	Building
Network 8000	Siebe Environmental Controls	Commercial	Building
LabView	National Instruments	Commercial	Component/ System
ALL Acoustic Leak Detection	Babcock & Wilcox	Commercial	Component

A transition of most building automation systems surveyed from Level 3 to Level 4 does not seem likely in the immediate future. BAS producers and end-users are more interested in open protocols and useability than automated diagnostic systems. The cost/benefit ratio of open protocols seems to outrank heavy development of more intelligent diagnostics.

Level 2: Marginally Automated Diagnostics Using Simple Alarming

Level 2 contains the lowest level of automated technologies available. This category includes components with very simple alarm set points and preprogrammed alarms. Alarms are generally sounded when a set point or desired specification is exceeded. Technologies in this category simply allow abnormal conditions to be recognized, with little or no indication of the cause. Most alarms are simple LEDs or printouts. Diagnostics in this category are analogous to a "Check Engine" light in an automobile. The Level 2 technologies we surveyed are listed in Table 3-4. Appendix A contains more detailed descriptions.

Table 3-4**Marginally Automated Diagnostics Using Simple Alarming**

Technology Description	Company	Category	Level
PDD 1000 Acoustical Corona Leak Detection	Babcock & Wilcox	Commercial	Component
Variable-Frequency-Drive Motors	Mototronics	Commercial	Component
Compression Chillers	Van Steenburgh	Commercial	Component
Absorption Chillers	American Yazaki Corp.	Commercial	Component
B6000 Boiler Control System	RayPack	Commercial	System
BCP 7000 Boiler Control	Rosemount	Commercial	System
Kotron Sentinel with Pulsatel Circuitry	Magnetrol	Commercial	Component
ChillGard	MSA	Commercial	System
Water-Source Heat Pumps	The Trane Co.	Commercial	Component/ System
HCFC-22 Flotronic Chiller	Carrier	Commercial	Component
Digital Controls	DataAire	Commercial	Component
Facility Management Software	Omni Corp.	Commercial	Component
Modular VAV Control Systems	Solidyne	Commercial	Component
VAV Control Units	Honeywell	Commercial	Component
Fume Hood Controllers	Accu-Aire	Commercial	System/ Component

Most level 2 technologies are focused on a particular component or subsystem. Although many of these technologies have interfaces to allow them to be networked to larger monitoring systems, their classification is based on their standalone ability.

Level 1: Data Acquisition

Level 1 contains technologies with no automated diagnostic capability. This category exists because manufacturers' claims of diagnostic capability are based on the belief that individuals can use the data delivered by these system to make accurate diagnosis. Surveyed technologies in this category are listed in Table 3-5. More detailed descriptions of the Level 1 technologies appear in Appendix A.

Table 3-5

Technologies with No Automated Diagnostic Capability

Technology Description	Company	Category	Level
Sensor Microphone	Sonic Technology Products	Commercial	Component
Occupancy Sensors	Heath	Commercial	Building
AET 5000	Babcock & Wilcox	Commercial	System

Level 1 technologies are best characterized by Sonic Technology Products' Sensor Microphone. The microphone is advertised as a diagnostic tool, but simply acts as a data collection device. While it is true that this data is required to diagnose a problem, none of the diagnostic analysis is performed by this product—it completely relies on human interpretation.

FINDINGS

The technology survey was conducted to determine the state of the art of diagnostic technologies from the commercial, research, and military sectors. The commercial technologies surveyed range from products with false claims of "diagnostic" capabilities to technologies that use artificial intelligence to aid in explaining abnormal conditions. However, no commercial or military technologies were found to include fully automated diagnostic capabilities. Many products incorporate most of the necessary information to make proper diagnosis, but the fourth step in the diagnostic process—explanation—is still left to the human. The available technologies improve data collection and presentation functions but are not capable of reasoning about *why* actual conditions vary from expected conditions.

Technologies demonstrating the highest level of automated diagnostic capability are classified as Level 5. These technologies incorporate model-based reasoning, neural networks, or detailed rule-based engines to intelligently diagnose problems. All the Level 5 technologies we surveyed are still in the research environment and the range of their application tends to be limited. The more elaborate a technology is, the more likely it is to be limited to a very small or unique application (the military applications were the strongest evidence of this). Most of this research is being done by educational institutions and military contractors; very little is designed for building applications.

Of all the technologies surveyed, most are classified as Level 3. These technologies enable an operator to make a diagnosis based on a wealth of information presented in very useable forms. Level 3 diagnostic technologies include most standard commercial building automation systems. These systems include simple alarming, trending, and low-level programmability.

The most commonly available technologies appear in Levels 1 and 2. These typically range from data collection to simple alarming. Although far more technologies are available in Levels 1 and 2 than in the next three levels, the low degree of automation of these samples is of less interest to the study; consequently, our sample size in Levels 1 and 2 is smaller.

Many technologies incorporate the ability to interface a component to a larger monitoring and evaluation system. These products generally incorporate basic alarming but have the potential to be interfaced with more advanced software. In general, commercial diagnostic technologies are more limited by hardware (sensor points, programmable memory, and network speed) than by software.

In summary, the survey of automated diagnostic technologies yields the following key findings:

- No commercial technology for application in buildings has fully automated diagnostic capabilities (although some are under development at research facilities). The most advanced commercial technologies we surveyed are at Level 4.
- The highest-level technologies are in the research environment.
- Most technologies commercially available are in Levels 1 and 2. Our sample size in these categories is disproportionately small, however, because they offer little in automated diagnostics.
- The more elaborate a technology, the more likely it has been designed for a unique application or component.
- Commercial diagnostic technologies for application in buildings appear to be limited more by hardware than by software.

Section 4

CONCLUSIONS

MEETING CURRENT NEEDS WITH EXISTING TECHNOLOGY

In this section, we discuss how existing technologies can be used to meet the diagnostic needs identified by the building operators we interviewed. We also present the limitations of existing technologies, and offer suggestions on how these limitations can be overcome. In some cases, we observe that new technologies must be developed to meet these and future diagnostic needs.

Diagnostics During Building Commissioning

The building engineers we interviewed found that diagnosing problems during building commissioning was far more difficult than diagnosing problems they observe during daily operation. The primary reason is because components and systems have not yet been balanced and adjusted, and do not yet function together as an integrated system. At this point in the building's life, the operators have yet to establish a base of experience from which to infer (im)proper behavior.

In commissioning, the first diagnostic task is to verify that the building automation system itself is operating correctly. Without this verification, the engineer is faced, for example, with the problem of attempting to determine if a BAS alarm signals a fault in the plant equipment or a fault in the BAS itself.

This problem is compounded by the fact that the building equipment experiences multiple simultaneous faults after installation and startup. Diagnosing multiple faults is a time-consuming task, requiring the building engineer to explore and test a wide range of parameter interdependencies. In the absence of rigorous methods, much of this testing is performed by trial and error.

Existing BAS technology can be useful in identifying faulty situations by providing alarms when various parameters exceed their prespecified bounds. Although these alarms can help identify problems with specific components, they provide very little assistance in system balancing, diagnosing multiple simultaneous faults, and finding the root cause of a problem. Some operators lack the necessary experience to resolve these problems and require assistance from the equipment manufacturer or controls company representative.

It is clear that there is a need to examine the role of diagnosis during the commissioning process. The process may be defined to include an adequate level of component testing so that simultaneous faults are less frequent. In this case, there is a need for simple, component-level diagnostics applied in a methodical

way. There may also be an opportunity to apply current research in automated multifault diagnosis to analyze systems with multiple interdependent components. We believe that building engineers still need a more rigorous methodology for bringing systems on-line and ensuring that they work well together.

Unmonitored/Unalarmed Conditions and Components

A building typically contains hundreds, if not thousands, of conditions and components that should be monitored continuously or on a regular basis. Before the introduction of building automation systems, the status of a condition or component was diagnosed on location by a human. The BAS made this task easier by collecting information from a remote sensor and feeding this information back to a central monitoring station.

Not all components are equipped with remote sensors. Therefore, a building operator may be required to visit components on location and assess status and conditions. This can be time-consuming, especially when the component is located some distance from the central monitoring station. In some cases, however, a site visit is not necessary. Building operators may be able to deduce conditions or status of components by observing the performance of other monitored conditions/components and applying knowledge about how these physically interact with the condition/component in question.

The ability to successfully "diagnose by deduction" depends on a number of factors: the accuracy of information gained from the monitored conditions/components, knowledge of how interconnected components behave, and knowledge of basic physical principles, to name a few. Not all humans can successfully diagnose a situation through deduction, usually because of incomplete or incorrect knowledge of some of these factors. Today's BASs offer no assistance in the deductive process either: they simply present information gathered by the remote sensor. As a result, human operators frequently spend the time to inspect the component "manually" to make a diagnosis, and even then may misdiagnose situations (Jarrell et al. 1990; Drost et al. 1991).

Research is currently being conducted to provide computers the requisite knowledge to perform "diagnosis by deduction." Automated diagnosis of this sort offers some advantages: it reduces the time required for humans to make on-site visits to component locations and it provides a common, accurate knowledge base that both novice and experienced building operators can access.

Current efforts in *model-based reasoning* (MBR), for example, could enable future BASs to assist in this process (Stratton and Jarrell 1991). In MBR, the computer represents and reasons about an internal model of the physical system. The computer also has sufficient knowledge of physical principles to make

deductions or inferences about the behavior of various components, even if those components have no sensors attached to them. Application of MBR and similar techniques can improve the diagnostic capabilities of system-level and building-level technologies, especially for reasoning about components for which data are not immediately available.

As the cost of sensor data points decreases, however, building operators and system designers must continue to assess the trade-off between the cost of adding more data points and the cost of developing and/or purchasing more sophisticated reasoning software (or hiring better-trained staff!). Data from additional sensors can enable an automated diagnostician to produce more extensive and/or more accurate diagnoses.

Cause and Effect Exploration

The building engineers we interviewed typically diagnose components and systems by "working backward." They begin at a point where the problem is identified, then ask what possible causes could contribute to the undesired effect. If these causes do not sufficiently explain the condition, then engineers back up one step further and ask what would influence *those* causes. This backward chaining approach (we also call this "root cause analysis") requires knowledge about component topology; i.e., how the pieces are connected.

Most current diagnostic technologies do not model these topologies explicitly. The backward chaining approach is pursued based on the building engineer's knowledge of the assembly of systems and components, and their relationships to conditions such as air or water temperatures. If the automation system cannot answer a question about a specific "link" in the chain, then the engineer must inspect the components directly to complete the diagnosis. In some cases, building operators who lack the knowledge or equipment to perform backward chaining may simply associate the symptoms with some previously-seen condition and assume there is a cause-and-effect relationship between them.

In the near future, BASs can be designed to help building engineers explore causes and effects. If BASs were programmed with knowledge about how components and systems are connected, they could automatically display a sequence of graphics or schematics that work backward from the alarm to the root cause of the problem. Such graphics could be used to identify components that may require visual inspection. Two of the building engineers interviewed said they would be "very interested" in a system that would automatically display system information related to a particular alarm.

Topological or geometric reasoning are topics that have been studied in the artificial intelligence area for many years. Very little if any of these techniques have found their way into commercial automation and control systems, yet a real opportunity exists for integrating these technologies. In the more distant future, building operators could use a topological model to examine causes and effects to find the root cause(s) of observed faults. Both the BAS and the topological modeling technologies exist: the challenge is to integrate them for automated diagnostic purposes.

Sensors and Fault Handling

The first step in automating the diagnostic process is to acquire sensor data in a digital form. Sensor technology has developed rapidly and continues to improve. Nevertheless, automated diagnostic technologies will always need to handle invalid data from uncalibrated or damaged sensors. Self-calibrating sensors may offer increased reliability, but the computer collecting the data should still be able to recognize "suspicious" (i.e., out of range) readings.

A second concern is the limitations of sensor technology. Humans are still required to "sense" conditions such as sounds, smells, and certain visual attributes of the equipment. The reasons for this are twofold: first, sensors of this type either do not exist or are too expensive for such diagnostic applications; second, even where inexpensive sensors can be used (e.g., video cameras), current technology is inadequate to interpret its signals automatically.

To improve automated diagnostic capabilities, we see three areas for improvement in sensor technology. The first two are hardware issues: increase the reliability of the sensor device itself and develop new sensors that can collect new kinds of information. For example, the "feel" of the equipment can be partially measured through accelerometers, and its "smell" can be determined by advanced "smoke" detectors ("artificial noses"). The third is a software issue: develop techniques to accurately analyze and interpret the output of sensors, especially to compensate for unreliable or malfunctioning sensors.

Trend Analysis for Degradation and "Predictive" Diagnosis

Although many of today's building automation systems include a trend-monitoring capability, this function is used infrequently by the building engineers we interviewed. We observed that most engineers do not monitor the degradation of components or systems to predict their failure ("predictive" diagnostics), but usually perform diagnostics after failure has occurred ("breakdown" diagnostics). Breakdown problems are easy to find, but expensive to fix, especially if the breakdown caused failures in other components and systems. Predictive diagnosis is somewhat more difficult because it requires careful monitoring for subtle

changes in equipment performance over time. However, preventive maintenance is usually far more economical than repair.

Some automation systems allow the engineer to set alarms on various trends, but none of the engineers we interviewed used this function. Furthermore, most engineers had neither the time nor the inclination to study several weeks' worth of numerical data to find potential problems. Currently, trend information is examined occasionally by the building engineers we interviewed to determine if programming changes are necessary for any of a system's control blocks.³

We believe that "intelligent" trend analysis methodologies can be developed to predict component and system failures. Such methodologies would monitor performance changes over time, processing large amounts of data to identify degradation patterns that may lead to future faults. Current research in *machine learning* offers opportunities for computers to acquire such diagnostic capabilities automatically. Neural networks, for example, have been particularly successful at pattern recognition and interpretation, and offer large benefits for trend analysis. Other machine learning techniques would allow the BAS to form connections between trend behavior and equipment failures, building the requisite knowledge for predicting faults. These techniques require that the computer is "trained" with a set of examples of both proper and faulty behavior. Because these examples would typically be extracted from actual system behavior, a considerable amount of time may be required by an expert to distinguish various types of behavior to prepare the training set.

Simulation and Optimization for Energy Management

Today's building automation systems are used primarily to assist humans control building lighting, HVAC, and other equipment. Although the first priority of the operators we interviewed was to satisfy occupants' comfort requirements, the operators prefer to do this in the most energy-efficient way possible. A variety of strategies can be used for energy-efficient operation, but trying to identify a "best" strategy can be difficult. For example, operators who wish to test the effectiveness of a specific strategy must wait for the right climatic conditions, then make adjustments to the operation of the building—sometimes risking a disturbance to its occupants.

A better approach would be to integrate a simulation program with the BAS. The simulation tool would allow the operator to simulate operational strategies, exploring "what if" questions about the energy

³After examining system behavior over weeks or months, the building engineers we interviewed sometimes make minor adjustments to the BAS's program (e.g., modification of set points, shortening or lengthening the schedule of operation) to improve performance. While these adjustments are usually minor, they do require programming knowledge to modify the BAS control blocks.

efficiency of various approaches (without affecting the building itself). By also integrating an optimization routine, the operator (or the computer) could also search for optimal values for operational parameters. Simulation and optimization programs currently exist and have widespread use, but we found none to be integrated with the surveyed building automation systems. This may suggest that further development of such programs is required before such integration can be accomplished.

Diagnostics and Preventive Maintenance

In the facilities we visited, we found no cases in which the BAS was used for preventive maintenance. Either the BAS did not support automated PM scheduling or the PM functions were supported but not used by the building engineer. Frequently PM scheduling was handled through spreadsheet-based software on a PC. Although it would make sense for the automation system to schedule PMs based on hours of actual operation or on characteristics of current operation, this capability was not used. The reason was primarily one of interface and ease-of-use: building engineers simply found the spreadsheet software much easier to work with.

It is clear that preventive maintenance can help prevent larger, more expensive repairs later in the life of a component or system, as well as extending the life of the equipment. Equipment can degrade or fail prematurely if PMs are not performed at appropriate intervals. The question, however, is "what is the appropriate frequency of preventive maintenance?" We believe that the BAS can be used to answer this question. The BAS can track the hours of operation for an individual component, and can also sense degradation of performance that would suggest a maintenance activity. Although current BASs do not use this information to schedule PMs, future automation systems can save time, energy, and money by "intelligently" scheduling maintenance at appropriate intervals.

OBSERVATIONS AND RECOMMENDATIONS FOR FUTURE WORK

Some of the diagnostic needs of building engineers can be satisfied by existing technologies. However, several needs can be fulfilled only by the research, development, and implementation of new technologies. Based on our assessment of needs (Section 2) and our evaluation of the current state of automated diagnostics (Section 3), we recommend the following areas for future research and development.

Diagnostics During Building Commissioning

- Tools and techniques to aid building engineers in diagnosing problems when systems and components are brought on-line during the commissioning process. Such tools would be particularly helpful if they have knowledge about how components and systems are integrated.

- Technology capable of automatically diagnosing multiple simultaneous faults.

Unmonitored/Unalarmed Conditions and Components

- Implementation of model-based reasoning and similar techniques to reason about components for which data are unavailable. These techniques can improve the automation of the diagnostic process when some of the components are unmonitored and/or unalarmed.
- Characterization of fault conditions at the component and system level, and incorporation into a knowledge base.

Cause and Effect Exploration

- Automated aids for BASs to support cause-and-effect backtracking (i.e., root cause analysis). BASs should be knowledgeable about interacting components and designed to respond to the operator's queries for status information during backward-chaining diagnostic procedures, or carry out these diagnoses automatically.
- Integration of advanced models (e.g., topological models) and modeling techniques with building automation systems to assist in root cause analysis.

Sensors and Fault Handling

- Development of more reliable, inexpensive sensors.
- Development and implementation of new, inexpensive sensors that provide data on smells, sounds, feels, and sights. Integration of these sensors with building automation systems.
- More intelligent systems that can identify and compensate for malfunctioning sensors.

Trend Analysis for Degradation and "Predictive" Diagnosis

- Development of advanced technologies (e.g., machine learning and neural networks) for analyzing trend information to detect equipment degradation and for acquiring knowledge to predict equipment failures.

Simulation and Optimization for Energy Management

- Development and integration of simulation and optimization with building automation systems to identify energy-conserving operational strategies.
- Integration of control, diagnostic, and preventive maintenance systems for cost-effective operation and energy efficiency.

Finally, we recommend a broader study of needs and diagnostic technologies. Although our sample was large enough to provide some insights on the needs for, and potential capabilities of, automated diagnostic technologies for a special class of buildings, we feel that it is not large enough to accurately represent the state of diagnostics in the buildings industry.

Section 5

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Appendix

AUTOMATED DIAGNOSTIC TECHNOLOGIES

AUTOMATED DIAGNOSTIC TECHNOLOGIES

LEVEL 5: FULLY AUTOMATED DIAGNOSTICS USING ARTIFICIAL INTELLIGENCE

In terms of complexity, Level 5 is the highest found in the technology survey. Technologies grouped in this category use artificial intelligence techniques to provide fully automated diagnostics. The Level 5 technologies we surveyed use model-based reasoning, complex rule-based reasoning, fuzzy logic, and/or neural networks to diagnose systems and components.

A Distributed Fault-Detection and Diagnosis System Using On-Line Parameter Estimation. Guo, Merrill, and Duyar (1991) describe a model-based fault-detection and diagnosis system based on a distributed system identification approach. The diagnostic system consists of a two-level process including parallel hypothesis-testing modules and a fault mode identification and estimation module. The proposed system is part of a distributed diagnostic system for use in an intelligent control system. The proposed approach employs a piecewise linear model to predict the system performance. The deviation between predicted and actual performance is used to identify the associated fault mode. Each hypothesis-testing module is associated with a specific class of fault modes and can be viewed as a condition monitor in a distributed diagnostic system hierarchy. The results of the hypothesis modules are processed by the fault-detection and estimation module. Using the results of the on-line diagnosis, the intelligent control system will be able to accommodate the fault modes, reduce maintenance cost, and increase system availability.

- Company: NASA
- Source: Research
- Application: System

A Failure Diagnosis System Based on a Neural Network Classifier for the Space Shuttle Main Engine

A conceptual design of a model-based failure detection and diagnosis system is developed for the space shuttle main engine (Duyar and Merrill 1990). This design relies on the accurate and reliable identification of the parameters of the highly nonlinear and very complex engine. The design approach is presented in some detail, and results for a failed valve are presented. These preliminary results verify that the developed parameter identification technique, together with a neural network classifier, can be used for this purpose.

- Company: NASA
- Source: Research

- Application: System

A Real-Time Simulation Evaluation of an Advanced Detection, Isolation, and Accommodation Algorithm for Sensor Failures in Turbine Engines

An advanced sensor failure detection, isolation, and accommodation (ADIA) algorithm has been developed for use with an aircraft turbofan engine control system (Merrill and DeLaat 1986). The evaluation used a real-time hybrid computer simulation of an F100 turbofan engine.

- Company: NASA
- Source: Research
- Application: System

Embedded Expert System Development for Monitoring Packaged HVAC Equipment

Kaler (1990) describes the developmental considerations for a commercially viable knowledge-based monitor for HVAC equipment. Previous papers and articles have been presented that describe the development of large-scale knowledge-based expert systems for assisting a human operator in a non-real-time diagnosis of comfort system problems. This paper examines the development of a real-time embedded expert system for evaluating the performance of an HVAC unit at any point in time and for the automatic diagnosis of potential fault conditions. The paper identifies and discusses some of the considerations that were addressed in the product design and summarizes several case studies.

- Company: Woolery Technology Corporation
- Source: Research
- Application: System

Fault Detection and Load Monitoring in Ventilation Systems

Faults in heating, ventilating, and air-conditioning systems comprise a range of problems that can increase energy consumption or equipment wear and can adversely affect building occupants (Norford and Little 1993). Faults can be detected by measuring equipment performance relative to a model-based prediction or relative to more common-sense expectations of what constitutes acceptable performance. This paper first classifies faults for ventilating systems consisting of fans, ducts, dampers, heat exchangers, and controls. It then reviews two forms of steady-state, parametric models for the electric power used by ventilation system fans and proposes a third: that of correlating power with variable-speed-drive control signals. The models are compared on the basis of prediction accuracy, sensor requirements, and ability to detect faults. Power-control signal correlations, in preference to other models, can be established with power measurements taken at the HVAC electrical distribution panel when other loads are constant, thereby eliminating the need for submetering. Error analysis associated with model fits, so crucial to determine the minimum detectable fault size, is discussed in detail. Finally, the use of parametric models to distinguish multiple fans from a single electric power measurement is described.

- Company: Department of Architecture, MIT
- Source: Research
- Application: System

LEVEL 4: MOSTLY AUTOMATED DIAGNOSTICS USING A SIMPLIFIED RULE BASE OR DATABASE

Level 4 contains the second-highest level of complexity found in the technology survey. Technologies grouped in this category are able to provide some reasoning for diagnostic purposes but lack the explanation facility of more robust artificial intelligence (AI) systems. Technologies in this group use simple rule-based algorithms for predefined problems or incorporate large linkable informational databases to compare actual conditions to previous or expected conditions. The main difference between levels 4 and 5 is that the technologies categorized as Level 4 have less domain knowledge and reasoning capability, and require a greater degree of human assistance to make diagnostic decisions.

Knowledge-Based Software Aids In Decision-Making

An agreement between Komatsu and Ford Motor allows Ford maintenance employees to use knowledge-based software to diagnose problems with machinery presses. Using software, workers are guided through a series of questions to determine the root cause of a difficulty. Then, the software assists with repairs. Although the software will not give the answers to every problem, it can help diagnose the most common and frequently encountered repair tasks (Orge undated).

- Company: Komatsu and Ford Motor Company
- Source: Commercial
- Application: Component

The Portable Operations and Maintenance Information System (POMIS)

An integrated system of hardware and software, POMIS delivers operation and maintenance (O&M) information, procedures, and advanced diagnostics to the people who need it most — O&M staff working in the field. All information display and diagnostic capabilities are provided directly by wireless communications. POMIS provides appropriate and complete information to the remote location by way of an informational database (Szydlowski 1993).

- Company: Battelle, Pacific Northwest Laboratories
- Source: Research
- Application: System

HOTIce Detection System

Rosemount HOT[™] detection system uses a microprocessor-based system to determine ice buildup levels on aircraft. The system uses current-resistance techniques to measure ice levels on critical components. The system can determine ice levels and sensor failure rates and reports. It also can intelligently operate de-icing equipment.

- Company: Rosemount Aerospace
- Source: Military
- Application: Component

TRAV Diagnostic Software

The TRAV software is designed for DDC building control systems with terminally regulated air volume (TRAV) boxes. During system off-hours, the software checks for damper position controls and air flow rates, producing a specific report for each TRAV box.

- Company: The Hartman Company
- Source: Commercial
- Application: Component

Smart Piping Diagnostic Software

After a piping system is installed or repaired, benchmark data is collected. That data includes system-wide information such as operating temperature, pressures, and hours. Piping information includes date of installation, calculated thermal and sustained stresses, and noticeable sagging or damaged insulation. Pipe support data includes hanger settings, rod offsets, pipe movements, and conditions of welds. The system compares new data collected to the benchmark data. It evaluates the data and troubleshoots by listing possible causes. The possibilities are ranked from most likely to least likely using a confidence factor.

- Company: Brown and Root, Inc.
- Source: Commercial
- Application: System

TrapMan Steam Trap Management System

TrapMan computerized steam trap management system provides total support for a predictive steam trap maintenance program. A portable test instrument records data by placing a probe at the inlet of a steam trap. TrapMan diagnoses the operating mode by comparing current data to a databank with predefined operating mode characteristics. The TrapMan system can suggest replacement steam trap types and record maintenance logs to be accessed on every diagnosis.

- Company: Control Specialist, Inc.
- Source: Commercial
- Application: Component

Chiller Compressor Acoustical Diagnostic Software

Research is being conducted to capture compressor acoustical signatures for multiple compressor off-normal conditions. The information is stored in a database. During actual operation, a diagnostic software will compare current acoustical signatures to this database and diagnose abnormal operation. It also allows effective predictive troubleshooting.

- Company: Johnson Controls
- Source: Research
- Application: Component

Automated Trouble Shooting Software

The automated troubleshooting software is used in Landis and Gyr Powers building control systems. Basically, internal application information/equations are developed, and the system programmability is used to customize absolute and relative information. The software is a database of system checks that helps the operator troubleshoot more effectively. The software is rarely fully installed because of unique building systems.

- Company: Landis and Gyr Powers, Inc.
- Source: Research
- Application: Building

Motor Diagnostics

MIT is conducting research on electric motor diagnostics. The research involves creating a database of motor performance based on operational status and the amount of current being drawn. The hope is to be able to predict and prevent motor failure by having an intelligent system monitor the motor current draw and diagnose operation problems using a predefined set of rules.

- Company: MIT
- Source: Research
- Application: Components

Local Area Network Scanners

The MT350 scanner incorporates an expert system architecture, sophisticated cable diagnostic, and certification technology into a hand-held instrument. The scanner certifies whether new or existing cables will support Ethernet or ARCNET local area networks (LANs). Based on predefined rules, the scanners can diagnose and certify networks.

- Company: Microtest
- Source: Commercial
- Application: System

Energy Analyzer Software

PSI Energy Analyzer software allows DDC software to alter system operation based on real-time pricing signals. The software uses operator-defined logic to alter system control strategies based on pricing signals and produce cost-efficient equipment operation.

- Company: PSI
- Source: Commercial
- Application: Building

ViewPort

ViewPort is a graphics-based operator system that lets building operators control all critical building systems from a central location. The software provides elaborate schematics of the building, system, and plant, with all critical information reported. Alarms are audible and visible. ViewPort contains an expert system that uses a set of predefined rules to help diagnose building operational problems. The expert system is an interactive aid that prompts the operator for problem specifics and then suggests possible causes.

- Company: Sems
- Source: Commercial
- Application: Building

LEVEL 3: PARTIALLY AUTOMATED DIAGNOSTICS USING DATA ACQUISITION, GRAPHICAL DISPLAYS, AND MULTIPLE-LEVEL ALARMING

Level 3 includes most commercially available building control systems and programmable control systems linked with components. The main difference between Levels 3 and 4 is that Level 4 technologies aid the individual by making diagnostic suggestions while Level 3 technologies simply provide the information needed to explain the discrepancy between actual and expected performance without actually making an analysis. Technologies in this category generally have set-point programmable alarming, graphical trend and real-time displays, and multiple visual aids for manual diagnostics. However, they are not generally intelligent. Although most building automation systems in this category may include some diagnostic logic, they offer very limited programmable memory and slow network speeds. The lack of some sensory information makes automated diagnostics impractical. Some diagnostic software for DDC systems is listed as Level 4, but the BAS itself is rated Level 3.

System 20/20

System 20/20 has a highly modular architecture that uses a network of microprocessor modules, each capable of stand-alone DDC system control. The stand-alone modules are interfaced with a central window-based software package. The central control monitor allows system interaction and displays

three-dimensional visual schematics of floor plans, systems, and plants with operation information overlain on the graphics. All critical set points can be alarmed, and simple programming is possible.

- Company: Automated Logic
- Source: Commercial
- Application: Building

INFINITY

INFINITY features a family of distributed, stand-alone controllers to meet many building control requirements. INFINITY controllers feature universal inputs and outputs, built-in override switches, and optional LCD displays. Dynamic, animated graphic screens are used by SX8000-0S/2, LAN Compatible Workstations. The system management software features a universal report generator, calendar scheduling, and long-term trending. The INFINITY system incorporates an extremely fast LAN system and simple-logic programmed alarming.

- Company: Andover Controls
- Source: Commercial
- Application: Building

AI2100 Building Brains

The Building Brains control package features distributed control modules integrated with AI2100/SPECTRA. SPECTRA is an informational management software tool that provides real-time information management and control for entire facilities. The software features dynamic color graphics, historical data trending, real-time data collection, dial-in/out communications, and database upload/download capabilities. Central monitoring capabilities allow visible and audible alarming and the ability to query routine maintenance information.

- Company: AutoMatrix
- Source: Commercial
- Application: Building

INTELLE-SYS

INTELLE-SYS is a high-speed, distributed building control system. INTELLE-SYS features fully distributed programming and network speed of over 1 million baud. The system is integrated with a central control terminal that includes dynamic graphics of equipment and floor plans, data trending, simple-logic programmability, and multiple levels of alarming.

- Company: Delta-Controls
- Source: Commercial
- Application: Building

KMDigital

KMDigital controller/energy management products are stand-alone controllers and monitors. The software interface incorporates three-dimensional dynamic graphics, trending capabilities, alarming, and simple programming. The system also offers predefined energy management programs to make system operation fast and efficient. These programs are application-modified to a specific buildings needs.

- Company: Kreuter Manufacturing Company
- Source: Commercial
- Application: Building

IMS 2000

Boiler Management software interfaces with local boiler control units. Boiler control is achieved using a windows-based software to monitor and operate equipment. Abnormal conditions are reported using audible and visible alarming.

- Company: Rosemount Boilers
- Source: Commercial
- Application: System

CCN Building Supervisor

A central control system that gives an operator a single access window to the entire building HVAC system, Building Supervisor allows graphical representation of the building HVAC system with simple alarming and minimal programmability.

- Company: Carrier
- Source: Commercial
- Application: Building

MAX1000

MAX1000 is a distributed control automation system that provides powerful data acquisition, process control, and information management capabilities. The system includes a distributed processing unit that performs all functions, reducing the need for maintenance training and spare parts. Information is passed using a fiber-optic data highway that ties together all devices without the need for gateways or bus interfaces. The user workstation is based on Microsoft Windows graphical environment and gives point and click control over processes. The system allows the user to view multiple windows of instrument faceplates, graphs, and trend plots. Both visible and audible alarming is used, based on predefined simple logic.

- Company: Leeds & Northrup
- Source: Commercial
- Application: System

Micromax2

Micromax2 is a local processing unit that combines data acquisition, loop control, and relay ladder logic to automate unit processes. The system includes set-point alarming via audible and visible signals. The system supplies graphical representation of process and records trend data accessible with a windows-based software.

- Company: Leeds & Northrup
- Source: Commercial
- Application: System

Trane Clinic

A clinic managed by the Trane Company that teaches building managers how to effectively use their BASs to troubleshoot building HVAC system breakdowns. There is no integration of clinic fundamentals into an intelligent system. All training rules are for manual application.

- Company: Trane
- Source: Commercial
- Application: Building

Metasys

Metasys performs environmental control, energy management, maintenance management, lighting control, fire management, and security functions. The basic architecture consists of multiple programmable control panels and an operator workstation that communicates using a high-speed LAN. The operator workstation is a programming and facility monitoring tool that allows the building manager to control the facility and interactively change equipment status, schedules, set points, and control strategies. Metasys allows the operator to program alarming based upon defined set points and simple logic. Alarms are displayed in multiple forms, and all system information is graphically represented using trend graphs and system schematics.

- Company: Johnson Controls
- Source: Commercial
- Application: Building

Service Net

Service Net is a service provided by Honeywell in which a remote staff monitors building performance. The remote staff alerts building supervisors/operators of any abnormal conditions or performance degradation.

- Company: Honeywell
- Source: Commercial
- Application: Building

Deltanet

Deltanet is a modular building control and management system. The control system uses local control units interfaced with an operator control unit. The central control unit allows the operator to observe the system status via graphical representation, active trending, and simple alarming. Much of the alarming is predefined, and the system has limited programmability.

- Company: Honeywell
- Source: Commercial
- Application: Building

Mobile Link

Ecolochem technology provides real-time and historical data for remote monitoring supplemental water treatment systems. The custom-engineered MobilLink DAS computer console records, analyzes, stores, and transmits data from checkpoints. At designated intervals, Ecolochem's central computer center automatically receives data from the jobsite computer, which it displays in graphs, dials, meters. Should an alarm set point be exceeded, both audible and visible alarm signals are triggered.

- Company: Ecolochem
- Source: Commercial
- Application: System

UNITY

Unity is a multivendor front-end platform to monitor building performance. Unity integrates field equipment from a variety of manufacturers and uses the IBM OS/2 multi-tasking operating system. The system is a graphic-based operator interface that allows operator-based diagnostics using displayed data. Unity is equipped with simple set-point alarming and minimal programmability.

- Company: Electronic Systems
- Source: Commercial
- Application: Building

INTEGRATOR

The INTEGRATOR control system features several semi-local control units linked with a moderate-speed LAN. Users interact with the control system using the MCP software, which is fully menu-driven with easy-to-use pull-down menus and extensive on-line help. A flexible color graphics option allows the operator all of the information in the control system through dynamic, visual representation of building equipment. The monitoring portion of the MCP allows the operator to view and change the values of input and output points, set points, alarm limits, and other variables. MCP maintains a comprehensive database of information for every point in the system. This trend data is easily accessible.

- Company: Teletrol
- Source: Commercial

- Application: Building

I/NET 7700

I/NET is a high-performance, network-based family of hardware and software designed for fully distributed control and data acquisition. I/NET employs multiple workstations to analyze system status. Maintenance-related data goes to maintenance workstations, cost data goes to an accounting station, and intelligent controllers trend the data. Critical information is archived, and reports are generated automatically. The interface is a color graphic set of screens to give easy access to diagnostic information. The system has simple programmable alarming.

- Company: CSI
- Source: Commercial
- Application: Building

System 600

The System 600 includes the MBC building controller system and the Insight graphics package. The MBC controllers are local, semi-stand-alone controllers that communicate with the DDC via a moderate-speed network. The Insight graphics package uses elaborate schematics of the building, system, and plant to display critical operational information. The Insight software records trend data, and incorporates set-point alarming and simple programmability for diagnostic rules.

- Company: Landis & Gyr Powers, Inc.
- Source: Commercial
- Application: Building

Network 8000

The heart of the Network 8000 is the Global Control Module (GCM). The GCM is a stand-alone controller. It controls up to 128 input/output devices while simultaneously managing facility function such as status reporting, alarm notification, and communications. The GCM is monitored by a PC-based interface that produces elaborate system graphics, data trending, and equipment status. Simple logic for diagnostic purposes can be used to alarm abnormal conditions. Alarms are visible and audible. The system communicates via a high-speed LAN.

- Company: Siebe Environmental Controls
- Source: Commercial
- Application: Building

LabVIEW

LabVIEW is a graphical programming system for data acquisition and control, data analysis, and data presentation. LabVIEW offers an innovative programming methodology in which the user graphically assembles software modules called virtual instruments. The virtual instruments acquire data from plug-in

boards and programmable instruments. The user then analyzes the data and presents the results with graphical interfaces. LabVIEW is designed for laboratory applications.

- Company: National Instruments
- Source: Commercial
- Application: Component/System

ALL Acoustic Leak Detection

Output from airborne or structure-borne noise sensors located on boilers and piping systems is fed through a central microprocessor unit to a graphical software interface. The ALL acoustic leak detection system enables this output to be projected onto schematics of equipment. Predefined conditions can be alarmed audibly and visibly.

- Company: Babcock & Wilcox
- Source: Commercial
- Application: Component

LEVEL 2: AUTOMATED DIAGNOSTICS USING SIMPLE ALARMING

Level 2 contains the lowest level of automated technologies available. This category includes components with very simple alarm set points and preprogrammed alarms. Alarms are generally sounded when a set point or desired specification is exceeded. Technologies in this category simply allow abnormal conditions to be recognized with little or no indication of the cause. Most alarms are simple LEDs or printouts. Diagnostics in this category are analogous to a "Check Engine" light in an automobile.

PDD 1000 Acoustical Corona Leak Detection

A portable leak detection system is used to detect corona emissions from transformers. The unit measures and reports the corona emission level.

- Company: Babcock & Wilcox
- Source: Commercial
- Application: Component

VFD Motors

The K-series controller is an alternating current (ac) inverter featuring digital operation using a front panel keypad interface for variable-speed ac motor drive application. The controller features 26 keypad-programmable features. Some of the monitored variables are motor acceleration, deceleration, present speed, and running speed. Another keypad programs the controller to monitor, sort, and display fault diagnostics. The digital display identifies basic predefined fault conditions with an easy-to-understand digital readout. The last three fault conditions are stored in memory.

- Company: Mototronics
- Source: Commercial

- Application: Component

Compression Chillers

The Chill-Track liquid chiller system provides simple diagnostics on critical parameters. Chiller operation mode, pump status, suction pressure, flow rate, and temperatures are monitored, and off-normal conditions are represented with lights and dials.

- Company: Van Steenburgh
- Source: Commercial
- Application: Component

Absorption Chillers

Yazaki gas-fired chiller heaters are designed for commercial applications and have simple component alarming. High- and low-temperature generators, condensers, evaporators, and absorbers are monitored and alarmed using simple LED status displays.

- Company: American Yazaki Corp.
- Source: Commercial
- Application: Component

B6000 Boiler Control System

The B6000 boiler management system is composed of a boiler monitor for each boiler in a system and one system control for each system. The B6000 system control has up to 13 separate displays that have the capability to give system status or allow the user to program new data.

- Company: RayPack
- Source: Commercial
- Application: System

BCP 7000 Boiler Control

The BCP 7000 is a unitized microprocessor-based package, with the capability to provide control of gas, oil- or coal-fired boilers and hot water generators. Pre-engineered configurations are provided to execute combustion control, feedwater control, draft control and oxygen trim. The BCP 700 contains an eight-alarm first-out annunciator panel with customized legends and alarm acknowledge push-buttons. Alarms are displayed on simple LED.

- Company: Rosemount
- Source: Commercial
- Application: System

Kotron Sentinel Point Level Switch with Pulsatel Circuitry

The Kotron Sentinel Point Level Switch is a microprocessor-based device that yields relay control and comprehensive self-diagnostics. The diagnostics check the system every 10 seconds, minimizing the

need for routine maintenance. Diagnostics display up to 16 error messages showing status of microprocessor, stored data, cable, preamplifier, and probe for simplified troubleshooting. Diagnostics check the actual integrity of the probe. One relay can be dedicated as a diagnostic alarm.

- Company: Magnetrol
- Source: Commercial
- Application: Component

ChillGard - Refrigerant Leak Detection

The ChillGard refrigerant leak detection system features highly stable infrared photo-acoustic sensing technology. This microprocessor-based analyzer provides local audible and visible indication of gas presence caused by leaks or spills from chillers, pipes, tanks, and storage areas.

- Company: MSA
- Source: Commercial
- Application: System

Water Source Heat Pumps

A micro-electronic controller or unit control processor is installed in most Trane water-source heat pump units. The features of this control are random start, anti-short cycle timer, common alarm output, enable/disable input, load shed input, and a TRACER communication interface to communicate with a building automation system. An automatic changeover sensor is equipped with LED indicator lights to indicate system status: cooling, heating, system on, and service. One diagnostic can be displayed at a time.

- Company: Trane
- Source: Commercial
- Application: Component/System

HCFC-22 Flotronic Chiller

External communications permit integration with building-wide control networks such as CCN. The chiller can also be linked to a personal computer for remote or off-site monitoring and control. An eight-character alphanumeric display facilitates control and diagnostics.

- Company: Carrier
- Source: Commercial
- Application: Component

Digital Controls

Data Aire supplies a line of digital, microprocessor-based controls. The controls include automatic self-test diagnostics. Multiple alarming capabilities are based on simple set points and displayed on simple LED.

Information is also sent to a central, PC-based network that stores alarm history and provides graphic strip charts and trend data.

- Company: Data Aire
- Source: Commercial
- Application: Component

Facility Management Software

Omni Corporation's energy management and maintenance software is used to store preventive maintenance schedules, work orders, equipment histories, and energy cost. The software has the ability to help diagnosis equipment problems based on histories and energy cost changes, but it is not connected to the building BAS or DDC system. The software is simply a data analysis tool that requires data input from operators.

- Company: Omni Corp
- Source: Commercial
- Application: Building

Modular VAV Control Systems

The MVAC zone control system is a microprocessor-based temperature control system designed for stand-alone or networked control of pressure-independent or -dependent VAV terminal units. The system allows programming of temperature and airflow set points and alarms based on preprogrammed set points. Alarming is audible and visible and can be integrated with the BAS.

- Company: Solidyne
- Source: Commercial
- Application: Component

VAV Control Units

Variable-air-volume control system features PI control. The system monitoring and alarming features included freeze stat, discharge air low temperature, high static pressure, outdoor enthalpy, compressor high/low pressure, dirty filter, air flow failure, low oil pressure, and fan motor failure.

- Company: Honeywell
- Source: Commercial
- Application: Component

Fume Hood Controllers

Laboratory fume hoods are controlled by several local control units and interfaced with a central control unit. The individual control unit regulates ventilation flows and purge rates, and the central system monitors and alarms off-normal conditions. Alarming is based on simple set-point violations.

- Company: Accu-Aire
- Source: Commercial
- Application: System

LEVEL 1: DATA ACQUISITION

Level 1 contains technologies with no automated diagnostic capability. This category exists because manufacturers' claims of diagnostic capability are based on the belief that individuals can use the data delivered by these systems to make accurate diagnosis.

Sensor Microphone

Promoted as a *sound diagnostic tool*, the sensor microphone allows equipment sounds to be amplified and pinpointed more accurately. It is simply an amplification device.

- Company: Sonic Technology Products
- Source: Commercial
- Application: System

Occupancy Sensors

These occupancy sensors are designed to avoid false signals, so are promoted as "smart" sensors." They can be connected to a BAS that is logically programmed, but the sensors are purely sensory components with no diagnostic features.

- Company: Heath
- Source: Commercial
- Application: Building

AET 5000

The AET 5500 acoustic emission system provides technology for detecting, monitoring, and correlating acoustic emission signals. When integrated with PostPlot software, the system allows data acquisition with a wide range of data analysis capabilities.

- Company: Babcock & Wilcox
- Source: Commercial
- Application: System

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