Integrated Smart Tool Concepts

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SUMMARY

Reductions in the size and cost of sensors, microprocessors, and transmission and data storage devices permit the development of construction tools with built-in sensing and data processing capabilities. Such "smart tools" could assess installation conditions and respond accordingly, allow inspection at the time of installation, and, with appropriate data transmission technology, provide timely feedback of information for use in project control. This paper presents a strategic plan for long range research into integrated smart tool systems, and provides an example of how smart tool technologies could improve the acquisition, transfer, and use of information in construction projects.

key words: automation, construction, databases, equipment, project controls, sensors, tools

INTRODUCTION

Accurate, timely, well-presented information aids in the effective control of any project. The automated processing of information has received a great deal of attention, and software which assists in planning, design, estimating, and scheduling is readily available. There has, however, been much less emphasis on the automated *collection* of information on construction work in progress.

Most information about the state of construction operations is currently obtained visually, recorded on paper, and eventually either transferred to a more permanent storage medium (paper or electronic) or lost. For example, a foreman will assign a crew to a particular task, and at various intervals (e.g. hourly, daily, weekly), determine what portion of the task has been completed. This information is then relayed to the field superintendent verbally or in writing. The field superintendent will either make a mental note of the information or record it on paper. The time and expense involved in transferring the information to a computer typically precludes its incorporation into a project database in time to be of use in project control. A cost effective means of automatically acquiring project status information in a computer-readable form could provide a project manager with up-to-date information upon which to base project control decisions.

Construction tools and equipment provide an excellent platform for this sort of data acquisition system. The past twenty years have seen an increase in the use of sensors and microprocessors to monitor and control both internal and external functions of heavy equipment. Electronic systems are used to monitor engine speed and control transmission output to maximize performance. Machine operators are further aided by sensing systems that allow real-time monitoring of work in progress and, in some cases, provide input to automatic control systems. As sensor and microprocessor prices fall, similar developments are beginning to be seen in hand and power tools. Several types of microprocessor-based tape measures and levels are commercially available. Power tool producers are following the lead of their heavy equipment counterparts, using sensors and microprocessors to monitor and control the internal and external functions of power tools.

Existing applications of sensors and microprocessors in tools and equipment have focused primarily on improving the "immediate" control of a process. However, once sensors and processors have been incorporated into a tool or piece of equipment, it is a logical and vital step to incorporate the capacity to store data for on-line or off-line downloading to project control system. The resulting "smart tools" could improve productivity not only at the time and place of installation, but, by providing near-real-time feedback of information for use in project control, at the management level as well. The following section provides a glimpse of the integrated project control system of the future.

A SMART TOOL SCENARIO

As project manager for a large powerplant project, Ben Crandall has special responsibility for cost and schedule performance on this leading edge project. Accordingly, he and his company have chosen to use a project control systems environment that is comparatively advanced for its time, 1999. Nevertheless, there is confidence among the team that this choice is cost effective.

Crandall starts his day perusing the color displays that graphically depict the concrete work on the foundation mat of the turbine-generator building. Yesterday's 4000 cubic yard lift was tracked using a video sensor mounted atop the concrete pump. A slightly larger lift is planned for today. The colorized lift placement schedule seen in one of the computer screen windows indicates that this pour is the largest that will have to placed for the next 3 months. A quick scan of concreting crew and productivity data assures Crandall that today's lift is under control. He then turns his attention to the extensive jackhammering operations that will need to be watched carefully.

Tie-in to an existing facility requires that a wall of very high strength concrete laced with dense reinforcement be demolished. Part of the work will be enclosed in a hot, dusty, poorly-lighted environment. Access for rubble removal won't be easy. As our project manager replays a video tape of the work area that was recorded during yesterday's end-of-shift scan, he sees that the scissor lifts are indeed in place as the large-equipment database indicates. However, the smaller lift won't be freed from duct installation in the water treatment facility until 10:00 am today. Checking the labor database, he sees that a crew of laborers led by Sarah Thompson will be going in to do the demolition work as scheduled. Crandall learns from his Intelligent Exception Reporter system that they did similar demolition work 3 weeks ago in the maintenance shop tie-in. With this behind him, Crandall scans the owner's shop drawing review status by paging over another screen on his workstation.

A short time later, the demolition crew has arrived at the site and is gearing up for the day. Sarah Thompson reviews her terminal and, just as she remembered, sees that the north wall breakthrough is on tap for today. She calls over two workers, Thanh and David, and lays the work out for them using the electronic as-built file; they ask for a hard-copy of the rebar schedule so they can anticipate where the major burns will take place. With the recent introduction of a remote-control rubble manipulator, they can now safely handle pieces that weigh 3 tons and measure 12 feet in length.

Thanh goes over to the tool shack to get a jackhammer. The barcode scanner records his employee number and the tool he's taking. He glances at the on-line maintenance record, and determines that this jackhammer was serviced just last week. For today's heavy workload, the on-line advisor recommends that Thanh take 3 extra bits with him just in case.

As Thanh proceeds to the work area, our project manager, Ben Crandall, receives an e-mail message from the client's representative saying that the delivery of the turbine-generator package has been accelerated 1 week. Delighted, but somewhat skeptical, he proposes a video-conference with client and vendor. During the call Crandall confirms the early delivery of the unit, and at the same time provides a "best guess" of the impact on start-up timing using the scheduling system at his disposal. In the back of his mind he realizes that his hunch of earlier in the day was right — demolition of that operating plant wall has just become the critical task.

As the conference call finishes, Crandall decides to consider alternative scenarios for the work in progress. He contacts Thompson, the crew leader. Working simultaneously from their computer screens, they check performance and progress data. Thompson looks at real-time data while talking to Crandall. Reviewing compressor output since the start of the day, she can see that the jackhammer operations have proceeded with little disruption. Rate of air flow data tells her that the compressor in the area is not being overtaxed. Indeed, another 2-person crew could probably be supported without bringing in more compressor capacity. A review of the as-built plan using 3D animation software indicates that an additional team could actually fit without overcrowding the work space. Output from the temperature, humidity, noise, and dust sensors in the OSHpack hazardous environment monitoring kit, however, suggests that less than optimum conditions exist for an additional crew.

While Thompson investigates the feasibility of putting two more people to work on the wall demolition, Crandall searches for the people and resources. Communicating with other superintendents and crew leaders, he finds that indeed there is a 2-person team finishing up on another part of the project, and that they could start on the demolition work tomorrow. They have been drilling anchor bolts in a mat for some large vessels. Tolerances on that task were of critical concern, and the sensing data and reports indicate that positional details were sufficiently accurate to preclude personal inspection by the client's staff. These people are clearly accustomed to precision quality "finish" work rather than the "blow & go" approach common to demolition.

With the wealth of real-time project control data available to them, project managers like Crandall have more information at hand to make project assignments and decisions wisely. Contemporary project control systems have been enriched by simulation utilities, easy-to-read graphical displays, and instantaneous multi-channel communication facilities.

POTENTIAL BENEFITS

In the above scenario (inspired in part by [Teicholz]), we outline in narrative form the possible advantages of an integrated approach to project control using data from smart tools (and other sources as well). A considerable amount of potentially valuable information could be collected relatively inexpensively with minor modifications to existing tools and work processes. This information is currently thrown away!

A second motivation for our smart tools fantasy is to make it easier to envision what integrated information really could mean for everyone connected to the jobsite. Better access to information could: 1) empower the worker to labor in a safer and smarter manner; 2) provide the crew leader with real-time analysis, simulation, and resource detection capabilities; and 3) equip the project manager with a decision support capacity not currently possible. The same data support these three 3 organizational levels, but for each it is cast in different views, or in database terminology, with different perspectives.

With so much data available, carefully designed analysis and display software with user-friendly interfaces will be necessary. Otherwise, the project controls professional will be faced with a data-overload nightmare. A cleverly structured data base with appropriate supporting software and well-designed video displays could glue the project participants together in a much neater, more rapid fashion. The data structure might take the form of object-oriented work packages [Ibbs].

The benefits of integrated smart tools can be grouped (perhaps somewhat arbitrarily) into the following categories.

Project Control Information

This paper's central hypothesis is that information acquired using smart tools equipped with sensing, data storage, and transmission capabilities could significantly improve project control. Broadly speaking, rate and duration of tool operation, rate and quantities of work advance, fuel and power consumption, and downtime are all trackable commodities in this scenario. Much of this information would be available virtually at the time the work was performed. This approach would free engineers and managers from mundane bookkeeping activities, and allow them to exercise creativity and planning skills.

It is also conceivable that there would be better integration of cost and schedule data since they would now be collected at the "source". Presently one of the difficulties integrating these data is that they are collected at different Work Breakdown Structure levels because of the human effort involved. That is, we collect labor costs essentially by the hour but schedule data by, at best, the day. Having the power to collect both cost and schedule data at the same WBS level would reveal a more complete picture of the project as well as aid in tracking any changes. That is, changed conditions could be documented by the equipment involved, providing more accurate records of the time and effort involved while reducing the overhead costs of having an engineer track these details.

Finally, work methods could be studied and improved since the project controls people no longer have to spend as much time in the dreary task of data collection. They would be unfettered to actually ponder, plan, and study the work.

Locational/Positional Data

Positional information can be useful in inferring the location of an individual worker who has been associated with a tool at check-out time. Though not entirely accurate, it is reasonable to assume that when our jackhammer is operating an operator is immediately present. This same information would be valuable in tracking misplaced implements, too.

Positional data could be used to correlate an operating tool's location with respect to a hazardous condition; e.g. an active gas pipeline or electrical cable. Sensors could be employed to detect how dangerous a particular environment actually is. Scent (particulate)- or magnetic-current-based sensors are examples.

Finally, it would be of substantial benefit to record as-built conditions with this type of data. The example alluded to in our jackhammer scenario was anchor bolts. This obviates the need for dedicating an expensive person to the task of developing as-built drawings at the conclusion of the project.

Inspection Data

Smart tools could allow inspection to take place at the time of installation. For example, if a worker could detect an improperly fitted structural connection at the time of installation, considerable reductions could be achieved in rework and inspection effort. Moreover, safety would be improved both to the general public and to other construction workers who might depend upon that detail. Similar analogies could be drawn for mechanical and electrical work. Projects would not be delayed waiting for inspectors to complete their checks; schedules would not have to be disrupted to allow for rework.

In addition, if the cost of inspection can be reduced with sensor technology, more inspection effort could be justified. Though difficult to quantify, this indirect, incremental increase in safety and operability is arguably a major plus for incorporating self-inspection capability.

Efficient Tool Usage

Incorporating sensors could lead to improved tool performance and safety, as operators would have more information about operating conditions and maintenance. An attached micro-CRT (or a simple LCD readout) could display temperature, power consumption and other data. From this the employee could adjust tool use until optimum conditions were reached. This would reduce tool breakdowns; worker fatigue, frustration and productivity; and installation mistakes (e.g. a welder that doesn't heat to the right temperature won't weld properly). At the same time, improved preventive maintenance scheduling would improve availability and repair costs.

It has been estimated that as much as one half of power tool sales are to replace stolen or misplaced tools. Better tool tracking on the jobsite would minimize tool loss. In addition, tool room handling costs would be reduced. And, as alluded to above, providing the operator with more information on tool function and maintenance could provide warnings of inefficient, improper or unsafe use.

POTENTIAL PROBLEMS

The potential benefits of integrated smart tools are significant. However, there are possible problems at each level of technology: sensing; local data storage, display, and transmission; and global data storage and information display.

Sensing

In selecting a sensor, such parameters as accuracy, response time, and stability must always be considered. Additional concerns particularly relevant to smart tool applications include durability, size, and power requirements.

A wide variety of sensors exist, and many are used in extremely harsh operating conditions. Even so, durability in a construction environment may be a problem. In some cases, using a less direct means of sensing may be the best approach. For example, the most direct way of assessing the integrity of a weld may be visual or x-ray inspection, or the application of a test load to the connection. Sensing the temperature at the tip of the welder is a less direct and probably less expensive approach; it has the drawback of requiring the sensor (and its electrical connections) to endure a harsh environment. Another indirect approach, measuring the electric current in the welder, is probably the least expensive and least demanding in terms of environment.

Sensors to be used in smart tools must be sized and located so that they do not interfere with tool function. Similarly, their power supply requirements must be met without impeding tool operation. For electrical tools, this is not likely to be a problem; the sensor power consumption will be small relative to the power requirements of the tool. However, for pneumatic tools (such as Thanh's jackhammer), an alternate source of power, for example, a battery, will be needed. Once again, size and mounting location must not interfere with tool use.

Local Data Storage, Display, and Transmission

A variety of data storage, display, and transmission technologies are available. Microprocessors, tape drives, and disk drives are examples of storage devices that might be suitable at the local (tool) level. Information might be displayed locally via simple LED or LCD indicators, multi-line LCD screens, audible signals, or perhaps mini-CRT screens. Possible transmission technologies include radio transmission, carrying a tape or disk to another machine, or even using a cable to "plug in" the tool to a more central data storage facility and download data at the end of a shift. Issues that must be addressed in determining the applicability of these and other technologies to an integrated smart tools environment fall into three categories: information needs, physical characteristics, and system requirements.

First and foremost, data storage, display, and transmission devices must be able to handle the information needs of smart tool applications. These can be expressed by such parameters as storage capacity, transmission rate, transmission duration, and the accuracy and integrity of data. Different ranges of these parameters will be appropriate for different smart tool applications. These parameters are interrelated, and in turn help determine the physical characteristics of a device.

Constraints on the physical characteristics of devices for data storage, display, and transmission — size, durability, power consumption — are similar to those for sensors, but may be harder to satisfy. Applications in other industries have required small, rugged sensors. However, in most cases, demands on data handling technology have been far less stringent. As a result, small, lightweight devices that could function, for example, while mounted on a jackhammer, may not be readily available. Human factors issues will be important in selecting and positioning data display devices; information must be clearly displayed and, in many circumstances, must be understandable by a multilingual workforce.

Information requirements and physical constraints will vary among applications. The appropriate data storage, display, and transmission technology will likely vary as well. However, the technology used in each application must be compatible with the requirements of the system as a whole. That is, there must be efficient transfer of information between the various devices and a central data base.

Global Data Storage and Information Display

Integrated smart tool systems could provide project managers with an immense amount of information upon which to base decisions. The storage media and format used at the global (project) level must allow rapid access to this information during the life of the project, and convenient updating of the company's historical database upon project completion. Information display devices must be capable of presenting large quantities of information clearly and concisely. The technology to accomplish this is available, for example, through high resolution monitors and video displays. It is the design of the user interface that will be critical; the interface must meet a project manger's needs and yet be easy to use. Screen displays will have to be carefully structured, with the organization and content of windows well planned. Appropriate command and data entry devices (for example, keyboard, mouse, trackball, light pen, voice recognition system) will also have to be selected.

Cost and Acceptance

Relevant to the smart tool system as a whole are two additional concerns: cost and acceptance. Many of the technical issues discussed above can be addressed with currently available technology. Whether the solutions will be cost-effective is another issue, one that requires further investigation. If portions of our proposed integrated smart tool scenario are to move from paper to practice, smart tools must not only be cost-effective; they must be perceived as such — by equipment manufacturers, by software developers, by contractors, and by construction workers. One way to help ensure that research on smart tools focuses on cost-effective applications, and that its results will be accepted in industry, is to solicit industry participation in all phases of smart tools research.

A SMART TOOLS RESEARCH STRATEGY

The integration of tool- and equipment-based sensor/microprocessor systems with project control software is an area that has not yet been addressed by equipment manufacturers, and one in which academic research can play an important role. In a university environment, it is relatively straightforward for researchers interested in equipment and sensing issues to collaborate with those whose interests lie in the area of project control. While any project is subject to short term "show me" demands, it is in general easier to focus on longer range goals in an academic, rather than a commercial, setting. Finally, the university provides an environment in which manufacturers of hardware and software may be more willing to participate in long range research.

The following paragraphs describe our strategy for pursuing research on integrated smart tool systems. Balance between the breadth and depth of research is an important consideration. The project must be broad enough on scope to address performance at the project control level, yet also deal with the details of implementation. An additional consideration is the need to obtain input from industry (oweners, tool and equipment manufacturers, contractors, workers) throughout the project.

Phase I: Identify promising applications

The amount of information that could be acquired using smart tools is overwhelming. The first phase of research in this area should be devoted to the identification of important applications. What are benefits of increased information at project control level? Where will these benefits be important? Which areas are technically feasible? These are the types of questions that must be addressed early on. Answering them will require the development of a decision framework within which the anticipated costs and benefits of various applications can be compared. Input from industry is vital at this stage.

Phase II: Select trial applications

From the promising applications identified in Phase I, several trial applications will be selected for further development. Together, these trial applications should provide sufficient breadth for a meaningful evaluation of performance at the project control level, serving as a microcosm of a full scale integrated smart tool system. Trial applications must be such that prototypes could be developed within a reasonable budget and schedule (perhaps with the assistance of tool and equipment manufacturers). In addition, applications must be such that the resulting "smart tools" could conveniently be tested on a construction site.

Phase III: Design and build prototype smart tool system

A prototype of the trial system will be designed and implemented. The development effort will address system design issues, hardware, and software, and incorporate laboratory testing. The result will be a functional system ready for testing in the field (though not necessarily a "hardened" system designed for long term use). If possible, Phase III should be a cooperative effort between university researchers and industry participants.

Phase IV: Field test prototype system

Field testing of the prototype smart tool system will result in both qualitative and quantitative information. Construction workers and management will play a vital role in this phase, providing feedback on the performance and acceptability of the system. Field testing should be of sufficient duration that objective measures of productivity can be made, at least at the local (tool) level. The tests should provide at least a qualitative indication of the effect on productivity at the project control level. Simulation could perhaps be used to generate additional data on the smart tool system's impact on project control.

Phase V: Evaluate prototype system

The prototype system will be evaluated based on the results of field tests, and on cost estimates formulated after Phase III. At the end of Phase V, all parties involved will have a much clearer picture of the benefits and costs of an integrated smart tool system, and further development efforts (perhaps primarily by manufacturers) can be planned.

CONCLUSION

Existing uses of sensors and microprossesors in tools and equipment have focused primarily on improving the "immediate" control of a construction process. This paper has shown, anecdotally, how the addition of data storage, transmission, and display capabilities might extend this improvement to the project control level. A program for research into integrated smart tool systems was presented as well.

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