IDENTIFICATION AND MEASUREMENT TECHNOLOGIES APPLICABLE TO CONSTRUCTION

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1 INTRODUCTION

Process control, in the highly automated flexible manufacturing systems (FMS), performs a dual function: CAD interfaces provide direct control of tasks, and parameters such as production rates and quality are monitored in real-time by various sensors located near the assembly lines. In the construction environment of the future, sparse automation will require that process control be left to the *"islands of automation"*, while the higher-level functions are handled by project control systems, which essentially automate the role of the construction manager. Other than [O'Brien84], which discusses automated data-acquisition, little work has been done toward the development of such systems for the construction industry, even though it has become clear that the monitoring capabilities of FMS are at least as desirable as the task automation. The goal of a construction manager is quite similar to those of a manager in manufacturing--to produce a quality product, making efficient use of resources including labor, materials and time. Judging the progress toward this goal is an inherently sensor-intensive process, with identification and measurement the primary sensory input.

A recent workshop [Evans86] acknowledged these input needs, defining "*development of real-time measurement technology for measuring position and dimensions...*" as an area for immediate investigation. This paper explores the abilities and limitations of some available technologies for measurement and identification to serve as a foundation for the development of automated project control systems. A bibliography is included for further study of the topics presented.

As long as their limitations are understood, single sensors are sufficient to provide much of the input, especially that in terms of location. Other information, notably identity, can often be gleaned only through the use of multiple sensors, a lesson only recently learned in manufacturing automation. After several sensors are examined in the context of construction project control (Section 3), integration, or sensor fusion, will be presented in Section 4 of this paper.

2 THE NATURE OF THE CONSTRUCTION ENVIRONMENT

In general, barriers to automation posed by the construction industry are well-known. In considering a sensor-based project control system, these barriers must be noted.

The construction environment is more harsh than the manufacturing setting. Weather is just as important to many sensing techniques as it is to work performance. Temperature extremes, as well as airborne moisture and dust, affect different sensors to varying degrees. Maintaining accurate models of this complex, dynamic world is difficult enough, to say nothing of measuring and identifying the disparate objects which comprise it. Vast amounts of sensory data are needed, and must often be obtained over great distances.

The organization of the work is also unlike those for which automation has been successful. Construction is typically job-oriented, not process-oriented, and the creation of a unique, built-in-place product requires different control than that used in the highly ordered work environment of factory automation. The scale of the job sets it apart from other job shop products, such as airplanes. Work often takes place in the product, not on it, and its size complicates the task of measuring it.

The size of the product, however, makes identification easier. The availability of remote vantage points for monitoring large portions of the process is another advantage to the nature of the construction environment.

3 SENSORS FOR AUTOMATED PROJECT CONTROL

For discussion purposes, this paper will classify sensors as either active or passive. Active sensors are taken as those in which the apparatus is local to the object being measured or identified, while passive technology operates remotely to the object being sensed. Each type has some inherent advantages, but the line between active and passive is often unclear.

Active sensors

Active sensors are preferable in that they are usually dedicated to one task. This is beneficial in two ways: first, the reliability of a system of dedicated components is greater than that of a centralized system, and second, they generally need less processing to extract information. There is, however, a trade-off. Local sensors require communications support in order to make their output available to the project control system, and they must also be rugged, in order to stand up to the rigors of the field. Active sensors judged applicable to construction include: the Global Positioning System, inertial navigation systems, active automatic identification systems, and laser ranging.

The Global Positioning System (GPS) is a satellite-based location system, with a full eighteen satellite constellation expected to be in place by 1989. Unlike many conventional means of locating objects, GPS can be used without a clear view between some sensor and the object. Location may be obtained by two methods: point positioning and relative positioning [Fell80]. Point positioning involves tracking one or more satellites, and computing position by triangulation, given the orbits. The accuracy of this method is currently limited, for strategic reasons concerning orbit secrecy, to plus or minus five to ten meters, in one hour of observation.

Relative positioning allows far more accurate measurement, by translocation between two GPS stations. Proposed systems, operating in "*kinematic mode*", promise real-time relative positioning for a moving target, with accuracies of + /- 2 centimeters.

The limiting factor in GPS performance is the processing, while the primary physical limitation is that both methods require line of sight to one of the four satellites overhead at a given time. For an in-depth look at the Global Positioning System, see [Wells87].

Inertial navigation systems provide continuous position information through the sensing and integration of linear and angular acceleration rates. They have the advantage of being an entirely self-contained means of finding position data. New ring laser [Martin86] and fiber optic [Kim86] gyroscopes are significantly more rugged and reliable than their early mechanical counterparts, and the mass-production possibilities for the latter promise low-cost.

Caterpillar Corporation is developing an automated guided vehicle (AGV), which will achieve "*off the wire*" capability by use of inertial navigation, and another company is investigating its use for automatic control of off-road trucks in the mining industry.

In manufacturing, automatic identification systems are used to identify directly and locate everything from small parts to cars on an assembly line.

Several new active systems hold particular promise.

Commercial radio-frequency systems, with limited two-way data transfer, have been used in vehicle dispatching, but need access to external navigation data, such as that from the U.S. government's LORAN-C network. New, highly-rugged local RF systems consist of any number of fixed transceivers, which interrogate mobile transponder tags for data on position and any other information programmed into the tag [Pretzsch84]. These devices can even "*see through*" non-metallic barriers. One type of tag simply echoes back a characteristically modulated version of the transceiver signal, thus requiring no internal power source. Available systems offer transponders costing as little as $10 U.S., but are intended for use over short distances, having ranges of no more than two meters.

Modern surveying pioneered the use of optical ranging for measurement, and it now finds use in several areas of automation. [Strand85] provides a good summary of optical range sensing, which includes active techniques such as time-of-flight ranging, and the interferometric methods used in surveying.

Time-of-flight rangefinders are commonly used in military applications, where accuracy within a few meters in less than real-time are acceptable.

Interferometry obtains range information from the interference pattern made by the reflection of a sinusoidally modulated laser beam. A wide range of distances can be measured, but for real-time use, resolution is inversely related to distance. The net result is accuracy on the order of millimeters, when retroreflective targets are used.

The targets for laser ranging are typically retroreflective cubes, but recent work [Wolfe85] employed a patch of patterned, retroreflective material to find orientation as well.

The active deployment of this technology involves mounting the laser on the object to located, and establishing a metric grid of retroreflectors over the site. The patterned retroreflector would be ideal for establishing such a coordinate system, as the pattern could convey absolute position information. A passive implementation might use a low-level vision system to track targets on objects to be located.

Current laser applications establish either reference lines or planes. These can be used for bi-directional and unidirectional guidance respectively. Grid systems for location in three dimensions are under testing for use in automated mining trucks.

Passive sensors

Passive sensors have significant advantages, compared to those covered up to this point. Their remote nature allows integrated, multi-function systems with direct access to massive central storage and processing capability. The generic nature of these systems also better justifies the sizeable initial capital outlays which any automated project control system will entail. To put it simply, a combination of passive sensors offers the varied observational capabilities of a human manager, and is far less disruptive.

Most of the traditional automatic identification methods used in manufacturing, such as bar codes and optical character recognition (OCR) are passive. With a few modifications required by the construction industry and current technical limitations, these non-contact sensing technologies may ultimately change the way the industry is managed, just as they revolutionized process control in manufacturing.

Bar coding was the primary vehicle of this change. The familiar striped labels are scanned by a laser, and the information coded in the reflected pattern is converted to alphanumeric form based on one of several coding standards.

The key to the performance of bar code systems is the intensity of the reflected light pattern. To maintain good resolution over the distances common on a jobsite, it would be necessary to increase both the size of the code label and the strength of the scanning beam used in conventional systems. At the power levels required, such a scanner would probably not be eyesafe. Clear paints which fluoresce when exposed to ultraviolet light could improve resolution, serving as a background, or be used to create permanent codes, invisible to the human eye [Hopkins85].

Bar code degradation, especially in harsh environments, is a serious problem. Where traditional printed and painted labels might be damaged, the code can be laser-etched onto a surface.

In a stable, manufacturing setting, an AGV has been developed which finds its position by triangulation from a grid of codes, and experience with automatic identification of railroad cars and marathon runners has demonstrated the suitability of available technology for harsh, dynamic environments as well.

Optical character recognition shares many of the advantages and limitations of bar code systems, in terms of range and resolution, but it sacrifices some efficiency by using a higher-level data representation. The benefit is an identification scheme which is intuitive to humans. Machine interpretation is by simple binary vision, with optical pattern recognition showing particular promise [Casasent85]. Commercial packages are available which can read several printed fonts, and recognition of hand-printed characters remains the subject of much research.

Passive automatic identification techniques may well be most valuable for "*pre-labeling*" objects, to simplify identification in a broad or cluttered field of view.

Ultrasonic ranging can be used to determine distance or to create range images--three-dimensional descriptions of an object's surface. Unfortunately, it is plagued by many problems.

Poor spatial resolution due to beam spreading limits common ultrasonic ranging systems to either large objects or distances less than 10 meters, and accuracies of +/- 2%, though the resolution can be improved by the use of overlapping ultrasonic transducer arrays. The operating range of such sensors is also limited by environmental noise, air temperature gradients, and the tendency of air to absorb ultrasonic wave energy, especially at the high frequencies necessary to obtain high detail in imaging.

[Oppenheim85] describes one application of ultrasonic ranging in the harsh environs of a mine, while a 2-D imaging system is discussed in [Kuroda83].

Conventional machine vision performs identification by feature matching with object models. Matching may involve only a simple geometric transformation, or manipulation of complex symbolic information involving gravity, occlusion, and spatial relationships. Barriers to applications in the construction environment lie on both the input and processing sides. As noted in [Brady83], features can be extracted from contour, shading, stereo images, and representions built up from generalized shapes such as cylinders or cones. While a common problem with these methods is dependence on good, even illumination, little has been done to relax this constraints. [Brady86] gives an example of the processing requirements which have prevented the development of real-time machine vision: when run on a moderately powerful computer, one common edge-detection algorithm takes 40 minutes to process one image. In a world containing more than a few objects, matching is very slow, but matching time can be minimized by the use of hierarchical model representations, each having more detail. Brady notes that highly parallel machines also can be used to advantage. Such a computer ran the edge-detection routine described above in only 0.01 seconds.

Most commercially available vision systems operate with grey-scale images, but color systems are being developed to simplify low-level matching. There is no reason not to extend vision systems to cover more of the electromagnetic spectrum, including the infrared band. This would allow identification by the characteristic spectral reflection of different materials, as in satellite remote sensing.

In addition to identification, vision has a place in metrology. Digitizing well-developed industrial photogrammetry techniques permits automated capture of as-built information.

Optical pattern recognition can use holograms to achieve rotation and translation invariant object identification. Laboratory systems successfully identify ships and planes from simulated silhouettes, but the value of such systems in the real world of dust and vibrations is unclear. A different optical technique [Rajala83] which identifies and tracks moving objects in noisy environments might be more applicable.

Vision is used in other severe environments, including lumber and steel mills, but until the problem of imperfect illumination is solved, and parallel processing fully exploited, it will be of limited use in the construction workplace.

While vision excels at identification, optical rangefinding provides fast measurement of distance. Structured light imaging uses the talents of the latter to build a range image of an object's surface. There are different methods to obtain the data. These are summarized in [Strand85]. The slowest method scans each point on the surface with a standard rangefinder and photodetector. [Kanade81] describes one such "*point-by point*" system. A faster method computes range from the distortion of a linear sheet of laser light moved across the surface in a prescribed manner. The "*contour*" nature of a single projection makes it ideal for identifying prismatic objects. Several systems based on this principle are described in [Agin73]. Another method of generating range images extends the light structure into a grid, making it possible to build the image in one projection. This is currently the only way to do real-time range imaging. The use of grid patterns for range image construction under indoor and outdoor lighting conditions is explored in [LeMoigne85].

Images from structured light ranging often show features, such as edges, not discernable in conventional (intensity) images. Thus, a good use of range images is in multi-sensor systems, which exploit the talents of complementary sensors for best efficiency.

4 MULTI-SENSOR SYSTEMS

Until recently, most of the efforts of the robotic sensing community centered around individual sensor technologies, such as ultrasonic ranging or intensity imaging. Single-sensor applications proved slow and inaccurate, making it necessary to constrain problems severely in order to solve them. With this realization, there has been a recent surge in related research, as evidenced by two full sessions devoted to sensor fusion in the 1986 IEEE Conference on Robotics and Automation. The nature of the construction environment, makes multi-sensor systems almost mandatory for automated project control.

Architectures

Little work on multi-sensor architectures was done prior to the last few years. This was most often for manipulator control. More recently, autonomous navigation applications, such as the DARPA Autonomous Land Vehicle (ALV) have accelerated efforts on the topic considerably.

Blackboard architectures have found application in autonomous navigation. Conceptually, a blackboard is a way to present information from multi-sensor systems, and coordinate the data acquisition process. Specific, high-level information is obtained by various program modules and updated to a central database (the blackboard). The controller selects one module at a time from all those for which the information prerequisite to firing is known, executes that module, and places the results on the blackboard.

NAVLAB, a testbed vehicle for autonomous navigation currently under development at Carnegie-Mellon University, employs a "*whiteboard*" architecture [Shafer87]. This is fundamentally the same as a blackboard system, but the modules run continuously, making data requests of the controller as needed, and suspending operations until the requests are filled. Consequently, such an architecture provides faster throughput, and is suitable for parallel implementation. One refinement over traditional blackboard architectures, is an ability to handle geometric and temporal data. This is essential for constructing and updating object models from different locations, at different times.

[Henderson83] presents the Multi-sensor Kernel System (MKS). It is different from a blackboard architecture in that it is easily reconfigured by the use of generic "*physical*" and "*logical*" sensors. Physical sensors are those defined by their operating parameters, while logical sensors are described by the combined effect of one or more physical sensor. This reconfigurability allows the controller to create modules specifically suited to filling a particular data request.

Another reconfigurable, partitionable architecture, similar to Henderson's MKS, is examined in great detail in [Ma85]. The paper emphasizes the partitioning of general-purpose VLSI processors for parallel use, and the interconnection networks necessary for sharing output.

Object representations

Because matching object representations to models makes up the bulk of the processing in any identification scheme, an efficient internal object representation scheme is crucial. Single models capable of handling disparate information from various sensors or multiple representations may be used.

One of the model types which Henderson's MKS supports is the spatial proximity graph (SPG). The nodes of the graph represent features. Arcs connect nodes within a specified distance, in order to show structural relationships. The SPG also allows the integration of non-visual information.

[Bajcsy85] advocates the use of a database containing one representation for each different sensor sub-system. To minimize time spent accessing the multiply-redundant representations, parallel access is provided by indexing each model by common primitives, such as areas, curvature, and holes. An additional dimension can be added to such a database by accommodating semantic relationships across representations. An application of a database using multiple representations is set forth in [Kent87]. An octree model, which breaks a space down into occupied or unoccupied cubes, is linked to a feature-based representation. Features which the octree predicts will be visible from a given view are sought, extracted, and matched to those in the database.

A blackboard architecture maintains one single frame representation of each object it senses. These frames contain information in object- attribute-value tuples, with the capability of assigning and modifying a level of confidence for each value.

Sensor control strategies

Determining the most efficient way to use multiple sensors to accomplish an identification or measurement task is the key to unlocking their full potential for project control systems. Sensor strategies can be either complementary, as mentioned earlier, or competitive [Shafer87]. Competitive use improves performance by weeding out spurious data gathered by different sensors from the same field of view.

Blackboard systems have built-in control strategies, which structure the information flow through the various modules in a pre-determined manner, firing each when all required input information is known. CMU's "*whiteboard*" makes the controller more than a traffic cop. When a request for information is made, the controller must determine, through knowledge similar to that presented in Section 3, which sensor to use in filling the request. DEVISER [Vere81] is an expert system for just such a purpose, selecting sensors using rules based on the abilities and limitations of each sensor.

The mix of symbolic and numeric information which sensors make available suggests knowledge-based methods for object identification. A goal-driven or event-driven approach to a problem can be taken, depending on how well it can be constrained by pre-labeling and contextual knowledge.

[Garvey76] proposes a multi-sensor, goal-driven perception system which uses knowledge about features and spatial relationships to narrow the search space. It also calculates confidence levels for sub-goals and final results. (Telephone SUPPORTED BY tabletop WITH PROBABILITY 0.95) is an example of a rule illustrating the type of contextual knowledge employed.

An event-driven approach is suggested in [Bajcsy85], on the premise that most problems can be sufficiently constrained to make such an approach efficient. Convergence rates, measured by the number of features matched, are used to detect faulty or feature-poor sensor input, indicating the need to seek new information, as from a different view. Event-driven sensor strategies appear perfectly acceptable for the purposes of automated project control system made up of a series of specific, independent applications.

Whatever the specifics of system architecture, internal models, or control strategies--the use of multiple sensors is the only way to identify and measure in the complex, dynamic construction environment.

5 CONCLUSION

The construction industry presents automation experts with their greatest challenge ever. The goal is process control systems which coordinate automated sub-systems for CAD, task performance, and project control. Any such integrated system will not be implemented as a whole, but will grow from stand-alone sub-systems for these three functions. Project control, as a management concern, is most often concerned with identification and measurement, both of which are sensor-intensive tasks. With the particular characteristics of the construction environment noted, this paper explored the abilities and limitations of several sensing technologies. Obviously, no one sensor is capable of finding all of the information needed for total control, so multi-sensor systems were also considered. The journey to a fully-developed project control system, combining multiple sensors to make efficient use of limited project resources, will be long, but it will leave only a short step to the integrated, highly-automated construction site of the future.

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