Advances in Control Systems for Construction Manipulators

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ABSTRACT

Fundamental advances in sensors, actuators, and control systems technology are creating opportunities to improve the performance of traditional construction equipment. New capabilities are being developed as well. These improvements in performance and new capabilities are resulting in better safety and efficiency. However, selecting control strategies can be confusing, and measuring and predicting their performance can be difficult. This paper identifies emerging control paradigms and describes methods for measuring their performance. Many control paradigms and corresponding example applications are identified, including single degree of freedom control sticks, multiple degree of freedom joysticks, operating and safety constraints, teach/learn capability, resolved motion with internal and external sensors, spatially correspondent controllers, tele-operation, graphical programming and control, and autonomous control. Methods described for measuring performance are based on American National Standard Institute (ANSI) standard tests, applications analysis, and ergonomics. Examples focus on the University of Texas at Austin's large scale hydraulic manipulator and automated pavement crack sealer with the results of performance tests on these manipulators being presented.

1. INTRODUCTION

The construction industry has been very resistant to the introduction of new construction methods. Instead, the industry chooses to rely on historically tried and trusted methods to construct all kinds of facilities and industrial plants. So, the industry fails to take advantage of the developments in automation technology that have been made in other industries. Due to this failure, the construction industry is behind other industrial sectors making it a prime market for the implementation of automation technology.

Due to an aging workforce in Japan and worker retention problems in the U.S. and Europe, there is a shrinking number of skilled equipment operators available in those regions. Automation and robotics will be needed to produce new machines that are user-friendly to facilitate their use by less-skilled operators. These new machines may also improve worker retention by making the work less dirty, less physically demanding, and more attractive as a profession [7]. As advanced robotics technologies are developed and applied to improve the control of construction equipment, the industry will see improvements in productivity and safety, and new capabilities will be developed.

This paper examines one component of automation technology, that of advanced control systems. First, the paper discusses various control paradigms. It then looks at examples of performance tests for different control systems used in projects at the University of Texas (UT) and summarizes key points.

2. CONTROL PARADIGMS

Many advanced control systems are currently being developed or are already widely used in the construction industry. Depending on the given task requirements, such as hazardous conditions, high precision specifications, remote operation, etc., different control systems may be used to the best effect. These include: single degree of freedom (DoF) control sticks, multiple DoF joysticks, operating and safety constraints, teach/learn capability, resolved motion with internal and external sensors, spatially correspondent controllers, tele-operation, graphical programming and control, and autonomous control. Each of these will be briefly discussed below.

2.1 SINGLE DEGREE OF FREEDOM CONTROL STICKS

Single DoF control sticks are the traditional method of controlling construction equipment such as backhoes, bulldozers, lift trucks, and cranes. Each control stick enables the actuation of a particular motion or degree of freedom by moving the lever from its neutral position. Often, as the control lever is moved further from its neutral position, the speed of the actuated motion increases. This is known as proportional or rate control. This was the original form of control of UT's large scale manipulator (LSM) shown in Figure 1. The eight lever system had a separate lever for each of the three degrees of freedom of the crane as well as the five DoF's on the manipulator.

The productivity rates of this form of control rely greatly on the skill and dexterity of the operator. Also, there is a long learning curve for operators due to the non-intuitive nature of the control sticks. The user must learn which stick controls which joint, as well as the direction of motion of each DoF that corresponds to each direction of the control stick. The operator's sight, hearing, and touch are the only forms of feedback. Due to sensory problems, like limited depth perception, productivity and safety can be decreased.

2.2 MULTIPLE DEGREE OF FREEDOM JOYSTICKS

The next logical progression from the single degree of freedom control levers is the use of one or two multiple degree of freedom joysticks. These joysticks make it easy to articulate multiple DoF's of the equipment at the same time which was difficult with the single DoF control sticks. Several companies manufacture robust, industrial joysticks with up to six DoF. Joysticks with seven or more DoF have been developed for specific applications. Each degree of freedom in the joystick is usually rate controlled. Ergosticks, developed at UT, are an example of a set of two multiple DoF joysticks being used to control the eight degrees of freedom of the LSM. One five DoF joystick controls the five motions of the manipulator while another three DoF joystick controls the three motions on the crane [9].

A newer 6 DoF "spaceball" has been acquired to control the LSM. It incorporates force-torque sensors to provide rate control along each of the three cartesian axes as well as rotation about each axis. It is currently used to control the LSM in its 6 DoF indoor test facility (see Figure 2). The indoor facility was developed to provide a stable environment for testing, but in doing this the LSM loses two of its DoF's since the crane has three DoF's while the test frame has only a single rotation DoF. The translation DoF's of the spaceball

Figure 1. The LSM on the Crane.

correspond to the rotation, lift and telescope joints while the rotation DoF's represent the roll, pitch, and yaw of the wrist of the LSM.

While this control option is more intuitive than single DoF levers, the multiple DoF joysticks still only have one motion for each DoF and just use operator sensory feedback.

2.3 OPERATING AND SAFETY CONSTRAINTS

Further enhancements to the control system can be made by adding sensors to construction equipment. The sensors and the kinematic model of the equipment allow its position to be known. The operating environment around the device along with safety constraints, such as load limits, can be modeled. Based on these models, limitations can be placed in software on the operation of the equipment. For instance, a mobile crane could be constrained from extending its boom beyond the safe operating envelope for a particular load. Also, the LSM in its indoor test bed could be prevented from hitting the floor, or a tower crane could be constrained from moving too close to an already existing building. These are examples of improved construction equipment operating safety that can be had with the addition of sensors and enhanced software control.

2.4 TEACH/LEARN CAPABILITY

With the sensors in place, it is a small step to achieve teach/learn capability. This involves the control computer memorizing points on a path traversed by the end-effector as it performs one or more tasks. Then it repeats those tasks automatically. For instance, if an LSM is fitted to sand-blast and paint oilfield tanks, the first pass over the structure is taught. Since every other pass is very much like the first except for a slight offset, the rest of the tank is done automatically. Also, if one uses the LSM for pipe manipulation, all of the large motions

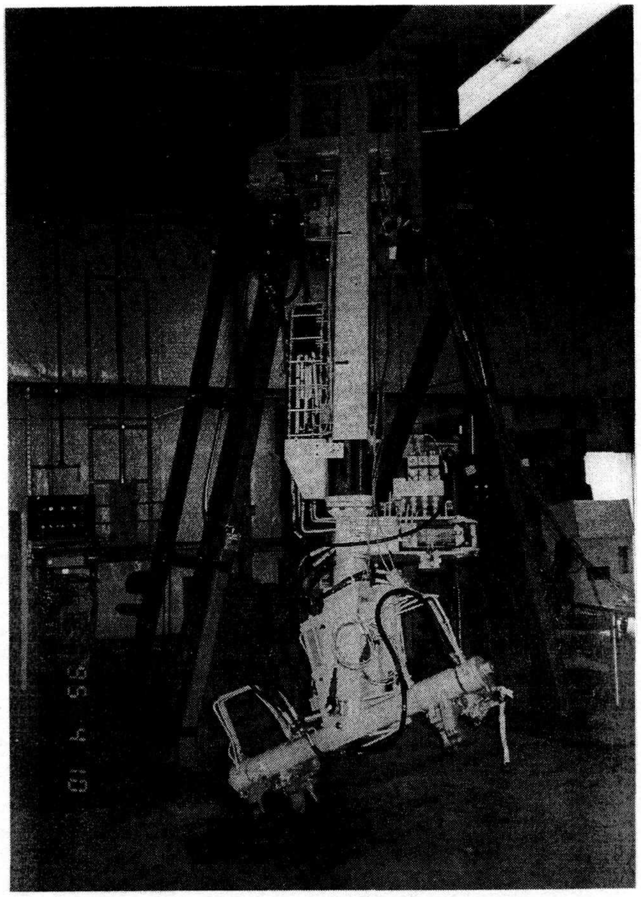

Figure 2. LSM in Indoor Test Facility

are taught and repeated. This would include any complex motions that are necessary to avoid obstacles. Only the final precise positioning for picking or placing pipe must be performed by the operator. By automatically performing repetitive tasks, teach/learn capability can improve productivity and reduce operator stress.

2.5 RESOLVED MOTION WITH INTERNAL AND EXTERNAL SENSORS

The advances in sensor technologies and more powerful control computers are making more refined control systems available for construction equipment. Resolved motion can be attained by using range sensors, position sensors, smart cylinders, vision sensors, etc. as feedback. This has already been seen for backhoes, manlifts, and loaders.

For resolved motion, the position data and possibly other information from the sensors is fed into the controlling computer which has been programmed with the kinematic properties for that particular piece of equipment. The computer interprets the sensor data, along with motion commands from the user, to determine the required actions of each actuator for the simultaneous motion of all joints to generate the commanded end-effector motion. For example, if the LSM operator uses the spaceball to command a motion in the x-direction, the end-effector will move precisely in the x-direction with the computer controlling which joints will be operated with their required rates. Resolved motion has been shown to be a valuable form of control in graphical simulations of the LSM for moving in a straight line in the cartesian directions and along the direction of the pipe axis [1]. Work is ongoing to implement this on the actual manipulator.

Resolved motion greatly simplifies the operation of equipment and reduces the variability of the quality of work due to the skill of the operator. It presents the opportunity to significantly improve productivity and reduce the duty stress on the operator. Resolved motion can be highly complex to implement, especially when dealing with redundant manipulators, which leaves many challenges to be overcome.

2.6 SPATIALLY CORRESPONDENT CONTROLLERS

Also referred to as telechiric, or master-slave control, spatially correspondent control represents a move away from standard velocity control to a more intuitive form of control for construction equipment. Operators encounter difficulty when the geometry and motions of the master controller do not represent those of the slave manipulator [13]. Telechiric systems avoid this problem by employing a force reflective controller that is kinematically equivalent to the actual equipment. As the operator moves the controller, its motion is mimicked by the slave manipulator. The velocity and position of the controller are representative of those of the end-effector. By being force reflective, the controller has actuators which prevent it from moving faster than the equipment or to positions it cannot attain. The operator can feel any load on the end-effector and any resistance to its motion, such as obstacles or the pressure of picking up an item. Two current systems in service are an electric line worker manipulator and a tree trimmer [4,5]. They rely on human vision and forces in the control stick for feedback. Spatially correspondent systems provide an intuitive form of control that offers significant benefits over velocity controllers.

2.7 TELE-OPERATION

Demand is increasing for the use of construction machines in hazardous conditions. These include chemical contamination, high radiation, and war zones which require the operator to be in a remote location. At times, it is more productive for the worker to be away from the machine, such as beside the LSM instead of in the crane cab [8]. Hard-wire, radio frequency, or fiber optic communication links allow the user to be in a safe remote location. Tele-operation provides the ability to work productively in hazardous environments without jeopardizing the operator.

With the equipment being a significant distance from the user, as good a perspective as possible of the operating environment must be provided to the operator. This can be accomplished by using different camera views, microphones, the resistance and spatial correspondence of the force reflective hand controller, and other sensing devices. Examples of the tele-operated control of construction equipment include a couple of remotely operated excavators [10, 11], as well as UT's automated pavement crack sealer shown below. The operator sits in the cab of a truck and views live video images from the crack sealer being towed behind to find cracks in the pavement. Once a crack is found, the vehicle stops and the operator traces the crack on the touch sensitive video screen. After the crack is repaired, the video image provides verification that the crack has been sealed.

2.8 GRAPHICAL PROGRAMMING AND CONTROL

Graphically controlled systems use a computer generated model of the equipment in its operating environment as feedback to the operator. These systems rely on the ability to generate an accurate work space model [7], which is difficult due to the fact that construction

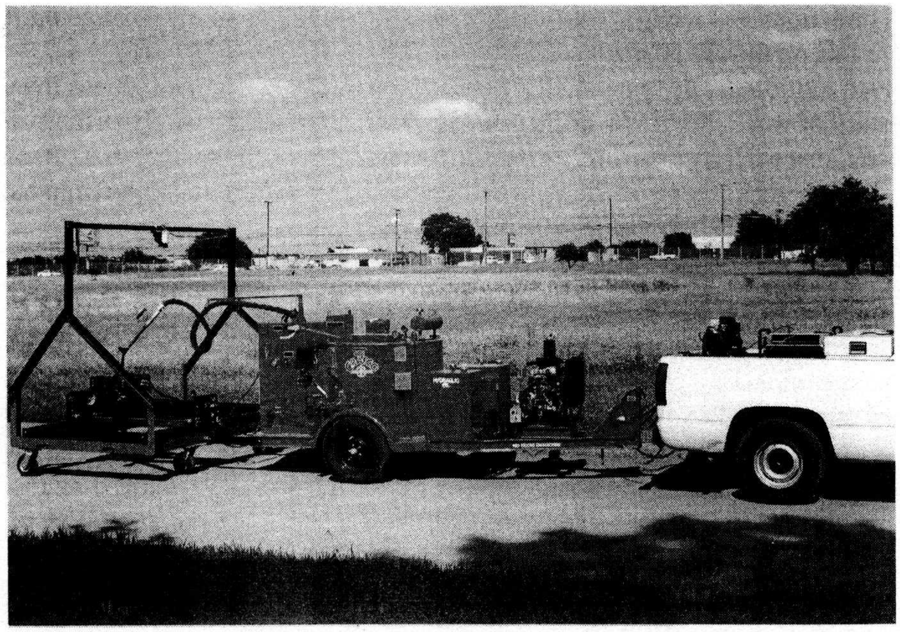

Figure 3. UT's Automated Pavement Crack Sealer

environments tend to be very dynamic. However, machines that work in a fairly static environment can use this technique. Models of as-built structures and obstacles can be created with real time equipment position updates in the model. Better visual feedback can be obtained by using view changes, zooming, and other graphical features. Graphical simulation allows off-line generation of the path of the equipment through its environment. So, the operator can make mistakes without damaging the equipment or its surroundings. Thus, graphical programming has been used a great deal on the LSM for path planning, control system testing, and for operator training [1].

2.9 AUTONOMOUS CONTROL

The highest level of control, and the toughest to achieve, is that of autonomous control. It involves taking the human out of the control loop. The amount of sensor data fusion that must be done to achieve autonomous control can seem untenable. Vision sensors, range sensors, force sensors, position sensors, accelerometers, etc. all may have to be incorporated into one machine in order to achieve autonomous control. Computer processing may be too slow to handle all of the data to keep the system stable or to be economically feasible when compared with conventional methods. However, systems are being developed, such as autonomous dump trucks in Japan [12]. An early version of the crack sealer was automated but was too slow to be economically feasible. It combined laser range data with processed image data to automatically find and seal cracks [6].

3.0 PERFORMANCE MEASUREMENT EXAMPLES

The above control systems vary in difficulty of implementation from the simple to the complex. The simple systems rely heavily on the operator. As the systems become more complex, the operator is removed from the control loop, allowing for computer control of many of the tasks. The selection of the correct control strategy for a given application is not always straightforward. One does not merely select the most automated system. There are economic and performance concerns that must be met by the equipment. So, tests must be run to measure the performance of machines using different control paradigms. Examples of such tests from research at UT are presented below.

3.1 THE UT LARGE SCALE MANIPULATOR

Early performance tests for the LSM were productivity analyses for its original application of pipe erection. A productivity analysis is a very good performance measure for selecting control systems. It provides comparison data between the automated control systems and the conventional method. These tests allow one to see the economic viability of using the automated equipment which will determine if it will be accepted by industry.

The LSM productivity tests compared the effectiveness of the LSM placing pipe using both the original eight lever system and the ergosticks against that of the conventional method which uses a 15-ton hydraulic crane, commonly called a cherry picker. For the first tests, the eight lever system and the cherry picker were made to perform the same pipe laydown procedures. Since the cherry picker can lift multiple pipes, it was found to be over five times more productive in terms of total work-hours [8]. The next test compared the eight lever system with the ergosticks by having operators perform the same pipe erection tasks with both control schemes. The pick and place locations were selected to force the use of all 8 DoF of the LSM. The ergosticks showed an improvement in the control of the LSM over the eight lever system due to the more intuitive nature of the multiple degree of freedom joysticks but was still unable to compete with a standard cherry picker for erecting pipe [9].

Several ergonomic problems surfaced during the productivity tests. The eight lever system was not intuitive and confused the operator at times. The ergosticks were not the correct height, the neutral positions were not firm enough, and there was still some confusion about which controller corresponded to which joint of the LSM. Both systems also have a problem with depth perception[9]. The operator had difficulty with accurately picking and placing pipe at a large distance. These design problems will be alleviated with a new control system in development which uses the 6 DoF spaceball as a resolved motion controller for the LSM along with some visual feedback from the end-effector.

As the research on the LSM has moved away from using it exclusively for pipe erection to it becoming a multi-functional manipulator, new tests are being developed which will allow for the comparison of performance parameters of different construction manipulators without regard to a specific task such as pipe erection or surface inspection. These tests are for automatically following a path or moving to a specific point. Therefore, the control scheme must involve at least a teach/playback level of control for positions and resolved motion for paths. They are designed to be automatic, with the operator just pre-programming the path to be followed or the points to be traversed.

The tests are based on the American National Standard ANSI/RIA 15.01-1 90 for Point-to-Point (Static) Performance and ANSI/RIA 15.01-2 92 for Path-Related (Dynamic) Performance evaluations of industrial robots and robot systems. They are to be run in a rigid environment to achieve consistent performance. The payload is set to be 50% of the rated maximum which is 363 kg (800 lbs.) for the LSM with the test point as close to its center of gravity as possible.

The static tests involve repeatedly moving the test point to various points on a rectangle in the test plane shown in Figure 4. The corners of the rectangle are points L_1 U_1 U_4 L_4. S_L is the test path segment length which is 1000 mm. for the LSM, the largest length recommended by ANSI. There are at least three segments. D_L is the rectangle side segment length, and it is one-half the size of S_L or 500 mm. The segment end-points are labeled U_1 through U_4 along the top (line U_1U_4) and L_1 through L_4 along the bottom (line L_1L_4). F_1 and F_2 are points on the center line of the workspace (the dashed line) and are each an equal distance from the boundary of the manipulator workspace. The performance criteria are accuracy, repeatability, cycle time, overshoot, and settling time.

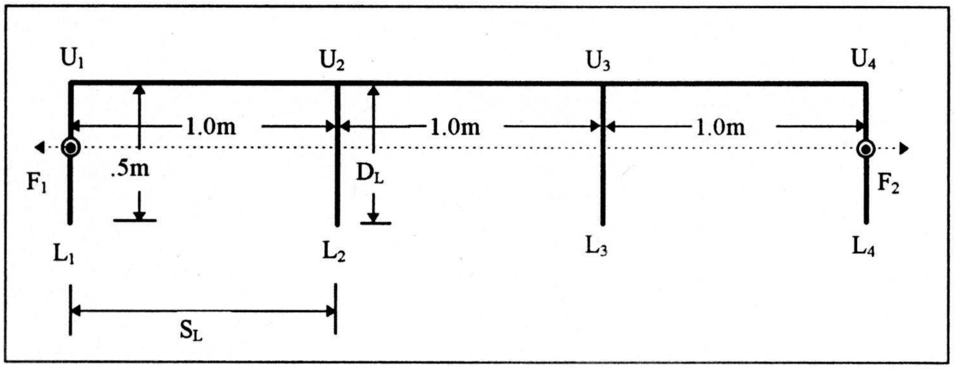

Figure 4. Static Test Path for LSM Lab Tests

The dynamic tests involve automatically following a rectangular path in the test plane with the test point for many cycles (see Figure 5). E_1 and E_2 are located at the intersection of the test plane and the boundary of the manipulator workspace along a horizontal line that passes through the work space center point (the dashed line). The center of the rectangular path will be the center point of the line E_1E_2. The four corner points of the rectangle are represented by R_1, R_2, R_3, and R_4. The segment length S_L is the same as for the static test above, and the length of the test rectangle will be $2S_L$ with a height of $1S_L$. The rotation will be clockwise from the starting point shown with a maximum speed of 1000 mm./sec. as recommended by ANSI. For dynamic performance, the criteria are relative path accuracy, path repeatability, path speed characteristics, and cornering overshoot.

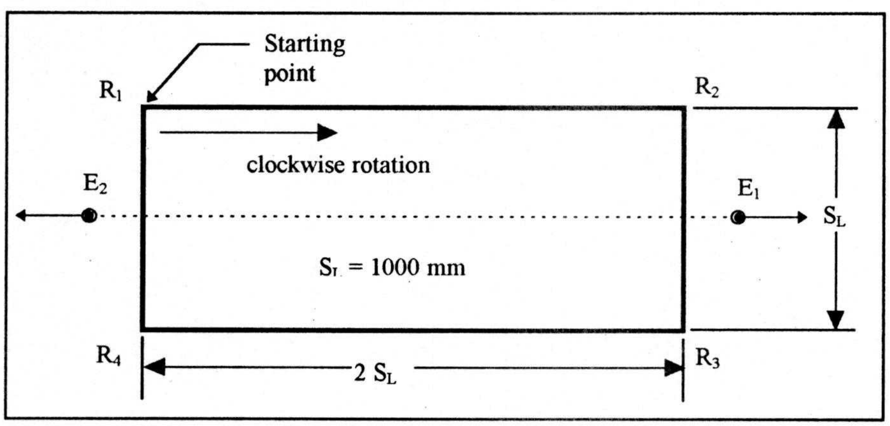

Figure 5. Dynamic Test Path for LSM Lab Tests

The LSM is currently being prepared to run the static and dynamic tests in its test bed with the addition of position sensors on all of its DoF's. For more details on the exact tests for the LSM consult [14] and for the standards look at [2,3].

3.2 THE UT AUTOMATED PAVEMENT CRACK SEALER

The main performance evaluation used for the crack sealer is a productivity analysis. With both the early fully automated and the later tele-operated versions, the main performance feature that had to be met was economic feasibility. To prove feasibility, tests were run on the systems to see if they could meet the productivity of a standard crack sealing crew. While the automated sealer could accurately find cracks and seal them in a manner that was deemed feasible due to its added benefits of reduced labor costs, improved quality, and improved safety [6], it was still too slow to be practical. So, a new version of the device was developed that was tele-operated by the driver of the truck that tows the crack sealer. Since both versions required a driver, there is no added labor cost. Plus, the cycle time once a crack has been found is reduced to around ten to fifteen seconds which compares favorably with conventional methods while maintaining the same benefits as the automated version. The reduced labor costs make the tele-operated unit feasible with a quick payback of the initial investment for the crack sealer with no loss in productivity.

There are also ergonomic factors that must be considered when selecting the man-machine interface. With the tele-operated pavement crack sealer, a choice must be made on how the operator will control which cracks are sealed. Currently, this is done by the operator tracing over the cracks in the image. There are several methods of tracing the cracks, and they include: mouse, light pen, stylus on touch-sensitive screen, and others. It is important to find which device the user will be most comfortable with in order for the most efficient operation. The proper placement of the drawing surface must also be studied. Tests have been developed that have the operator trace the same crack images with different devices to measure speed as well as operator satisfaction with the device. Preliminary research has shown that using a touch sensitive screen is the fastest and most intuitive method for most people since it allows them to draw directly over the crack. However, the research into the proper man-machine interface is continuing and other methods are being considered.

4.0 CONCLUSIONS

Because the construction industry has lagged behind many others in the adoption of automation technologies, there is a gap that offers the potential for the application of selected technologies. Advanced control systems for construction equipment is one of these technologies. New control systems for construction equipment are developing at a rapid pace as the industry is trying to close the technology gap. Recent advances have seen the influx of highly advanced control systems for construction equipment which are improving quality and safety while reducing labor costs. Control schemes that have been developed range from resolved motion and teach/learn capability to tele-operated, and even automated systems.

As the new control paradigms are developed, there is a vital need for benchmark performance testing to insure their quick acceptance into practice. Non-application specific methods for such testing are being developed at the University of Texas for large scale manipulators that are based on ANSI standards. Application specific tests that have been developed at UT are based upon the productivity of the device in performing the tasks for which it was designed or to determine the most ergonomic form of control. By being application specific, a new set of experiments must be developed for each task, but there are usually logical parameters that can be used as a guide for their development, such as best speed, most economical, etc. Nevertheless, these tests must be created in order for the new control paradigms to be proven effective, and quickly accepted by the construction industry.

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