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Pipe Manipulator Enhancements for Increased Automation

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Abstract: Piping commonly makes up 20–30% of the installed cost of a process plant. The prospects for making piping erection a repetitive, efficient process create a new demand for powerful, specialized pipe erection equipment. A pipe manipulator has been developed which is an adapation of a 20 ton rough terrain hydraulic crane, consisting of an attachment to the main boom. This paper explores desirable enhancements to the pipe manipulator to allow for increased automation, with an emphasis on fully automatic manipulator desirable new features. Three prime issues are discussed: management of the local state of the manipulator arm, with incremental development of an arm motion control system; management of the global state of the manipulator, with a large scale manipulator metrology system; and navigation in a construction environment.

Introduction

Piping Construction

Piping commonly makes up 20–30% of the installed cost of a process plant and a large plant can contain 50 miles of piping, ranging from 0.75–90 in. in diameter. The complexity of process plant pipe erection is high and much of the work still occurs at or near the final installed position. Extensive documentation is needed to describe the piping and its erection.

Construction equipment used in pipe erection remains general purpose, meeting the needs of constantly varying requirements. Substantial developments have occurred in construction equipment used on cross-country pipeline projects. In process plant pipe erection, however, the substitution of hydraulic cranes for lattice boom cranes has been the only major development since the 1940s. Pipe erection for process plants is generally accomplished with the aid of the rough terrain hydraulic crane, or cherry picker. This crane provides a basic hoisting function and is commonly seen in plant maintenance and small- to moderate-sized construction projects. A rigging crew typically prepares the lifts with slings and chokers and guides the pipe into supporting structures. A typical operation may involve a variety of personnel, including a rigger foreman, riggers on the ground, riggers in the structure, and one or more heavy equipment operators.

Process plant pipe erection owes its historical lack of automation to technical obstacles in three critical areas. These are organization, information, and equipment.

1. Organization. The complexity of the plant, unreliable materials supply, and

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distant parallel activities requiring coordination result in frequent disruptions to orderly planning.

2. Information. In general, each pipe spool is unique in its configuration and erected condition. Constant reference to design, procurement, and management documentation is a must.

3. Equipment. Despite the repetitive nature of piping, each lift is generally a one-of-a-kind job. While the equipment is generally capable, adaptable, and general purpose, it is not task-specific. Loads are rigged and positioned manually.

The prospects for making piping erection a repetitive, efficient process create a new demand for powerful, specialized pipe erection equipment. This paper explores desirable enhancements to an existing pipe manipulator to allow for increased automation, with an emphasis on fully automatic manipulator control.

Pipe Manipulator

The pipe manipulator developed by Grove Manufacturing Company is an adaptation of a 20-ton rough-terrain hydraulic crane with an attachment to the main boom. The attachment provides an elevating, telescoping auxiliary boom with a wrist and pipe-gripping jaws. These result in an eight-joint axis boom with a 65-ft radius.

The deployment of the manipulator on a process plant construction project on the Texas Gulf Coast, as well as suggested improvements, are described in Glass (1984). With complete hydraulic control of gripping, location, and orientation, this machine possesses the mechanical fundamentals of a true pipe erector and may thus be considered as the best point of departure for automation enhancements to present practice.

Automation Enhancements

Table 1 outlines user needs and desirable features for a pipe-erecting manipulator. Noteworthy features include a simple man-machine interface, ease of operator observation of activity, automated information presentation to the operator, coordinated manipulator arm motion for straight-line motion, and automation of repetitive lifts.

Effective control of the manipulator arm is the most important enhancement not presently available. This is best implemented with digital electronics. Three areas are most promising for digital enhancement of manipulator control:

1. Straight-line motions. The computer allows the operator to function in a global reference frame, translating intuitive operator instructions into local joint-axis instructions. This capability also permits inclusion of experienced operator techniques, such as smooth speed changes. This is useful for manipulator operation by craft personnel.

2. Automation of repetitive motions. Computers are much more efficient than people at replicating repetitive motions. Operator attention and energies are then preserved for more complex, less predictable tasks and situations. The "manual teach-playback" method appears to have the greatest potential.

3. Complete pick-and-place automation. The computer is capable of driving the manipulator from limited digital instructions related to the task objective.

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TABLE 1. User Needs and Desirable Features for Pipe-Erecting Manipulator

Need (1)	Feature (2)
Eliminate ground level riggers	Pipe gripping jaws
Not limited to pipe	Multipurpose or changeable jaws
Complete control of spool position and orientation	Jaws on wrist; flexible manipulator arm
Task structure not limited by manipulator mobility	No-setup-time chassis
Simple man-machine interface despite many manipulator functions	Natural, multifunction controls
Continuous, direct observation of lift by operator	Vision aids or mobile control station
Information presentation to operator	Graphic aids or displays, customize data files
Coordinated arm motion	Digital logic, open- or closed-loop automatic control of joint-axis drives
Automate repetitive lifts	Digital logic, closed-loop automatic control of joint-axis drives, "robotics," adaptation to construction environment uncertainties
Executional link between data bases	"Robotics," large scale metrology, upstream information system

These instructions may be generated from the project CAD data base. Obstacle avoidance capability is necessary in complex environments.

These advanced enhancements depend on the use of a digital computer. Automation requires a real-time intelligent representation of manipulator location, orientation, configuration, and future states.

Three successive issues are addressed in the following discussion: first, management of the local state of the manipulator arm, with incremental development of an arm motion control system; second, management of the global state of the manipulator, with a large scale manipulator metrology system; and finally, navigation in a construction environment. These issues are presented in a general form, since they are really applicable to any large-scale construction manipulator.

Development of Arm Motion Control System

Manual Joint Rate Control

Manual operation of a multi-axis manipulator is cumbersome with conventional lever-operated controls. These may be replaced with a more intuitive interface, such as a master-slave rate controller, which may take the form of one or two control levers or "ergosticks" with a structure analogous to that of the manipulator arm. With other manipulator functions (gripper open/close, horn) incorporated in the "ergosticks," operator concentration on the job at hand is maximized.

This simple manual controller may be implemented using conventional electric valves and analog potentiometers. But such an approach limits any

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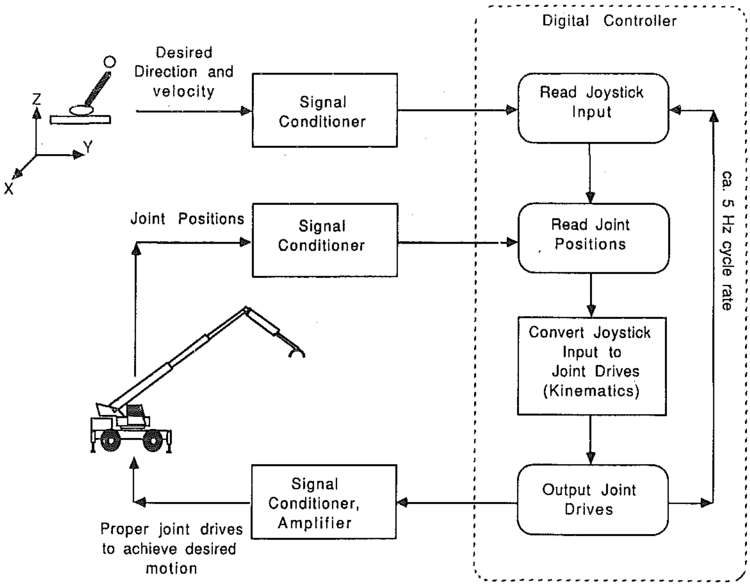

FIG. 1. Open-Loop Operator-Assisted Control

further enhancement. A digital interface using encoders, a small computer, and pulse-width modulated electric valve drivers is still simple. This configuration may be readily improved in the future to allow open-loop operator-assisted control.

Open-Loop Operator-Assisted Control

An open-loop system may be used for straight-line-motion operator assistance. The digital controller translates instructions from the global reference frame of the operator to the local joint-axis reference frames. From this, straight-line motions are obtained from a manipulator with revolute joints that move naturally in arcs. For this condition, position sensing of joint positions is required because of the kinematics used to develop joint motions.

For operator-assisted control, only low-accuracy position sensors are required. A joystick can be used to indicate travel velocity for straight-line motion in a particular direction. The controller reads this input, which it then translates into joint-axis drives using kinematics based on current joint positions. The read-translate-drive cycle is repeated at perhaps 5 Hz rate, as illustrated in Fig. 1.

The kinematic equations may take the form of look-up tables for simple arm configurations. These equations become complex trigonometric expressions for full locational and positional control of a multi-axis arm. Their derivation, and speedy real-time application, requires some insight.

Operator-assisted control may be developed incrementally on the manual control system. The first step is installation of position sensors on a few major axes, and addition of a kinematic look-up table in the control software. The manual control "ergosticks" may be used, now as a direction indicator,

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or a new joystick added if required. Succeeding incremental steps lead to sensors on all axes and extension of the kinematic equations.

Closed-Loop Automatic Control

Programmed motions involve closed-loop automatic control of all arm motions. Such controls for robot manipulator arms are well described (Paul 1981).

A construction manipulator arm raises new control issues. These include effective position sensing with a long reach arm, hydraulic rather than electric motor actuation, and dealing with arm dynamics and high kinetic energies by means of "operator techniques" or dynamic equations.

The first step with automatic control may be with the operator-assisted control position sensors and simple control routines in the central control computer. Succeeding steps leading to precision automatic control include high-accuracy precision sensors, distributed-control loop processors freeing the central computer for higher tasks, redesign of mechanical manipulator arm elements for reduced backlash and faster response, and more sophisticated control equations, correcting for arm droop and dynamics.

Manipulator Metrology

Coordinate Representation

Real-time metrology is a major challenge to productive automation. Pick and final placement positions for pipe spools will be represented to the pipe manipulator in the form of absolute coordinates from a benchmark. The manipulator must be able to locate itself with reference to a benchmark and then locate its gripper with respect to itself. This must be done rapidly and automatically, free of persons with surveyor's transits.

In what form should these coordinates be represented? The form should include all six coordinates: three for location in space and three for orientation. The form should reflect the actual information measured, without adding inferred information and without depending on adjacent measurements. Finally, if a series of measurements is needed to find a position, then the form should allow easy combination of the measurements.

A familiar form of representation is a vector. A vector can include the required six coordinates. Vectors can be added together to get a resultant vector from benchmark to gripper. But vectors are not acceptable because inferred information is added.

The vector does not contain information about its coordinate frame, so it must refer to the absolute coordinate frame. To keep the coordinate frame consistent among all vectors, each vector in a series refers to all previous vectors. This results in progressive distortion along a chain of measurements. Another problem is that a position vector for each point in the chain must be calculated to obtain the end position, even when the intermediate positions are not of interest.

A better form is that of homogeneous transformations (Paul 1981). In this case, the position of each joint is represented by a transformation matrix. The transformation specifies the position of a point relative to a previous point, defining a new local frame for each link in the chain. For a link in a manipulator arm, its content reflects only the constant dimensions of that link and the variable travel of its joint axis.

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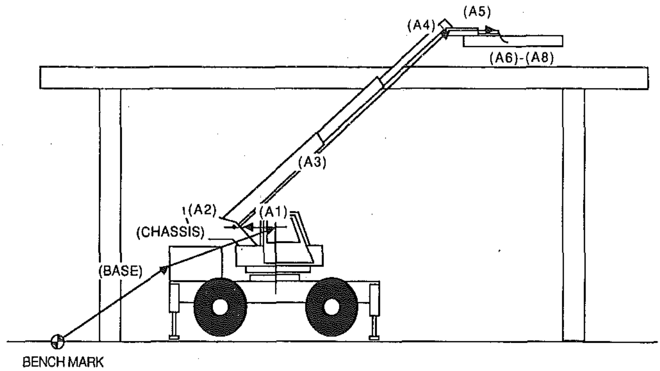

Transformation matrices are shown as (BASE), etc.
(A1) through (A8) refer to manipulator arm links.
Position of gripper relative to bench mark equals
(BASE) (CHASSIS) (A1) (A2) . . . (A8)

FIG. 2. Gripper Position Calculated from Benchmark

The transformation does not add inferred information and does not depend on adjacent measurements. Transformations are readily combined by multiplication. A single combined matrix can be used to calculate the gripper position, free of the burden of finding positions of intermediate joints. The homogeneous transformation qualifies as an adequate representation of measurement for an automation system.

In the case of the pipe manipulator, the position of the gripper is determined by a continuous series of measurements from a benchmark. Each measurement is represented as a homogeneous transformation matrix from benchmark to a fixed position on the chassis, from a fixed position on the chassis to the first joint axis (the boom swing axis), from the boom swing axis to the boom elevation axis, etc. The series of transformation matrices are derived from kinematic relationships and position measurements. The complete series of transformation matrices is multiplied together to obtain the gripper position. This is shown in Fig. 2.

Real-Time Metrology

How is each measurement to be made accurately and in real time? This is largely a matter of sensor technology. Fig. 2 illustrates the measurements under consideration. Typical approaches are:

1. Measurement from a benchmark to a fixed position on the manipulator chassis: the position of the benchmark may be established by conventional surveying methods. Methods of measuring the manipulator chassis relative to the benchmark are described in the literature (Evans 1985; Yavnai 1987). If the manipulator moves down a fixed path as it works, linear measurement may be accomplished with a fifth wheel odometer or an ultrasonic or laser range finder. If forward motion drifts from side to side, triangulating range finders are necessary.
2. Measurement from a fixed position on the chassis to the boom swing axis:

J. Constr. Eng. Manage., 1989, 115(3): 412-423

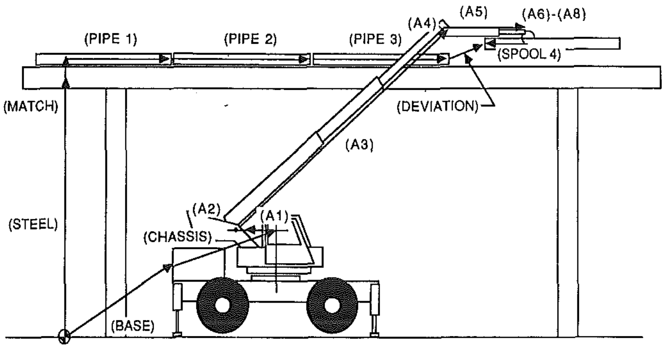

FIG. 3. Dimensional Loop

this distance is constant and is determined by prior measurement.

3. Measurement from the boom swing axis to the boom elevation axis: the constant portion of this distance is determined by prior measurement. Boom swing angle is variable and may be measured by a rotary analog potentiometer or digital encoder. Coarse measurement may be obtained from the swing actuating motor shaft. Fine measurement must be made directly from the swing spindle or ring gear.

4. Measurement from the boom elevation axis to the boom extended axis: the constant portion of this distance is determined by prior measurement. Boom lift angle is variable and may be determined by a rotary on the boom elevation hinge pin or by a linear measurement device on a boom lift hydraulic cylinder. The latter approach requires a geometric conversion to obtain the desired lift angle.

What sort of inaccuracies can be expected, what is their effect, and how can they be overcome? These questions are best addressed by looking at the complete dimensional loop: the circular series of measurements that establish the deviation of the load from its final placement position (Fig. 3).

This deviation is measured between match marks: one on the load, and the other at the open end of previously erected pipe. The position of the load match mark is found from a benchmark by simple extension from the gripper position. The other match mark is found from the same benchmark but traverses a second series of measurements through structural steel and previously erected pipe.

This dimensional loop presents the manipulator with a numerical description of the deviation between match points. The manipulator controller may then act to remove the deviation and align the match points.

Of course, when the manipulator controller has successfully aligned these numerical match points, errors in the dimensional loop will result in an actual position error. Table 2 indicates that this position error is on the order of one foot, intolerable for even gross positioning tasks.

Transformation errors in the dimensional loop may be improved individually, collectively, or both. Transformation errors may be improved individually by prior analysis and design. This includes tighter dimensional tolerances of foundations and support steel and corrections for predictable structural flexure of support steel and the manipulator arm.

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TABLE 2. Transformation Errors

Transform matrix (1)	Type of dimensional error (2)	Typical magnitude (in.) (3)
Steel	Foundation placement tolerance	1.0
	Steel fabrication tolerance	0.125
	Warpage from galvanizing process	0.25
	Solar and atmospheric temperature changes	0.375
	Steel assembly tolerance	0.125
	Matchmark placement tolerance	0.063
	Structural flexure	0.50
Match	Spool placement tolerance	0.125
	Matchmark placement tolerance	0.063
Pipe 1 etc.	Spool diameter tolerance	0.010
	Spool length tolerance	0.063
	Misalignment at joints	0.063 + 0.5°
	Welding process temperature changes	0.125 per hot joint
	Solar and atmospheric temperature changes	0.063
Spool 4	Location of gripper	0.125
	Spool length tolerance	0.063
	Sag of unsupported pipe	0.010
A1 to A8	As-built dimensional tolerance	0.010
	Bearing surface backlash, looseness, wear	0.005 per surface
	Structural flexure due to weight	4.0
	Structural flexure due to dynamic transients	1.0 decaying
	Position sensor error	0.063 + 0.025°
	Position control error	???
	Structural vibration from engine	0.010
	Solar, atmospheric temperature changes	0.125
	Hydraulic fluid warm-up temperature changes	0.125
	Wind load on boom	1.00
Chassis	As-built dimensional tolerance	0.25
	Structural flexure due to weight	0.50
	Structural vibration from engine	0.010
	Irregularity in pavement	0.50
	Engine warm-up temperature changes	0.125
Base	Sensor error	0.125

Transformation errors may be improved collectively during execution of the task. The manipulator may be "taught" the true position of support steel or match points with local calibration. Error-correcting input may also be obtained from the operator. The collective error is then removed by incorporating a correction transformation into the dimensional loop.

If best performance with the dimensional loop remains inadequate, error may be lessened by direct observation and correction. A local match-mark

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alignment sensor may be employed to measure the deviation. Manipulator joints can then be manually driven based on the deviation. In practice, closing the dimensional loop would be used for coarse positioning and local sensing for fine positioning.

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NAVIGATION IN CONSTRUCTION ENVIRONMENT

Obstacle Avoidance and Spool Erection Strategy

It must be assumed that pipe spools cannot be driven directly from pick positions to final place positions because of possible intervening obstacles. To avoid obstacles, the manipulator must generate an erection strategy: a series of stations between which straight-line motion is possible. The series of stations offers a detour around obstacles and sums up to the total desired move between initial pick and final place positions (Fig. 4). Obstacle-avoidance motion, then, differs from simple straight-line motion in that a relatively complex erection strategy must be developed. This defines the series of intermediate stations, while taking into account the surrounding environment as well as the limitations of the manipulator itself.

Of course, it is desirable for the erection strategy to be developed by a computer. In principle, a computer can keep track of all interfering elements in the manipulator's environment, including foundations, and both locally stored and previously erected structural steel and pipe. However, on the basis of current technology, system response time for path generation is expected to be intolerable for a productive operation. This problem may be combated in part with advancements in computing technology and knowledge representations. More essential are attempts at enhancing constructibility. This

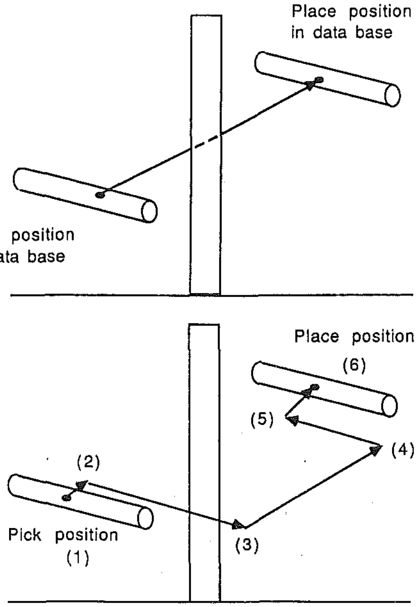

FIG. 4. Erection Strategy

may be accomplished through design simplification along with systematic planning of construction operations and jobsite maintenance. The tactics are discussed in detail in Fisher et al. (1988).

Pipe Rack Erection Strategy

Perhaps a simplified erection strategy is best illustrated with the case of the simple horizontal pipe rack, in which pipe erection consists of a series of moves between 14 standardized stations:

1. Approach to pick position.
2. At place position.
3. Grip pipe.
4. Depart place position.
5. Boom raised.
6. Facing structure.
7. Position for insertion into structure.
8. Insert into structure.
9. Approach to place position.
10. At place position.
11. Open gripper.
12. Depart place position.
13. Arm out of structure.
14. Arm at safe position.

This strategy is repeated as long as the project geometry remains repetitive or constant. Thus, very significant geometric parameters for automation are established early in project design and should be thoroughly scrutinized. These include spool fit in the workspace envelope, pipe support conformance to standards, and manipulator spotting unobstructed by foundation. During design, conformance to the parameters should be reviewed for each spool and results flagged for each spool. Nonconforming spools should be recorded in a spool data file and in these instances the control of the manipulator turned over to the operator at its erection.

Of course, proper sequencing to facilitate erection is essential. Items for early erection include spools inside structures and spools that support other spools. Items for later erection include spools on the outside of structures and spools supported by other spools and vessels. These points are also elaborated on in Fisher et al. (1988).

Collision Avoidance

Collision avoidance during automated motion will depend on close conformance with predetermined task parameters and operator intervention. Automatic collision avoidance through the use of sensors remains a difficult problem. Short-range (contact) sensors are inadequate because of the large size and high kinetic energy of the manipulator arm, combined with its tendency to whip with a sudden stop. Long-range (ultrasonic) sensors would interfere with normal final positioning maneuvers, where the arm is close to support structures.

New Safety Concerns

The automated manipulator will introduce a new potential for accidents. Examples of new hazards include uncontrolled movements after an acciden-

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tal severing of control lines and the catapulting of a spool from an unintentional release of the gripper.

Practical safety evaluation of a robot manipulator is described in Bonney and Young (1985). Basic safeguarding principles include:

1. Eliminate or reduce hazard potential. Example: place an upper limit on travel speed.
2. Separate personnel from hazards. Area sterilization from casual personnel entry will be required for a distance of one manipulator-arm's length around the machine. Barricading, such as in the case of welded joint radiography, may be necessary.
3. Prevent aberrations. The basic control system must be reliable and contain appropriate redundancies. Suggested elements include protective sensors driving interlocks, such as gripper closure interlocked with hydraulic flow or pressure; armoring of critical control wiring; and a deadman switch on the control console.

A manipulator newly introduced to a site must be accompanied by supervisory personnel, prepared to act on aberrations as they develop. Failure to take corrective action after repetitive accidents will result in dangerous exposure, with loss of automation program credibility and ultimately its feasibility.

Conclusions

Automated control enhancements for pipe erection offer faster, more accurate motion for the manipulator. Specifically, straight-line motion and the automation of repetitive motion are control areas with promise for digital enhancement. These advancements require that the control system possess a real-time representation of the manipulator, its location, orientation, and arm configuration. Homogeneous transformations have been found to offer certain advantages in representing manipulator metrology. Obstacle avoidance is another complexity to be addressed. Here, spool-erection strategies offer one solution that is less dependent on sensor technology developments. Finally, however automation is enhanced, safety considerations appear to become more acute and are deserving of additional research attention.

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