Constructability for Piping Automation: Field Operations

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Abstract: This paper focuses on how the productivity of semi-automated piping construction for process plants may be improved through constructability-enhancement tactics. This paper answers the question regarding how field operations activities must be altered to support the automated field effort. The semi-automated environment of piping erection assumes a pipe manipulator attached to the boom of a 22-ton, rough-terrain crane for the base piece of pipe-lifting equipment. This study concentrates on horizontal process piping erection. Three major categories of constructability issues are addressed. These issues include material handling, equipment capabilities, and equipment configuration. Quantitative techniques used to compile empirical data regarding innovations for a semi-automated construction process include physical modeling and computer simulation, via a three-dimensional computed-aided design simulation software package. There is a 24% construction-productivity savings occurring when these constructability issues for the automated piping erection system are implemented.

Introduction

There are various motivating factors that cause automation to have potential application in the construction industry. The nuclear- and toxic-waste industries have been investigating the potential for automation due to reasons of safety. Deep-sea pipeline construction and construction in space are driven to automation due to accessibility (Paulson 1985). Clean rooms in the high-tech industry are now built and maintained by robots, in order to maintain a high degree of quality, or sterilization. Dirty, labor-intensive construction tasks, such as sandblasting and insulation, concrete, and paint spraying have been automated because of their undesirability (Skibniewski and Hendrickson 1988). A national economic reason for research on construction robotics is to keep from losing U.S. technological advancement to overseas imports (Paulson 1984). For many years robots have been performing economically useful tasks in the field for major Japanese construction contractors ("Japan" 1983).

The principle motivation behind construction automation, however, with which this paper deals and with which the United States should be concerned, is productivity. Because of the alarming decline in productivity growth rates during the past 20 years in the U.S. construction industry (Sundareswaran and Arditi 1988), construction automation has been considered as a method of improving productivity (Fisher 1989). Piping construction was selected for this study as a direct result of the Business Roundtable's "Construction Industry Cost Effectiveness Report" (1982), which stated that piping is the most inefficient and single largest cost element of major industrial construction projects. It also stated that the task of piping construction is

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one of three areas having the highest potential for technological advancement.

Background

This study employs the concept of constructability to achieve productivity enhancements for an automated system. Constructability has been defined by the Construction Industry Institute (CII) as "the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives" (*Constructability, A Primer* 1986). Constructability underscores the importance of up-front decisions during project planning, design, and procurement in support of the construction effort. Constructability is a key objective for achieving project success, particularly for projects involving some degree of automation. Constructability-improvement programs have been initiated on conventional projects and have been shown to have positive impacts in the areas of construction-delay decreases, construction-manpower decreases, and construction-activity-duration decreases (O'Connor 1985). This study addresses how conventional field operation practices must be modified to support the automated field effort (O'Connor and Fisher 1988). Constructability is enhanced when innovative construction methods are used. Innovative methods are those not generally considered common practice and that are creative solutions to field challenges (O'Connor and Davis 1988). By use of creative brainstorming, this study looks at various innovative alternatives regarding the constructability issues of material handling, equipment capabilities, and equipment configuration to determine "lessons learned" (heuristics) from those innovative solutions (Fisher and O'Connor 1988).

The semi-automated environment for piping erection assumes an enhanced pipe manipulator attached to the boom nose of a 22-ton, rough-terrain crane for the base piece of lifting equipment (Skibniewski and Russell 1989). A study was conducted in 1984, comparing the productivity of the pipe manipulator with conventional piping erection, using a 15-ton hydraulic "cherry picker" (Glass 1984). Findings from more than 55 hours of accurate, objective, time-lapse film, indicated that the pipe manipulator was superior to conventional piping erection when lifting large diameter (>3 in./>76.2 mm), vertical and bent pipe configurations. Horizontal piping erection by the pipe manipulator was less effective, and the cherry picker, in this instance, outperformed the pipe manipulator by a factor of 2. Because of these results, this study concentrated on the lifting of horizontal pipe only. Constructability analysis was employed to improve upon the productivity of the pipe manipulator so that it was competitive with conventional piping erection methods. Through constructability analysis, some lessons learned, or rules of thumb (heuristics), were compiled for the pipe manipulator in a semi-automated piping erection system.

Issue Identification

The identification of constructability issues for a conventional construction system is a fairly involved process. For the automated system it is even more complex, because one is dealing with a new system that has not been widely implemented and that which does not have a large prior history of construc-

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TABLE 1. Constructability Issues for an Automated Piping Construction System

Issue number (1)	Description (2)	Criticality (3)	Difficulty (4)
1	Plant configuration for materials handling	High	Medium
2	Plant configuration for manipulator access	High	Medium
3	Sequencing	High	Low
4	Materials management and handling	High	Low
5	Preassembly of pipe spools	High	Medium
6	Parallel activity schedule	High	Low
7	Piping material identification	High	Low
8	Design standardization	High	High
9	Spool or module manipulation to avoid double handling	High	High
10	Preplanning for manipulator ground preparation, seasonal considerations and manipulator breakdown	Medium	Medium
11	Work packaging	Medium	Low
12	Automated procedure for small bore pipe fabrication	Medium	High
13	Equipment selection	Medium	Medium
14	Simulation of operation	Medium	High
15	Pipe spool or module fabrication—remote versus on-site	Medium	Low
16	Automatic welding (connections)	Medium	High
17	Underground pipe application	Medium	Low
18	Vessel dress-out	Low	Low
19	Pipe bending	Low	High
20	Rapid changing technologies	Low	High

tion knowledge and experience. Initial constructability-issue generation evolved from review of the CII *Constructability Concepts File* (1987) and from earlier studies performed on the automated piping construction system (Glass 1984). An initial list of 20 issues, related to an automated piping construction system, was developed from these sources (see Table 1). In addition, a subjective assessment by the researchers of criticality (degree to which an issue impacts constructability) and difficulty (feasibility, cost, etc.) for each issue was added. To eliminate some of the subjectivity of such an analysis, these issues were presented in random order (with difficulty and criticality assessments deleted) to three selected, knowledgeable industry representatives for review. These selected experts had more than 100 years of industrial piping design and conventional construction experience among them (Fisher 1989). Their expertise was used to obtain a consensus of what were recognized to be the top seven most-important issues for an automated piping construction system. The issues selected by these experts were as follows: Plant configuratigon; accessibility; sequencing; preassembly; parallel scheduling; material handling; and connections. Six of the seven issues selected were those for which research and development efforts had been rated by the researchers as having a high degree of criticality and a medium-to-low degree of difficulty. These results substantiated the researchers' previous assessment.

All of the issues selected by the experts, with the exception of materials handling, are related to the planning and design phases of piping construction and not the field operations phase. This is in keeping with the traditional construction management concept that states: "Any decision made at the beginning stage of a project life cycle (conceptual planning and design) has far greater influence than those made at later stages" (Hendrickson and Au 1989). Researchers found an even greater impact on productivity savings when planning and design are altered to facilitate implementation of automated equipment (Fisher 1989). These results, however, are beyond the scope of this paper, which will only address the field operations phase issue of material handling.

This study also addresses two other issues initially overlooked by both the researchers and the experts. One area is the design configuration and capabilities of the equipment used in the field operations phase. Indirectly, this is a design issue because it deals with the design configuration of the manipulator. However, because it impacts the field oeprations phase, it will be addressed in this paper. The other field operations issue that cannot be overlooked when evaluating the automation of construction systems is that of crew balancing. The labor-saving advantage of automation cannot be ignored when analyzing constructability for an automated construction system.

METHODOLOGY

As stated earlier, previous research substantiated that horizontal piping erection by conventional means with a cherry picker was superior to the pipe manipulator, by a factor of 2 (Glass 1984). As a result, this study concentrated on selecting a simulation method for the lifting of horizontal pipe into a pipe rack. The steps for this piping erection process are as follows: (1) Stage pipe manipulator; (2) grip pipe; (3) lift pipe and place into pipe rack (gross motions); (4) feather controls for final pipe alignment (fine motions); (5) return manipulator to original position to grip next pipe (repeat steps 2 through 5 until crane must be respotted); and (6) respot manipulator (return to step 1). Other portions of the total cycle interspersed among the above steps include changing of manipulator jaws and break time.

It was necessary to develop a means to quantify and compare productivity of piping erection for both conventional and automated methods, as well as a method that could quantify productivity both before and after constructability analysis. To achieve this goal, the preceding steps needed to be quantified and simulated. Data from previous research and from time-lapse film that were collected for this research (Glass 1984) was used to determine the percentage breakdown of total piping erection cycle time for the aforementioned steps. Table 2 contains the results of this analysis.

Simulation techniques were more challenging to develop. Upon initiation of this study in 1987, the researchers were unaware of software animation packages that had both robotics and on-line, interactive interference-checking capabilities. Both of these capabilities were required to accurately simulate an operator maneuvering a piece of pipe into a pipe rack with the manipulator. There were static computer-aided design (CAD) modeling packages that conducted interference checking in batch mode. There were

TABLE 2. Piping Erection Activities and Percent of Cycle Breakdown (Fisher 1989)

Piping erection activities (1)	% of total cycle time (2)
Staging, gripping, returning	21
Gross motion	30
Fine motion	25
Respotting	13
Jaw change	8
Breaks	3

numerous robotics packages that could model the kinematics of the manipulator, but they did not have interference-checking capabilities. For this reason, a physical plastic model of the piping erection system (crane, pipe manipulator, and pipe racks) was initially built.

Once this analysis was under way, the software Walkthru was found to have limited on-line interference-checking capabilities. Walkthru is a real-time, three-dimensional simulation system developed by Bechtel Eastern Power Corp., Gaithersburg, Maryland. It has the capability of recording and replaying object motions in real time on demand so that the simulation of construction activities can be planned and analyzed. The pipe manipulator, pipe-rack configurations, and material cart with pipes were created on an Intergraph CAD system. The ASCII file format was then imported to a Silicon Graphics 4D workstation, on which Walkthru was run.

Quantitative data were collected from 161 plastic model cycles and 165 computer simulation cycles on constructability issues for all phases of the project life cycle. Comparison and validation techniques were performed on the two modeling methods (both physical and CAD) to verify their accuracy. From Table 2, only 38% of the total piping erection cycle time was simulated with physical and CAD modeling (steps 3 and 7). Other portions of the cycle time were not modeled, because of their difficulty in simulating and because of their variability. These other steps in the piping erection process would be possible candidates for future research.

Graphical Computer Constructability Analysis (GCCA)

The application of computer-based modeling of construction activities has received the attention of researchers since the mid-1970's. Halpin's early work with CYCLONE took the form of a computer program used for the batch processing of large simulation model networks (Halpin 1977). Subsequent work by Bernold at the University of Maryland has permitted the development of a microcomputer program, called MICROCYCLONE, that takes information about production to assess nonsteady state processes in construction (Bernold 1985). Bernold's goal is to have real-time, automated data collection about production information in order to improve the effectiveness of process planning. INSIGHT, developed under Paulson at Stanford, is an interactive data-acquisition tool for videotape information on construction processes (Paulson et al. 1987). Interactive processing, extraction, and statistical analysis permit the development of a "network-based simu-

TABLE 3. History of Computer-Based Simulation of Construction

Year (1)	Developers (2)	Simulation method (3)	Application (4)
1976	Halpin and Woodhead	CYCLONE (CYCLic Operations NEtwork)	Batch processing of construction model networks
1982	Lluch and Halpin	MICROCYCLONE	CYCLONE for microcomputers
1984	Bernold and Halpin	CYCLONE	Continued work for nonsteady construction processes
1985	Paulson, Chan, and Koo	INSIGHT (INteractive SImulation using GrapHics Techniques)	Statistical analysis of videotape information
1987	Paulson, Chan, and Koo	VIP (Video-data Interactive Processing) VIE (Video Interactive Extraction) VISA (Video-data Interactive Statistical Analysis)	
1988	Fisher and O'Connor	GCCA (Graphical Computer Constructability Analysis)	Visual and quantitative analysis of detailed construction process (i.e. interaction of components, equipment and tools, and the user)

lation model which replicates the performance of the real-time system" (Paulson et al. 1987).

The role of computer-aided design (CAD) as a simulation tool for automated construction processes, up to this point, has been to provide information to a construction process so that discrepancies between design and actual data can be assessed. Information about actual data is provided via sensory feedback. Design information is imported into CYCLONE for sensitivity analysis and system productivity optimization (Bernold 1989). CAD's other historical applications in the construction industry have been as a means for the rapid production of drawings, and, more recently, as a means to design intelligently (Gero et al. 1986) and provide information for the management of construction projects (Atkin 1986).

The application of CAD in this research endeavor was as a tool for graphical computer constructability analysis (GCCA). GCCA was used for studying the detailed construction process itself and the complex interaction of components, equipment and tools, and the user. CAD was used to animate the semi-automated system and compile both heuristics and empirical quantitative data regarding innovations for the construction process. Computer-based simulation of a semi-automated piping construction system was realized to be a powerful method of system simulation, due to its high accuracy,

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speed, and ease with which variables could be changed. The use of CAD would be even more powerful, long-term, because of large amounts of information already existing in CAD data bases. Table 3 summarizes the history of the various computer simulation techniques that have evolved over the last 15 years.

Constructability Issue Analysis Findings

This section reviews the detailed results of the analysis methods of physical modeling and GCCA as they were applied to the constructability issues for the field operations phase of a project. The following subsections review the heuristics that resulted from the simulation of the field constructability issues of material handling, equipment capabilities, and equipment configuration. This section also contains the quantitative cycle-time analysis, model validation, and productivity savings resulting from simulation, as well as a discussion of the impact of crew balancing on the automated piping erection construction system productivity.

Material-Handling Heuristics

Material-handling issues that were simulated, and proven to be significant, included manipulator and material spotting location (in the X-, Y-, and Z-directions of the Cartesian coordinate system), manipulator or material orientation, and material pickup. These concepts are illustrated in Figs. 1, 2, and 3.

Sensitivity analyses were performed for material location in the X-direction of the Cartesian coordinate system. Results indicated that the optimum place to spot the material and manipulator is not directly in front of a pipe-rack bay, but at a distance approximately 25% (5 ft) to the left of center. This point is illustrated in Fig. 4(*a*). This figure is a typical sensitivity analysis diagram containing the impact of cycle time (vertical scale) as a function of the percent of change of a variable (horizontal scale). The steeper the slope of the curve, the more sensitive the variable. Diagrams such as this were prepared for all of the material-handling constructability issues. Fig. 4(*a*) illustrates that cycle time can increase significantly, the farther over from the center of the pipe-rack bay in the X-direction that the material and manipulator are spotted, until pipe installation becomes impossible (cycle time = infinity). This is because more complex motions are required to align the pipe from a skewed position. Cycle times can increase as much as 161% if the material and manipulator are spotted 30 ft over in the X-direction from the center of the pipe-rack bay; any greater than 30 ft over causes installation to be impossible.

The concept that cycle time is increased by increasing the distance of the material and manipulator from the pipe rack in the Y-direction is illustrated in Fig. 4(*b*). One would intuitively assume this to be the case, but what is significant is how sensitive this variable is (steepness of the curve). What is also significant is the determination of the boundaries at which cycle time goes to infinity. Both pieces of information are valuable for planning and optimizing the field operations. Cycle time can be increased as much as 138% if the material and manipulator are spotted back as far as 33 ft [see Fig. 4(*b*)]. Spotting any farther back makes pipe installation impossible (all booms are fully extended at this point). If pipe is to be installed all the way

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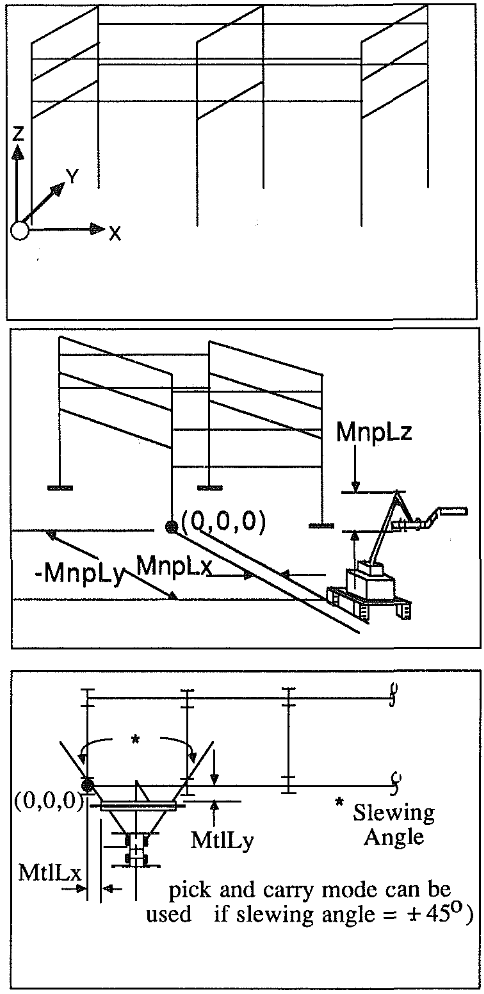

FIG. 1. Material and Manipulator Spotting Location: (*a*) Cartesian Coordinate System for Pipe-Rack Bay; (*b*) Manipulator Spotting Location; (*c*) Material Spotting Location (Plan View)

to the back of a 20-ft-wide pipe rack (standard data were measured to the middle, which is 10 ft back), there is a material spotting zone in the Y-direction, of 5 to 23 ft away from the rack (28 ft for the manipulator), in which pipe can be installed. Spotting outside this zone makes installation impossible with current manipulator joint ranges. This is important information for field operations planning and site layout.

The pipe manipulator can be operated either by picking up the pipe and driving it forward (pick-and-carry mode) or by having the base of the pipe manipulator remain stationary with outriggers extended while the load is boomed or extended into place (outrigger mode). The rotation, or "slewing,"

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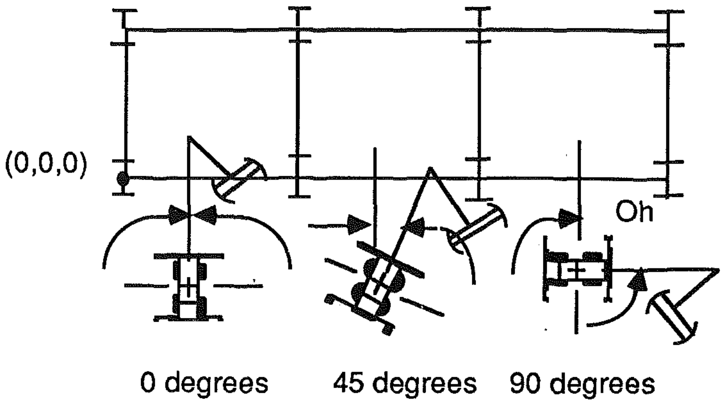

FIG. 2. Material and Manipulator Orientation

angle of the boom must remain over the front tires (+/−45°, see Fig. 1) in order to use the pick-and-carry mode. Booming is a considerably slower joint motion than driving. For this reason, booming should be avoided by not installing equipment in an area around the rack more than 10-ft wide and 15-ft tall, or the manipulator will have to boom over the equipment rather than driving up to the rack.

Material staging in the vertical (Z-) direction also was analyzed. There is no significant cycle-time gain [see Fig. 4(*c*)] when staging the material above the level of the material cart (standard material cart height = 5 ft). If the

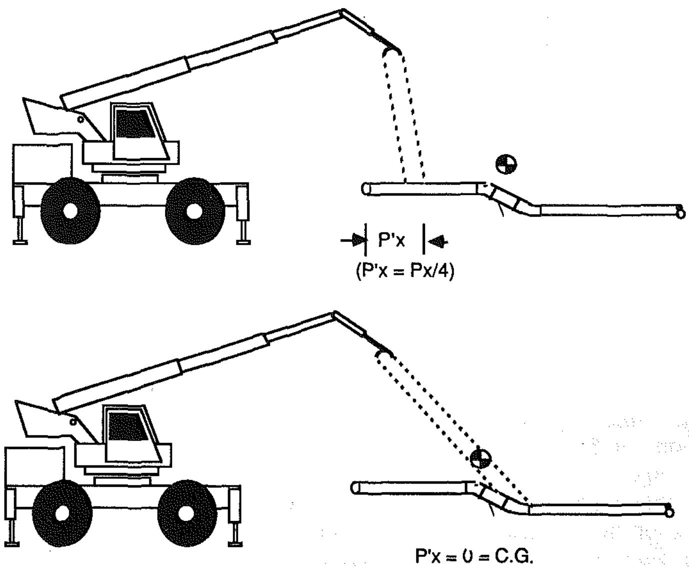

FIG. 3. Material Pickup: (*a*) Eccentric Pickup Point; (*b*) Center of Gravity Pickup Point

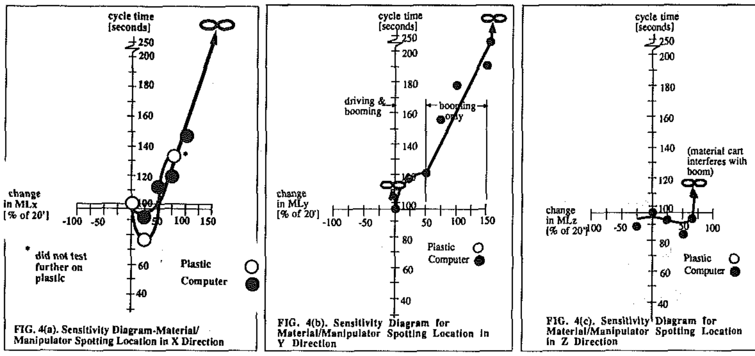

FIG. 4(a). Sensitivity Diagram-Material/Manipulator Spotting Location in X Direction

FIG. 4(b). Sensitivity Diagram for Material/Manipulator Spotting Location in Y Direction

FIG. 4(c). Sensitivity Diagram for Material/Manipulator Spotting Location in Z Direction

FIG. 4. Material and Manipulator Location in X-, Y-, and Z-Directions (18 Physical Model and 36 GCCA Cycles)

material is lifted greater than 13 ft into the air, the manipulator boom bumps into the material cart and cannot install the pipe [also illustrated in Fig. 4(*c*)].

The next issue analyzed was material and manipulator orientation and its effect on cycle time. Results appear in Fig. 5(*a*). This significant cycle-time increase associated with material and manipulator orientation indicates that it is best to try and keep the manipulator facing the piperack directly. Once again, this would be obvious to the user, but what is important here is the sensitivity of the variable (steepness of curve). The high sensitivity of this constructability variable is attributed to the fact that the manipulator is rotated around (swung) and boomed (telescoped) into the rack, rather than using the faster motion of driving when facing head-on (standard pick-and-carry mode).

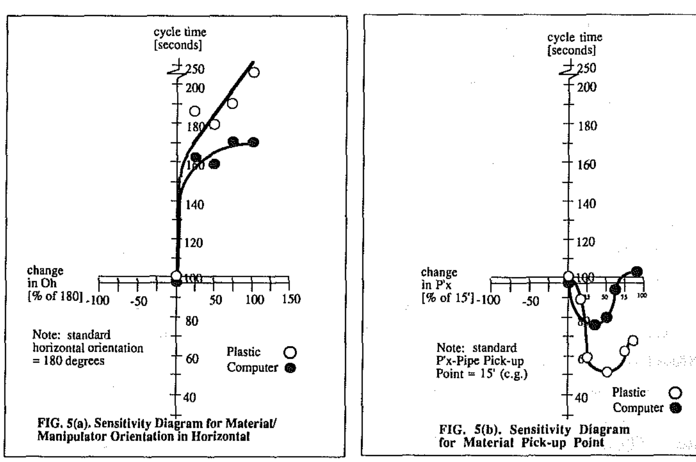

FIG. 5(a). Sensitivity Diagram for Material/Manipulator Orientation in Horizontal

FIG. 5(b). Sensitivity Diagram for Material Pick-up Point

FIG. 5. Sensitivity Diagrams for Material and Manipulator Orientation (15 Physical Model and 23 GCCA Cycles) and Pickup Point (23 Physical Model and 27 GCCA Cycles)

TABLE 4. Hydraulic Joint Velocities for Manipulator (Smith 1988)

Degree of freedom (1)	Joint velocity with operator in control basket (2)	Joint velocity with operator on ground (3)
Slew angle (swing)	5.1 degrees/sec	19.8 degrees/sec
Main boom elevation (lift)	1.28 degrees/sec	4.59 degrees/sec
Main boom extension (telescope)	0.25 ft/sec	0.89 ft/sec
Position elevation (lift)	2.5 degrees/sec	5.0 degrees/sec
Vertical rotation	5.0 degrees/sec	5.0 degrees/sec
Horizontal pivot	5.83 degrees/sec	5.83 degrees/sec
Arc of rotation (roll)	52.78 degrees/sec	52.78 degrees/sec

There is an optimum pickup point for the pipe of 33–50% over from the center of gravity [see Fig. 5(*b*)]. The magnitudes of the impact on cycle time, however, are not as significant as some of the previous curves.

Equipment Capabilities Heuristics

The four general areas covered in this section are operator location, desired joint motions and ranges, booming versus driving, and single- versus multiple-degree-of-freedom (DOF) controls.

When Grove Manufacturing originally developed the manipulator to attach to its conventional 22-ton crane, the company were concerned about the safety of the manipulator operator. Being located in a gravity-leveling control basket at the end of a crane boom put the operator in a vulnerable position. For this reason Grove engineers chose to reduce the hydraulic velocities of the crane when the manipulator attachment was used. These joint velocity comparisons are shown in Table 4. The majority of velocities can be increased with the operator on the ground. Note that vertical rotation, horizontal pivot, and arc of rotation are not increased, in order to prevent a long piece of pipe from being whipped around dangerously at high speeds (S. D. Smith, senior project engineer at Grove, personal interview, 1988). When joint velocities are allowed to be increased (assume operator on ground), average cycle time significantly improves. Using the velocities with the operator on the ground and recalculating cycle times for all 161 plastic-model cycles and 165 computer-simulation cycles, resulted in a savings of 44% (87.2 sec versus 49.1) for the physical model and 48% for GCCA (99.7 versus 52.2 sec).

The control basket hanging down 7 ft from the end of the boom not only posed a hazard to the operator, but also caused an accessibility problem. Often times when lifting pipe into the pipe rack, the bottom of the control basket would strike the horizontal steel members (stringers) or the side of the basket would interfere with the steel columns. Additional cycles were taken on the computer with the basket completely removed from the manipulator model so that the effects of lessened interference could be isolated from the effects of joint velocity increases. The effect of basket removal was an additional savings of 38% (60 sec versus 96 sec with basket-attached standard conditions). The combination of lessened basket interference and joint velocity increases due to removal of the control basket resulted in an overall total savings of 65% (34 sec versus 96 sec with basket attached).

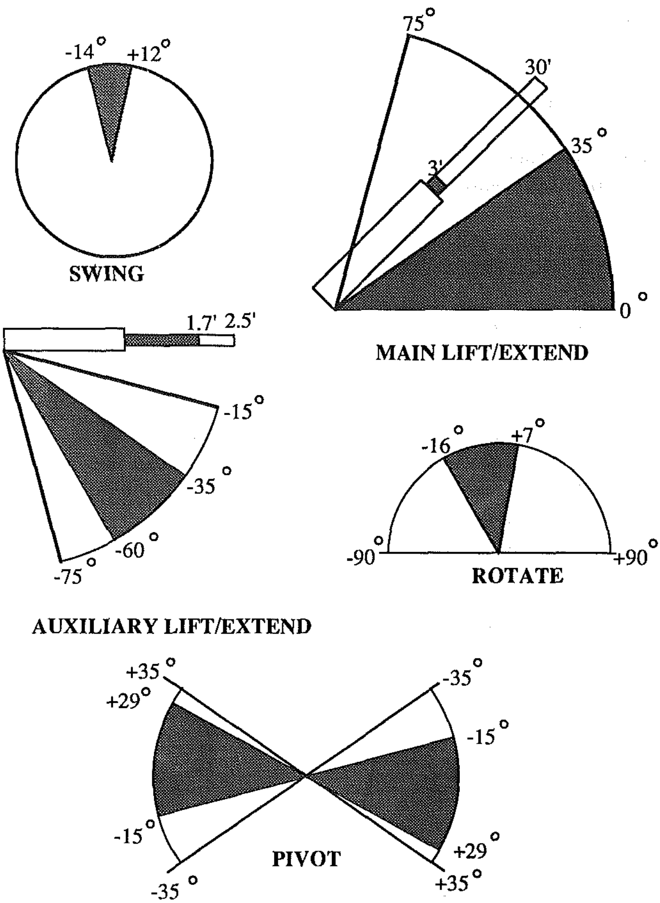

FIG. 6. Average DOF Ranges Used for Computer Simulation

This savings, plus the added advantage of increased lifting capacity of the manipulator, make removal of the control basket an attractive option.

Another issue relating to equipment capabilities is desired joint motions and ranges. Fig. 6 is a graphical view of the DOF range data. The shaded portion of each DOF is the average range of that joint motion that was used during computer simulation. Note that all of the joint motions were used extensively during computer simulation except for main extend (used only 29.66% of the time) and roll (used less than 1% of the time). The minimal use of main extend is attributed to the fact that no lines higher than 30 ft were installed (extend was used occasionally to reach over, not lift up). This was because only horizontal pipe-rack piping was handled. The only time main extend would be used extensively would be during installation of tall vertical lines along towers. This is not a frequent activity, in light of the fact that 85% of process piping is below 30 ft and 50% of all process piping is yard rack piping (Fisher 1989). These facts point out the need for a redesign of the manipulator to do away with the "crane concept" (discussed further in the next section on equipment and tools configuration). The other joint motion not used at all during computer simulation, according to Fig. 6, is rolling. This is expected, since this motion would be used only in orienting and aligning bent spools of pipe. All pipes tested during computer simulation were horizontal lines. Fig. 6 also illustrates that very small percentages of the joint ranges were used during computer simulation. The two highest degrees of freedom, which were used two-thirds of the time, were auxiliary extend and pivot. This confirms earlier work stating that these were two DOFs whose ranges needed to be increased (Glass 1984).

A significant advantage of computer simulation is that data could be easily collected with the joint-range motion limits removed from the manipulator model. In this case, operators can use whatever joint-range motions they desire to erect a pipe under standard conditions. Two cycles were taken where joint limits were totally removed. The results confirm what was previously stated. All DOFs were used with the exception of main extend and roll, just as before, and auxiliary extend was increased to 174% of its joint-range motion. Pivoting was only 72% of its range, but the range taken was from $-1°$ to $49°$. This is a range skewed out of the current $+/-35°$ range. This confirms the previous statement, indicating a need to increase the ranges of pivoting and auxiliary extend.

However, before the pipe manipulator is redesigned to increase these two joint motions, anlaysis of cycle time is warranted. The cycle time was 103 sec when joint limits were totally removed. This is slightly slower than the average cycle time of 96 sec for standard conditions. Thus, even though it may be desirable to increase joint motions for convenience, such modification would only slightly increase cycle time. This is because the two joint motions that would appear to be practical to increase have slower joint velocities associated with them, offering little gain for productivity. It is therefore the recommendation of the author that even though high joint-range use and Glass' earlier work indicate a manufacturing joint-range increase to pivoting and auxiliary extend, the measured productivity results with no joint-range limits indicate that pivoting and auxiliary extend should not be increased because of increased cycle time.

The next issue to address under the area of equipment capabilities is to compare the joint motions of driving versus booming. As data were being collected, it became evident that booming was a very slow joint motion and should be avoided if possible. This means making sure equipment is kept clear of the pipe rack, or at least on one side of the rack. The productivity difference is significant. The difference was compared in computer simulation under standard pipe-rack conditions and found to have a cycle-time savings of 49% if the pipe manipulator is driven rather than boomed (1,897 sec versus 96 sec for all standard cycles where the manipulator was driven).

The last issue to be discussed under the subject of equipment capabilities is single- versus multiple-DOF controls. Single-DOF controls are the way the manipulator is currently configured, which is to say that only one joint can be moved at a time. Multiple-DOF controls mean that an operator can select several joint motions at one time, such as in the case of wanting to move the manipulator in a straight line from the material cart to the rack by using boom lifting (radial motion) at the same time as boom extending (linear motion). This can be achieved by the use of joystick controls, which imitate the more natural motions of a human being. The menu-driven Silicon Graphics workstation, in its current controls configuration, models a single-DOF control situation. Only one joint at a time can be selected from the menu and moved. If joystick controls were attached to the Silicon Graphics workstation, it would model a multiple-DOF control situation. This research topic was addressed by a separate research team (Hughes et al. 1989).

A prediction of operator performance with multiple-DOF controls (joystick) can be extrapolated from the plastic-model data. A comparison of identical cycles imitated from time-lapse film with plastic and computer shows 24 motions for the plastic model, 32 motions for the time-lapse film, and 38 motions for the computer simulation. Because of its fewer numbers of motions, the plastic model is the closest simulation to a multiple-DOF control system. During data collection, for example, if the objective was to clear the end of a long pipe around a column, the operator would merely simultaneously swing and pivot around the column in two motions when using the physical model. The only way this could be achieved with the computer model was to go through a series of alternating swings and pivots that might take as many as eight motions. The actual machine in the time-lapse film is almost a single-DOF control situation with eight separate control knobs for each DOF. The operator, however, still has two hands and may occasionally get confident and move more than one knob at a time. This explains the slight difference in 32 motions for the time-lapse film and 38 motions for the computer. However, comparing time lapse with plastic modeling, a 25% savings in the number of motions could potentially occur with the use of a multi-DOF control scheme.

Equipment Configuration Heuristics

If the pipe-manipulator jaw configuration were changed to a slotted, scissor-action jaw design, this would eliminate the need to change jaws for different size ranges of pipe. In its current configuration, the pipe manipulator has four different jaw sizes (Glass 1984). The reduction to only one jaw would reduce the part of the cycle time spent changing jaws by at least 75% (attaching only one jaw rather than four). This savings could be even greater depending on how often during the day the same jaws were changed and reattached.

A survey on piping attributes reveals varying characteristics of piping construction among differing systems or plant types (Fisher 1989). Piping is more dense in a power plant due to economy of building space, and less dense in a process plant because of the hazards of fire, explosions, and toxicity. This implies that differing industries should have varying sizes and configurations of manipulators, as well as variations in the base piece of equipment to which the manipulator is attached. Also, piping elevations differ among industries, implying varying designs for joint configurations.

Model Validation and Productivity Savings

Time-lapse film analysis was used to validate the accuracy of both plastic and computer modeling. The time-lapse film paths used to determine the overall piping erection cycle-time breakdown were imitated with the plastic model and the computer simulation in order to predict what the overall total piping erection productivity improvement from time-lapse conditions would be. The savings between time-lapse conditions and the optimal cycle time

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TABLE 5. Cycle-Time Savings from Constructability Analysis

Constructability issue (1)	Constructability subissue (2)	% savings of total cycle time (3)	Affects cherry picker or manipulator (4)	Affects horizontal, vertical, bent pipe configuration (5)
Material handling	Manipulator and material orientation	4	Cherry picker or manipulator	Horizontal, vertical, and bent
Equipment and tool capabilities	Operator location	5	Manipulator	Horizontal, vertical and bent
	booming versus driving single	3	Manipulator	and bent
	versus multi-DOF controls	6	Manipulator	Horizontal, vertical and bent
				Horizontal, vertical, and bent
Equipment and tool configuration	Manipulator jaw configuration (one jaw size versus four)	6	Manipulator	Horizontal, vertical, and bent
		24%		

Note: % savings; horizontal-manipulator = 24%; vertical and bent-manipulator = 24%; horizontal-cherry picker = 4%; and vertical and bent-cherry picker = 4%.

encountered were compared. These savings were then prorated on the basis of sensitivity of each influencing constructability issue variable. The fact that only a portion of the entire piping erection process from Table 2 (steps 3 and 7, or 38%) was taken into account when calculating final percent savings. Table 5 is an overview of the total piping construction savings by constructability issue from the field operations phase analysis. Issues that were isolated and tested using sensitivity analysis and not found to be sensitive (small slope) were not included in Table 5. A total of 24% cycle-time

TABLE 6. Savings from Constructability Issue Analysis and Crew Balance

Item (1)	Manipulator unimproved (glass) (worker hours per lift) (2)	Manipulator improved (worker hours per lift) (3)	Cherry picker unimproved (glass) (worker hours per lift) (4)	Cherry picker improved (worker hours per lift) (5)
Horizontal pipe configuration (50%)[a]	1.20	0.91 (24% savings)	0.58	0.56 (4% savings)
Optimal constructability conditions		−0.30 (33% savings)		—
Crew balance savings				
Subtotal	—	0.31	—	0.56
Vertical or bent pipe configuration (50%)[a]	2.17		2.34	
Optimal constructability conditions		1.65 (24% savings)		2.25 (4% savings)
Crew balance savings		−0.54 (33% savings)		—
Subtotal	—	1.11	—	2.25
Prorated total (50:50 split)[a]	1.68	0.86	1.46	1.40

[a]Ratio for process industry (Fisher 1989).

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savings is the overall result of constructability analysis for the field operations phase of the semi-automated piping erection system.

All of the constructability issues in Table 5 affect horizontal piping erection with the pipe manipulator. Some of these constructability issues, however, also affect conventional piping erection with the cherry picker, as well as vertical and bent-pipe-spool configurations. The breakdown in the various types of savings is summarized at the bottom of Table 5.

Crew Balancing

During previous research, it was concluded that the three-member manipulator crew could be reduced by one member. This would reduce manipulator time-lapse idle time from 45% to 17%, which is more comparable to conventional piping erection (with cherry picker) time-lapse idle time of 19% (Glass 1984). By eliminating one crew member, a savings in worker hours per lift for the manipulator would then equate to 33.3%.

When this savings is combined with the previous 24% productivity savings discussed in the previous section, an overall piping erection productivity savings of 39% between piping erection with a pipe manipulator and conventional piping erection with a cherry picker (0.86 worker hours per lift for manipulator versus 1.40 for cherry picker in Table 6) is the end result. This savings becomes even greater with other plant types. This is because the ratio between horizontal and bent or vertical pipe spools is 8:92 and 0:100 for power plants and marine facilities, respectively (Fisher 1989).

Summary Conclusions and Research Contributions

This research endeavor contributes to the advancement of construction engineering and management not only in the quantitative results of productivity improvement, but also in the methodology used to conduct this research. Three major areas of contributions are described as follows.

Constructability for Automation

Constructability analysis programs for conventional construction processes have been initiated with some degree of success. The challenge is to extrapolate the constructability issue identification process to automated construction processes that do not have a long prior history of construction knowledge and experience. For the field operations phase of the life cycle of a project, this paper identifies the constructability issues of material handling, equipment configuration and capabilities, and crew balancing as critical issues for constructability analysis of an automated construction system. The paper also sites plant configuration, accessibility, sequencing, preassembly, parallel scheduling, and connections as issues that need to be included in constructability analysis during the planning and design phases of an automated construction system.

Graphical Computer Constructability Analysis (GCCA)

The development of GCCA as a way to graphically analyze construction processes is a significant step in the development of computer simulation techniques for construction systems. By this method, one is able to generate both heuristics and quantitative data for the construction system, regardless of whether it is an automated or conventional process. GCCA is a viable tool to implement in today's construction industry, primarily because it uses static CAD ASCII files that are already in place in most design offices.

Productivity Improvement

A semi-automated piping erection system was initially dismissed by the field as not being totally cost effective. Initial findings from studies of the system indicated that for horizontal piping erection, conventional methods outperformed the semi-automated system by a factor of 2 (0.58 worker hours per lift for conventional versus 1.20 for automated from Table 6). Constructability analysis for automation, was used to determine how field operations should be altered to support the automated field effort. Through implementation of constructability analysis, the semi-automated process became competitive with conventional piping erection methods (0.86 worker hours per lift for automated versus 1.40 for conventional from Table 6). This proves that the productivity of semi-automated piping construction for process plants may be improved through constructability enhancement tactics. It answers the question regarding how field operations activities must be altered to support the automated field effort.

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