Automation and Robotics in Construction X
G.H. Watson, R.L. Tucker and J.K. Walters (Editors)

Performance Evaluation Model for Construction Manipulators

Hsieh, Ting-Ya, Research Assistant
Dr. Haas, Carl T., Assistant Professor

Department of Civil Engineering
University of Texas at Austin
Austin, Texas 78712, USA

ABSTRACT

This paper describes a model for evaluating the performance of construction manipulators. It involves four steps: (1) constructing the operation plan, (2) evaluating task and machine related parameters, (3) evaluating time components and (4) total time study. Each of these steps is described in detail, and a hypothetical example is used to demonstrate the procedure. The results indicate that based on the physical capabilities of a prototype pipe manipulator, a well designed control system may reduce the task completion time by a factor of 4.25 to 6.33. The example also reveals that the manipulator's existing 8-lever control system will result in lengthy sensing-and-decision delays. Although this evaluation model is developed for construction manipulators, it is perceived that it will also be useful for a larger group of automated construction equipment with some minor modifications. It can be used to examine performance of an operating system, or to predict the performance of a system design.

1. INTRODUCTION

Construction manipulators are a new class of construction equipment which has just started to be utilized in a number of construction applications. Currently, their applications include fireproof material spraying [1], interior partition installation [2], concrete masonry walls construction [2], piping erection [3], concrete placement [4,5,6], facade/surface finishing [7], reinforcement steel placement [8], palletized load handling [9], and interior finishing [10]. A more in-depth discussion of the characteristics of construction manipulators can be found in [11].

One important issue related to the application of construction manipulators is their performance evaluation. Since this research domain is rather new, a systematic approach to evaluate their performance is still non-existent. Similar performance evaluation studies have been found in the realms of industrial engineering and industrial robotics [12,13,14]. However, significant deficiencies exist for construction applications in these methods, primarily due to the complexity and the unstructured nature of construction.

This paper describes an evaluation model that incorporates the critical factors and variables undefined in previous methods. This model is developed for evaluating the performance of a construction manipulator but can also be useful for similar types of construction equipment. The paper begins by discussing the task environment of construction manipulators in order to establish the basis for understanding the difficulties and uniqueness of evaluating their performance. Then, the performance evaluation model is introduced and discussed. To demonstrate the application of this model, a hypothetical example is used. From this example, sensitivity analyses of the evaluation results are presented. Finally, a summary of the potential of this model and concluding remarks are given.

2. TASK ENVIRONMENT OF CONSTRUCTION MANIPULATORS

The task environment of a construction manipulator consists of the task, the manipulator and human workers. Under ideal conditions, the manipulator operator will employ the strength of a manipulator to perform a specific task such as picking and placing a length of pipe. The completion time is determined solely by joint motion time. In other words, if he or she operates one joint at a time, the total operation time is the sum of all joint motion time. If all joints can be move simultaneously, the completion time is the maximum of all joint motion times.

In reality, errors, machine characteristics and uncertainties complicate the calculation of total completion time. A task may encounter geometric errors of the building envelope and dimension tolerance of the material. More often, the manipulator will have platform positioning/orientation errors, joint actuating errors, arm deflection, attachment changeover time and some inherent lags of joint motion. As well, human performance depends on the experience, the information provided prior to and during the operation, and many other factors. Consequently, numerous forms of delays are inevitable during operation and can be substantial in terms of the percentage of the total completion time. The evaluation results could be highly inaccurate if these variables are not modeled.

3. PERFORMANCE EVALUATION MODEL

The proposed model assumes that the total completion time is the most important criterion for performance evaluation. Therefore, the whole focus of the performance evaluation is on systematically identifying time components and objectively approximating their values. Other likely criteria for performance evaluation such as total cost, quality and workers' satisfaction are not within the scope of this model. Four steps are involved in this model, explained as follows.

I. Constructing the Operation Plan

In nature, the operation of a construction manipulator is similar to that of a human hand. Therefore, there exists a set of pre-defined elemental motions to describe all operations of a construction manipulator. A set of such elemental motions is proposed in Table 1. With this set, an operation plan can be constructed.

II. Evaluating Task and Machine Related Parameters

The parameters related to the task and the machine's physical capabilities are identified in Table 2. In evaluating the task related parameters, the ground conditions dictate the time requirement for platform leveling. The motion rate reduction in the fine arm motion category is a direct result of safety considerations for the case where a collision between the manipulator and other objects may be encountered. The tolerance level[1] determines the number of segments to which a continuous fine motion needs to be disintegrated as high motion precision is required. The machine related parameters are obtainable from either field experiments or manufacturer's specifications.

III. Evaluating Time Components

This step involves the calculations of motion time, including the platform motion, the gross arm motion, the fine arm motion and the end effector motion, and the evaluation of three types of delay as described in Table 3. The calculation of motion times is fairly straightforward. It can be done simply by dividing a motion range such as a distance of travel or degrees of rotation by a given motion rate. Special attention needs to be paid to the motion sequence of arm motions. Sequential and parallel motions have to be distinguished and evaluated separately. If several motions start at the same time and act in parallel, the total motion time is the longest of these joint motion times. If they take place sequentially (only one joint moves at a time), the total motion time is the sum of all joint motion times.

In evaluating the sensing-and-decision delay, two variables need to be estimated. First, all occurrences of sensing-and-decision delay should be identified for the entire operation. This process is done by thoroughly examining each joint motion according to two criteria: (1) the tolerance level and (2) whether it demands external sensing. For example, when an end effector is approaching to the "Pick" position to grasp an object, this fine motion may require frequent external sensing to recognize the end effector's actual distance and relative orientation to the object and to adjust for ensuing motion. This continuous motion is therefore divided into three segments and three sensing and decision processes are involved, each preceding one segment of motion.

Table 1 Description of Element Motions

Motion Type	Elemental Motions	Description
Platform Motion	Re-spot Platform	Re-positioning the machine platform from one location to another on the job site, measured by driving speed and travel distance
	Level Platform	Leveling the machine platform close to horizontal level, involving adjusting the outriggers and/or providing a sound base to support the machine's weight
Gross Arm Motion	Reach	Elemental gross arm motion employed to move the arm and the unoccupied end effector to a destination without payload
	Move	Elemental gross arm motion employed to move the arm and the payload which is secured by the end effector to a destination
	Orient	Elemental gross wrist motion employed to rotate the unoccupied end effector to a certain orientation without payload
	Turn	Elemental gross wrist motion employed to rotate the payload which is secured by the end effector to a certain orientation
Fine Arm Motion	Disengage	Combined fine arm/wrist motions employed to separate one piece of material from a cluster of others involving micro scale of slow translation and rotation of the handled material
	Pre-position	Combined fine arm/wrist motions employed to position and align the end effector to an intangible point with very high precision involving micro scale of slow translation and rotation of the end effector
	Approach	Elemental fine arm motion employed to locate the end effector to a physical point with very high precision involving micro scale of slow translation of the end effector
	Slide	Elemental fine arm motion employed to move the end effector and/or material along a fixed trajectory on a surface with very high precision
End Effector Motion	Grasp	Elemental type I end effector motion employed to secure the control of a piece of material
	Release	Elemental type I end effector motion employed to abandon the control of a piece of material

Table 2 Task and Machine Related Parameters

Motion Type	Task Related Parameter	Machine Related Parameter
Platform Motion	• Travel Distance • Ground Conditions	• Desirable Travel Speed • Outrigger Motion Rates
Gross Arm Motion	• Joint Motion Ranges	• Maximum Joint Motion Rates
Fine Arm Motion	• Joint Motion Ranges • Motion Rate Reduction • Tolerance level	• Maximum Joint Motion Rates
End Effector Motion	N/A	• Grasp Time per Cycle • Release Time per Cycle

Table 3 Delay Factors

Delay Factor	Description
Sensing & Decision (S&D)	The time which is required in one cycle of sensing information of task and environment, waiting for instructions, processing information, and making decisions regarding ensuing motions and is evaluated according to the technology used: 1. Automated sensing-and-decision and 2. Manual trial and error
Force Buildup	The time which is required between the operator sending a motion command and the actual motion response from the machine, usually varied from actuator to actuator and subject to kinematic and dynamic parameters
Attachment Changeover	The time which is required by occasional supportive operations, consisted of end effector changeover time and other attachment assembly/disassembly time

A second variable is the duration of sensing-and-decision. If a sensing-and-decision process is done by manual trial-and-error, the duration depends on the experience of the operator and the means of communication to acquire external information between the operator and other workers involved. If it is achieved by sensors and a computer with possible input from the operator, the duration is determined by the efficiency of this control loop. To construct the evaluation model, one must first establish the base values of delay duration for either case. Then, the likely upper and lower bounds of the duration variation may be considered indicating the most difficult and the simplest cases respectively. Since uncertainties are explicitly dealt with here, more insight is gained by sensitivity analyses.

The force buildup delay can then be incorporated into the calculated joint motion time. The basic rule is that, whenever a joint moves from a static state, i.e. a complete stop, there is a force buildup delay accompanying that joint motion. Finally, the attachment changeover delay can be obtained either from the experience or the suggested data from the manufacturer. Usually, if the operator's skill remains at the same level, the attachment changeover time is close to a constant.

IV. Total Time Analysis

The total time analysis consists of calculating the total completion time and a series of sensitivity analyses. Since the total motion time constitutes a number of estimated values, it is necessary to analyze the sensitivity of these estimates. These values include the maximum joint motion speeds, the reduced joint motion speeds due to safety, the total number of sensing-and-decision delays, the duration of sensing-and-decision cycles, and the duration of force buildup delays. Three techniques can be used to perform sensitivity analyses: (1) the Tornado Diagram, (2) the Two-Way Sensitivity Graph and (3) the Spider Diagram. In this paper, only the Spider Diagram will be used in the example. The description of these techniques can be found in various sources [15].

4. CASE STUDY

This example assumes a hypothetical piping erection task which involves a stationary truck delivering pipes and a 30-foot high T-shape pipe rack. Pipe erection will be performed by a construction manipulator. The physical capabilities of the construction manipulator are obtained from those of the Grove Pipe Manipulator. Detailed information on this machine can be found in [3]. Two levels of control capabilities are assumed available for this machine. The full control capabilities include internal and external sensors for the joints and the end effector, a computer-aided task planner to interface with the operator and provide motion commands, and a servo-controller. The primitive control capabilities have only joint encoders and an 8-lever controller. Two identical manipulators are each equipped with one of the control capabilities. In essence, this evaluation example compares the performance of the same manipulator with different control capabilities.

The first step of the evaluation is to construct an operation plan. By using the elemental motions in Table 1, this plan is described as follows:

(1) Re-spot Platform and Level Platform: Drive the manipulator platform and station to the proper position for handling pipes.
(2) Reach and Orient: Move the manipulator arm to reach the proximity of one length of pipe on the truck.
(3) Pre-position and Approach: Align and move the gripper to the "Pick" position of the pipe.
(4) Grasp: Gain control over the pipe.
(5) Disengage, Move and Turn: Move the end effector away from the pipe cluster and move the arm to a stable configuration.
(6) Move and Turn: Move the end effector to reach the proximity of the designated "Place" location.
(7) Pre-position and Approach: Align the pipe and move the end effector to the "Place" location.
(8) Release: Release the pipe.
(9) Pre-position: Move the end effector back to the previous position, away from the pipe.
(10) Move and Orient: Move the arm back to a stable configuration and complete this cycle.

The next step is to evaluate machine and task related parameters. The values of machine related parameters were obtained from manufacturer's specifications and verified by field experiment, as shown in Table

4. Regarding the task related parameters, the travel distance of the platform is estimated to be 600 feet. The location at which the platform will be stationed is flat and roughly leveled. Also, the tolerance level of this task is considered medium and therefore the reduced fine motion speeds can be 50% of the gross motion speeds. The ranges of joint motion are listed in Table 5.

Table 4 Physical Characteristics of the Grove Pipe Manipulator

Manipulator Function	Left/Up/In/Close	Right/Down/Out/Open	Build Pressure
Outrigger	6 seconds	4 seconds	0
Platform Travel	3.67 ft/sec	N/A	N/A
Swing on Base	19.8 deg/sec	19.8 deg/sec	0
Main Lift	4.6 deg/sec	4.6 deg/sec	0
Main Telescope	10.7 inch/sec	10.7 inch/sec	0
Secondary Lift	2.2 deg/sec	3.2 deg/sec	0
Secondary Telescope	1.5 inch/sec	1.4 inch/sec	1.5 seconds
Roll	32 deg/sec	32 deg/sec	1 seconds
Rotate	13 deg/sec	13 deg/sec	3 seconds
Pivot	2.3 deg/sec	2.3 deg/sec	10 seconds
Jaw	7 seconds	8 seconds	1 seconds

Table 5 Ranges of Joint Motions in the Hypothetical Example

Motion Elements	Ranges of Joint Motion
Reach & Orient	Swing(+90°), Main Lift(-41°), Secondary Lift(+20°)
Pre-position	Roll(+105°), Secondary Telescope(+7")
Approach	Roll(-5°), Secondary Telescope(+2")
Grasp	Jaw Close
Disengage	Roll(-5°)
Move & Turn	Roll(-50°), Main Lift(+41°), Secondary Lift(-20°), Secondary Telescope(+9")
Move & Turn	Swing(-90°), Main Telescope(+115"), Main Lift(-16°), Secondary Lift(+30°)
Pre-position	Roll(-30°), Secondary Telescope(+15")
Approach	Roll(5°), Secondary Telescope(+2")
Release	Jaw Open
Pre-position	Roll(-5°), Secondary Telescope(-2")
Reach & Orient	Main Lift(-25°), Main Telescope(-115"), Secondary Lift(-10°), Secondary Telescope(-17")

As described in the model, to proceed to the evaluation of time components, one has to identify (1) the motion sequence, i.e. whether a set of joint motions is in parallel or sequential, and (2) the occurrence of sensing-and-decision delays. Such findings for both manipulators are presented in Table 6. The duration of the sensing-and-decision delays is estimated according to the observations in field experiments, shown in Table 7.

Based on all the data derived above, the completion time for both manipulators is presented in Table 8. It can be seen that, depending on the complexity of the sensing-and-decision delays, the total completion time varies from 325.57 seconds (full control) or 1384.81 seconds (primitive control) to 460.57 seconds or 2914.81 seconds. In other words, the improvement on performance resulted from a better control system is in a ratio of 4.25:1 to 6.33:1.

Sensitivity analyses on three variables were performed: (1) the maximum joint motion rates, (2) the reduced joint motion rates due to safety and (3) the duration of sensing-and-decision delays. The results are shown in Figure 1. The spider diagram in the left represents the sensitivity of the manipulator with primitive control capabilities and the right the full control capabilities. It should be noted that both diagrams were drawn in the same scale (vertical axis representing the total completion time in seconds and horizontal axis representing the percentage of change); and therefore, the range of changes is comparative. Clearly, sensing-and-decision delays have the highest impact on both cases and the maximum joint rate the second. *In other words, the most significant benefit of investing in a better control system is to reduce the amount of sensing-and-decision delays.*

Table 6 Motion Sequence and Occurrence of Sensing-and-Decision Delay

		Primitive Control Capabilities		Full Control Capabilities	
Operation Plan	Motion Aggregates	Motion Sequence	Sensing-and-Decision	Motion Sequence	Sensing-and-Decision
Re-spot Platform	• Driving Platform • Leveling	• Sequential, each in one segment	• 1 manual trial and error	• Sequential, each in one segment	• One automated S&D
Reach & Orient	• Swing • Main Lift • Secondary Lift	• Sequential, each in one segment	• N/A	• Parallel in one segment	• N/A
Pre-position	• Roll • Secondary Telescope	• Sequential, each in one segment	• 2 manual trial and errors	• Parallel in one segment	• One automated S&D
Approach	• Roll • Secondary Telescope	• Sequential, each in two segments	• 4 manual trial and errors	• Parallel in two segments	• Two automated S&D
Grasp	• Close Jaws	• N/A	• N/A	• N/A	• N/A
Disengage	• Roll	• Sequential in two segments	• 2 manual trial and errors	• Parallel in one segment	• One automated S&D
Move & Turn	• Roll • Main lift • Secondary Lift • Secondary Telescope	• Sequential, each in one segment	• N/A	• Parallel in one segment	• N/A
Move & Turn	• Swing • Main Telescope • Main Lift • Second Lift	• Sequential, each in one segment	• N/A	• Parallel in one segment	• N/A
Pre-position	• Roll • Secondary Telescope	• Sequential, each in one segment	• 2 manual trial and errors	• Parallel in one segment	• One automated S&D
Approach	• Roll • Secondary Telescope	• Sequential, each in two segments	• 4 manual trial and errors	• Parallel in two segments	• Two automated S&D
Release	• Open Jaws	• N/A	• N/A	N/A	• N/A
Pre-position	• Roll • Secondary Telescope	• Sequential, each in one segment	• 2 manual trial and errors	• Parallel in one segment	• One automated S&D
Reach & Orient	• Secondary Telescope • Main Telescope • Secondary Lift • Main Lift	• Sequential, each in one segment	• N/A	• Parallel in one segment	• N/A

Table 7 Duration Estimates of Sensing-and-Decision Process

Control Capabilities	Normal Case	Most Difficult Case	Simplest Case
Automated S&D	10 seconds	20 seconds	5 seconds
Manual T&E	80 seconds	150 seconds	60 seconds

Table 8 Total Completion Time of Both Levels of Control Capabilities

(in seconds)	Motion Time	Force Buildup	Sensing & Decision	Total
Manipulator with Primitive Control Capabilities	340.31	24.5	1020 1360 2550	1384.81 1724.81 2914.81
Manipulator with Full Control Capabilities	257.57	23	45 90 180	325.57 370.57 460.57

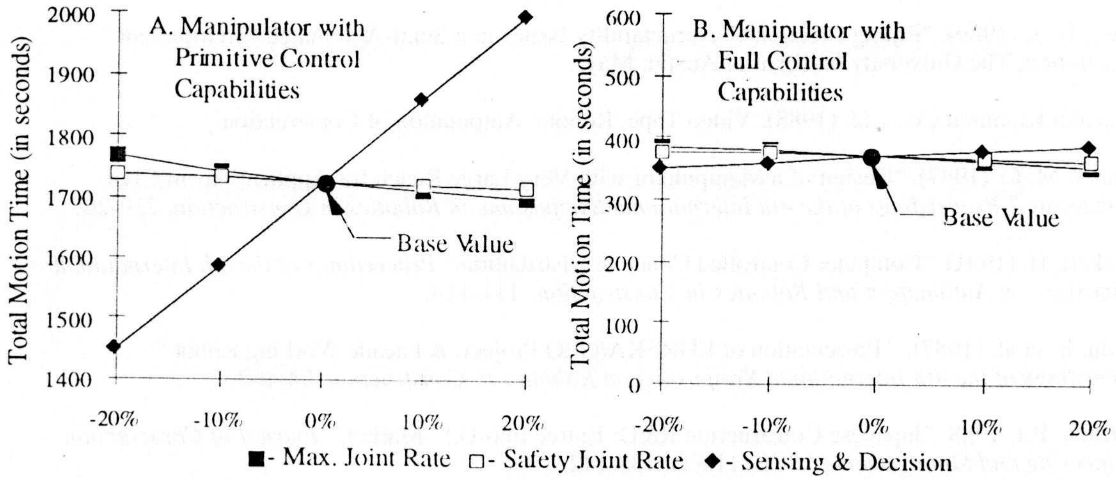

Figure 1 Sensitivity of the Performance of Both Manipulators

5. DISCUSSION AND CONCLUSIONS

This paper has described the proposed performance evaluation model for construction manipulators in a step-by-step fashion and demonstrated one important application of this model which is to predict the potential improvement on task completion time if a better control system is provided for a prototype pipe manipulator. Some insightful findings are revealed in the final portion of the evaluation.

Another potential application of this model is to evaluate the usefulness of a single manipulator for different types of construction tasks. By varying the targeted task, it is possible to foresee what type of construction task is particularly suitable for a given manipulator. By the same token, by varying the physical capabilities and control capabilities, it is possible to examine the type of manipulator that is particularly useful or productive for a given construction task. The immediate benefit generated from this process is the substantial savings of time and money made possible by reducing the necessity for field experiments during a prototyping stage.

As more and more automation technologies now are being introduced to construction, the proposed model can also be used to evaluate the performance of other types of automated equipment such as automatic backhoes, computer-controlled cranes and automatic forklifts. Although this model is developed for construction manipulators, it does provide flexibility for more general use in construction, with some minor modifications such as renewing the terminology of motion elements and re-defining task and machine related parameters. It also provides a key element for a machine performance simulation system for design. Both aspects, however, remain to be explored later.

NOTE

1. For a more in-depth analysis, the tolerance level of a construction task needs to be further defined in terms of accuracy and repeatability, in that accuracy deals with the closeness to the task requirement and repeatability with closeness of replicate manipulator motions.

REFERENCES

1. Yoshida, T. and Ueno, T. (1985). "Development of a Spray Robot for Fireproof Treatment." *Shimizu Technical Research Bulletin 4*, Tokyo, Japan, 48-63.

2. Slocum, A. H. et al. (1987). "Construction Automation Research at the Massachusetts Institute of Technology." *Proceedings of the 4th International Symposium on Robotics & Artificial Intelligence in Building Construction*, Building Reseach Station, Haifa, Israel.

3. Fisher, D. J. (1989). "Piping Erection Constructability Issues in a Semi-Automated Environment." *Dissertation*, The University of Texas at Austin, May.

4. Takenaka Komuten Co., Ltd. (1988). Video Tape, Robots: Automation of Construction.

5. Wanner, M. C. (1987). "Design of a Manipulator with Very Large Reach for Applications in Civil Engineering." *Proceedings of the 4th International Symposium on Robotics in Construction*, 259-267.

6. Benckert, H. (1991). "Computer Controlled Concrete Distribution." *Proceedings of the 8th International Symposium on Automation and Robotics in Construction*, 111-118.

7. Tondu, B. et al. (1987). "Presentation of EUREKA/GEO Project: A Facade Working Robot." *Proceedings of the 4th International Symposium on Robotics in Construction*, 94-102.

8. Sherman, P.J. 1988. "Japanese Construction R&D: Entree into U.S. Market," *Journal of Construction Engineering and Management*, ASCE, 114(1), 138-142.

9. Johnson, D. W. et al. (1991). "Towards an Autonomous Heavy Lift Robot for Field Applications." *Proceedings of the 8th International Symposium on Automation and Robotics in Construction*, 455-464.

10. Warszawski, A. and Navon, R. (1991). "Robot for Interior-Finishing Works." *Journal of Construction Engineering and Management*, ASCE, 117(3), 402-421.

11. Hsieh, T. Y. and Haas, C. T. (1993). "Applications of Large-Scale Manipulators in the Construction Environment." *Proceedings of the 10th International Symposium on Automation and Robotics in Construction*, May.

12. McGovern, D. E. (1974). "Factors Affecting Control Allocation for Augmented Remote Manipulation." *Ph.D. Thesis*, Stanford Univeristy, Novermber.

13. Book, W. J. and Hannema, D. (1980). "Master-Slave Manipulator Performance for Various Dynamic Characteristics and Positioning Task Parameters." *IEEE Transactions on Systems Man and Cybernetics*, Vol. SMC-10, No. 11, November, 764-771.

14. Hill, J. W. (1979). "Study of Modeling and Evaluation of Remote Manipulation Tasks with Force Feedback." *Final Report, SRI International Project 7696*, March.

15. Clemen, R. T. (1991). *Making Hard Decisions: An Introduction to Decision Analysis*. PWS-Kent Publishing Co., Boston.