The Use of Simulation Results in the Economic Analysis of Robotized Construction Tasks

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Abstract:
Adequate economic justification is a key requirement for the implementation of robotic systems in the construction industry. In the present work the concept of off-line simulation is used to provide the user with a rational approach for economic decision making with regard to the use of robotics. The proposed off-line simulation process helps the user in planning, scheduling and costing the whole job. With the aid of a graphical simulation package, the user can estimate the whole job time that reflects the cost of the individual tasks. A simple criterion is developed to estimate the task cost based on the task simulation time. The criterion takes into account the individual costs of the robotic system components, labour, transportation, site preparation and office work. This work is applied to Starlifter, a heavy tool deployment manipulator.

Keywords: Construction Robotics, Economic justification, Simulation, Cost analysis.

1. Introduction

Investment in the construction industry represents a major part of the world economy. Any effort to improve the efficiency and the economics of this industry is significant. The evolution of the construction industry moves forward in several directions: management, the use of information technology and automation. Many attempts have been made to use robots in the construction industry in the last decade [1-15]. The trend towards research into the use of robotic systems continues to increase significantly not only in the building construction sector but also in different areas such as inspection and service tasks, road construction and decommissioning. However the actual implementation of robotic systems on sites increases slowly owing to many reasons such as the lack of suitable economic justification, difficult adaptability of current construction sites to accommodate robots, the reaction of the labour organizations, etc [1]

The economic justification is a major part of a global feasibility analysis, which should be done before deciding on the implementation of a robotic system. This feasibility study as described by Kangari et al [2], includes needs based feasibility, technical feasibility and safety and risk feasibility in addition to economical feasibility.

In the present work, as a part of the global feasibility analysis, a detailed economic analysis is performed to produce a criterion for helping the user to make a decision whether or not to use robotic systems. The parameters introduced by Warszawski and Roesenfeld [5] and O'Brien [6] are taken into account as part of a task oriented cost analysis. In addition the parameters proposed by O'Brien [6] for designing a cost-effective robotic system are identified. With the aid of a graphical simulation of the robot and the environment, a detailed report can be produced to describe the task and the time consumed in the individual processes and their cost. The simulation process is an integral part of the robotic system and a part of the off-line simulation of the robot before doing the actual work. The present work is applied to Starlifter, the first robot developed for heavy tool deployment in construction [7], shown in Figure 1. Starlifter is a hydraulically powered portable robot that has six-degrees of freedom. Other properties include:

Figure (1)- Starlifter Robot

a- A load carrying capacity of 200 kg at any orientation of the first joint.
b- The joints can be simultaneously locked in any selected position with power and control

shut down to provide a stable platform to deploy heavy duty tooling systems.

c- Fully automatic tool changing capabilities.

d- Fully arterial supplies to tooling-manifold/adapter:

- 200 bar hydraulics
- 3-phase power
- 2-video channels
- 10 tool-function controls

e- Teleoperation control with programmable capability. In conjunction with the on board video camera and automatic tool changing, the machine may be controlled with the operator distant from the work environment.

f-

2. Justification for the use of Starlifter in construction

The key application area identified for Starlifter is heavy tool manipulation. Heavy tools are extensively used in construction and civil works for example diamond core drills, anchoring tools and concrete sawing equipment. The manual use of these tools is tedious and includes many hazards to health such as those identified by the Drilling and Sawing Association in the UK [16, 17]. In particular there is considerable concern about hand-arm vibration hazards due to the prolonged use of vibrating percussive tools. It is obvious from this simple example that the use of robots to carry out the tool deployment is the best solution from the safety point of view. The safety issue becomes bigger if it is intended to use heavy tools in hard-to-reach places or in places with an uncomfortable environment such as railway tunnels. Working in such environments leads, to a reduction in the productivity of workers, which produces an increase in the task cost.

3. Off-line Simulation

The purpose of off-line simulation is to develop a detailed plan for the task that the actual robotic system will carry out [18]. The task plan includes all the details that the user/robot needs to perform the task. The following is required:

1. Robotic system identification
2. Task schedules
3. Safety procedures
4. Task cost

Figure (2) describes the procedure to produce a detailed work sheet and cost report. Starting from the client request to carry out a specific job on a specific site, the user starts collecting data about the site from visits or CAD drawings etc., from this point the user starts to identify the tasks involved in the job. The next step is to specify the robotic system modules that will be used in performing the tasks according to the task schedule. We can consider the scanning process of the task area as a task, the tool positioning as a task and so on. It is possible to break a task down into sub-tasks for easy programming of the robot. Tasks may be divided into parallel tasks or serial tasks. Examples of robotic system modules are as follows:

- Delivery Vehicle

Because of the nature of the construction site, it may be required to place the robot on the tip of a telescopic boom, on tracks or on a trailer. It is possible to use a telescopic boom to deal with places which are hard to reach by tracks or trailer for instance underneath a bridge over a river or in high places. Also it is possible to place the robot on a rail track truck to perform jobs inside rail tunnels.

- Control Module

According to the site nature and the tasks involved, the user has the choice to use either pre-programming or teleoperation control modes. In some situations it could be safer and more cost effective to use a pre-programmed control mode rather than using

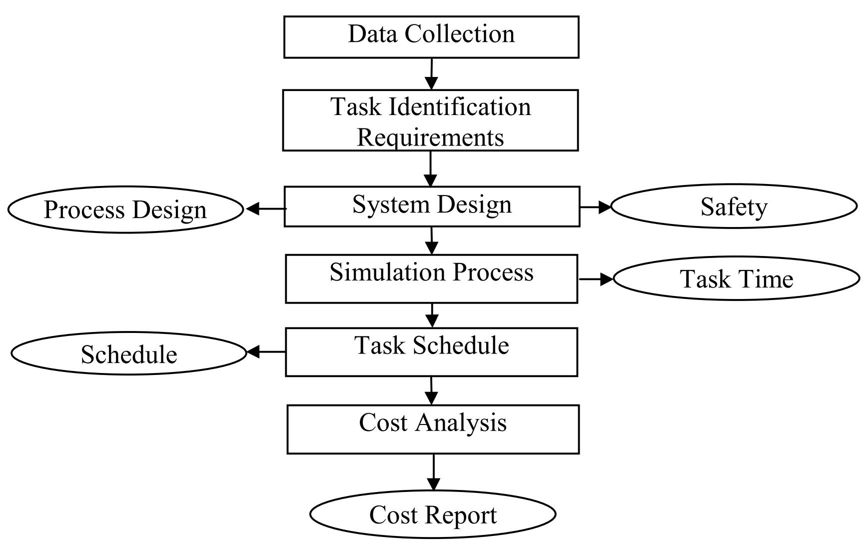

Figure (2) Off-line Simulation Process

teleoperation mode. This is particularly the case where the task requires high precision and repetition.

- Effector tools

Tool changer capability makes the robot versatile, so it can carry any type of tool. Each tool is attached to a dock, which can easily be installed in a rack on the robot base. The user can specify the required tools to perform a task or sequence of tasks.

- Environmental sensors

The sensing strategy depends on the site nature, robot mobility, control mode and the tools to be used [19]. Sensors may be permanently fixed to the robot such as monitoring cameras or a laser scanner, or temporarily attached to the end effector in the case of a rebar locator. Sensors may be required to ensure that the end effector is adjusted parallel to the surface. The user should specify the sensing strategy to be used as it reflects on the cost of the operation.

After specifying the robotic system modules and sequencing the tasks a safety procedure should be prepared to ensure safe operation of the robot. The safety procedure to be used should include steps to be carried out in case of errors, unexpected behaviour of the robotic system, tool jam or damage to the site due to uncontrolled movement of the robot (emergency safety procedure).

The next step is a complete graphical simulation of the whole process using a proprietary robot simulation package such as Workspace.

4. The role of the simulation process

Simulation process provides immediate feedback of the robot motion and its interaction with the surrounding environment [20]. Thus access and collision problems can be resolved before the site operation begins. It also provides useful information about the capability of the robot to carryout a job. In case of motion planning it is very useful to try alternatives for the path or even to find the most economic motion of the arm to perform a task. Immediate use of the robot on the actual site could lead to economic disaster, especially in sites not prepared to accommodate robots. Organizing the tasks and choosing the suitable robotic system components off-line using the simulation process is safe and economically feasible.

The role of the simulation process in this study is to provide data for the user in the form of end effector path trajectories, optimal positions of the robot base relative to the task area and the time consumed in performing the tasks. It is also possible to generate complete task programs and download them to the actual robot controller for use on site. From the cost analysis point of view, the time consumed in performing a task is the key issue in evaluating the operating cost of the robotic system. It is essential to take into account extra time for unsuccessful tasks or errors occurring during operation.

4.1. Task Time evaluation technique

In this study, a task time evaluation technique will be used to determine the time consumed by the simulated robot to perform a task. A delay time based on experimental work will be calculated to obtain the actual time that the robot takes to perform the same task in the real world. This delay time is site/task/robot dependent.

Four types of motion are considered based on those defined by Hass [9] et al in 1993 as the elemental motions which describe all the operations of a construction manipulator:

a. Platform Motion
b. Gross Arm Motion
c. Fine Arm Motion
d. End Effector Motion

Considering the fact that the simulation process does not take into account the effect of the environment on the robot performance (the simulated robot moves in an ideal environment with instant response to the required motion), the calculated time for each motion type should consider the delays generated due to the effect of the environment. For instance when using a

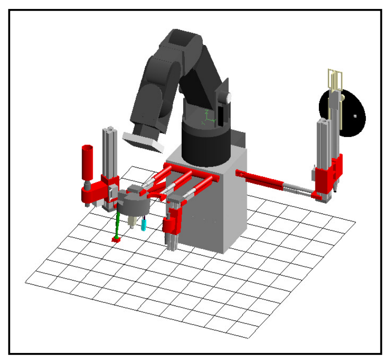

Figure (3)
Starlifter simulation model

telescopic boom to position the robot, the simulated boom does not consider lateral vibrations of the actual boom tip and the effect of friction and wind force on the time taken to reach the desired position. In addition there is the error due to human factors in operating the boom which are corrected by trial and error and which add additional time to the estimated time. Other delays could be generated due to the sensing & decision process and from force build-up time, especially for hydraulic robots. The following equation is proposed to calculate the actual time consumed by the robot in performing a task:

$$t_{act} = t_{sim} + t_{dly} \quad (1)$$

t_{act} : Total actual time of the actual task

t_{sim} : Total time of the simulated task

t_{dly} : Total delays

$$t_{sim} = t_{pfm} + t_{gam} + t_{fam} + t_{eem} + t_{sad} \quad (2)$$

Where:

t_{pfm} : Time of the simulated Platform Motion

t_{gam} : Time of the simulated Gross Arm Motion

t_{fam} : Time of the simulated Fine Arm Motion

t_{eem} : Time of the simulated End Effector Motion.

t_{sad} : Pause Time for Sensing and Decision

Advanced graphical simulation packages provide an excellent match between the simulated robot and the actual robot from the kinematics point of view. So by comparing the time consumed to reach a specific position by the simulated robot and the actual robot at no load, a correction factor k_{r1} can be used to correct the simulated time. In addition there is another correction factor k_{r2} generated by comparing the time taken to move the end effector to a specific position at no load and at different loads. These factors will be used to calculate the delay of the actual robot motion. Another factor k_{pfm} is introduced to calculate the delay due to the platform motion in terms of the simulated platform time. Sensing and decision will be simulated as a 'pause time' in the task sequence if it occurs in series or the longest time will be considered if it occurs in parallel with other motion. The delay due to sensing and decision will be estimated as a fraction of the pause time if it occurs in series, or it will be ignored if it occurs in parallel with other motion. In the actual sensing process it is expected that the sensing time is significant and cannot be ignored. From these factors it is possible to express the total delay in terms of the simulation time as follows:.

$$t_{dly} = k_{pfm}\, t_{pfm} + k_{r1}\, k_{r2}\, (t_{gam} + t_{fam} + t_{eem}) + k_{sad}\, t_{sad} \quad (3)$$

Substitute in equation (1) by equation (3) one can get the equation for the actual time consumed in performing the task

$$t_{act} = (1 + k_{pfm})\, t_{pfm} + (1 + k_{r1}\, k_{r2})\,(t_{gam} + t_{fam} + t_{eem}) + (1 + k_{sad})\, t_{sad} \quad (4)$$

$$t_{act} = T_{pfm} + T_{arm} \quad (5)$$

$$T_{pfm} = (1 + k_{pfm})\, t_{pfm}$$

$$T_{arm} = (1 + k_{r1}\, k_{r2})(t_{gam} + t_{fam} + t_{eem}) + (1 + k_{sad})\, t_{sad}$$

5. Task costing and cost parameters

Costing of a robotized task includes many parameters that should be addressed to help the user in taking the decision to use the robotic system in performing a particular task. Several parameters are identified by Warszawski and Rosenfeld [5] in costing robotized tasks. In the present work another parameter is introduced to give the user a more precise cost of the robotized task, and this is derived from the off-line simulation. By using this parameter the user can give the client the expected cost before the actual work starts.

5.1 Robotic systems cost parameters

This represents the direct cost of the robotic system,: the robot, the tool docks used in performing the task, the cost of the control system and the cost of sensing system. The cost value is estimated per working hour, and is estimated based on the cost of robot ownership. In this estimation, several factors are taken into account such as depreciation, insurance, taxes, interest rate, and maintenance [21-23].

The total annual cost based on sum-of-the-digits depreciation and for five years ownership [21]:

$$C_{ow} = \left[\frac{7(P_p + P_x + P_g)}{3U} + \left(P_i + \frac{K_j}{U} + K_g \right) \right] C_o \quad (£) \quad (6)$$

Where:

P_p : Percentage of insurance to find annual protection cost

P_x : Percentage of taxes to find annual tax charge

P_g : Percentage of average investment (A) to find annual storage charge

P_i : Percentage of the original cost (C_o) to find annual interest charge

K_j : Percentage of the original cost (C_o) to find the annual repair charge and maintenance.

K_g : Percentage or proportion of depreciation

U: The useful life of the robot

To find out the hourly charges of ownership of the robotic system c_{ow}, divide the ownership cost by the average number of the robotic system working hours per year H_{cy}. This value is independent from the estimated time of the actual task execution.

$$c_{ow} = \frac{C_{ow}}{H_{cy}} \quad (£/hr) \quad (7)$$

Another term of ownership cost may be used based on the contribution of the present task time in the robotic system working hours, which is the task utilization cost, $C_{ut} = c_{ow} t_{ut}$

Where t_{ut} the robot utilization in performing the task.

Because the robotic system under study is modular and it uses only the modules that the task requires, the original cost of the robot varies according to the modules used to perform the task. It is possible to express the original cost by the following equation which takes into account all the modules involved.

$$C_o = C_{robot} + C_{tools} + C_{sensors} \qquad (£) \qquad (8)$$

Where

C_{robot} : The original cost of the robot, power pack and control system.

C_{tools} : The cost of the tools used in performing a task, sometime it is required to use several tools to finish a job. On the other hand the task could be finished by one tool. It is useful and cost effective to eliminate the tools those are not required in doing the job.

$C_{sensors}$: The costs of the modularised sensors such as rebar locator and video camera. In some construction sites the task area could be clear to the operator and not require scanning. This will be reflected on the cost of the task.

5.2 Task dependent cost parameters

This parameter determines the cost of the robot operation when carrying out the task, labour costs, supervision costs, tool operating cost and the cost of consumed power . The following equation is used to determine the total operating cost of the robotic system.

$$C_{op} = c_w t_w + (c_p T_{arm} + c_{tools} t_{tool})_i \quad (£) \ (9)$$

Where:

C_{op} : The robot operating cost

c_w : Labour cost per hour. Labour is needed for preliminary trials, safety procedures, monitoring robot performance, minor repairs and field adjustment. It is also required for making adjustments during operation such as pressure and oil flow rate.

c_p : Operating power cost estimated in (£/hr)

c_{tools} : Cost of operating the tool per hour (power and bits)

i : Number of tasks

5.3 Site dependent cost parameters

These parameters determine the indirect time that the robot spends on activities not directly related to its work such as time of installation, movement, transfers, positioning at the work place and routine maintenance. In the present work the transfer costs and the platform positioning costs will be considered only in so far as they relate to movements between individual tasks. The site dependent cost c_{site} can be calculated using the following equation

$$C_{site} = C_{tr} + (c_{pfm}\, t_{act})_i \qquad (£) \qquad (10)$$

Where:

C_{tr} : The transportation cost between workstations

c_{pfm} : The positioning cost of platform per hour

5.4 Off-line simulation cost

The off-line simulation cost C_{ols} represents the office work required to prepare for performing a job. It includes site visits, CAD drawings preparation, building the simulation model of the environment, work sheet preparation and cost estimation.

5.5 The total cost estimation

From the above cost parameters the total cost of the job can be estimated as the summation of the previous costs (equations 7-9) using the following relation

$$C = C_{ut} + C_{op} + C_{site} + C_{ols} \qquad (£) \qquad (11)$$

6. Conclusions and further work

Off-line simulation is used to plan, schedule and cost a job carried out using a robotic system. This process is useful in process design and timing, safety procedure preparation and cost calculation. A cost criterion is developed to calculate the exact cost of carrying out a task taking into account the cost of the robotic system, labour, transportation, site preparation and office work. In future work this criterion will be tested starting with simple core drilling tasks and the results will be compared with the actual cost calculated by traditional methods. A user interface is under development for the user to enter the job information and to select suitable robotic system components. The user interface will enable the user to produce a report that includes all the information required to carry out the job together with its related cost and work schedule.

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