An Agent-based Approach for Modeling Human-robot Collaboration in Bricklaying

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Abstract -

Construction robots have drawn attention in research and practice for decades. Considering most of the construction robots are not fully automated and humans are always involved in the construction process, how humans and robots collaborate has a great impact on the total productivity. Unlike collaboration systems between human-human, human-device and robot-robot, human-robot collaboration process has its complexity and uniqueness. Thus, this paper starts with analysis of human-robot collaboration system in construction, then provides an agent-based approach to simulate the process in bricklaying with emphasis on its complexity. A real project in Beijing is utilized to validate the feasibility of the proposed method. Besides, managerial insights useful for the workers to better utilize construction robots can be drawn from the results, which shows the effectiveness of the proposed model. This research contributes to the body of knowledge an agent-based approach to modeling, simulating, and analyzing the human-robot collaboration process in construction sites. This research serves as a foundation for further in-depth investigation in this area.

Keywords –

Construction robots; human-robot collaboration; agent-based simulation; communication mode; human factor

1 Introduction

Construction robots have drawn attention in research and practice these years to cover the shortage of conventional construction. In terms of the entire industry, its productivity has been declining in recent years and the conventional construction paradigm has reached the technological performance limit[1]. In terms of workers in this industry, construction tasks are usually of high physical demand, and sometimes are harmful to their health[2]. Therefore, construction robots have aroused increasing interest in the last 15-20 years because it can improve the productivity while replace workers from doing heavy duties and dangerous tasks[3]. The application of robots involves nearly every construction-related tasks, including glazing[4], beam assembly[5], earthmoving[6], concrete wall fabrication[7], etc.

However, construction industry cannot be fully automated currently even with the aid from robots[3]. As a result, various operations and tasks still need to be fulfilled by human workers. In other words, human-robot collaboration is a critical part of the construction process.

Agent-based (AB) modeling, a simulation approach to model systems by using virtual agents to imitate the behaviors and interactions of participated individuals[8] is commonly used to simulate construction scenarios to understand and further optimize the process. Multiple collaboration systems between human-human[9], human-device[10] and robot-robot[11] in construction have been studied. However, human-robot collaboration system has its specific complexity and uniqueness comparing to other collaboration systems, which calls for further investigation.

This research starts with analysis of human-robot collaboration system in construction, then chooses bricklaying process as a typical application in the construction domain, and adopts an agent-based (AB) modeling approach to simulate human-robot collaboration process with emphasis on its characteristics. Managerial insights are drawn to show the applicability and benefits of the proposed model. The remainder of the article is organized as follows. Section 2 introduces the methodology used in the research. Section 3 provides the analysis for human-robot collaboration systems in construction. Section 4 proposes the development of the AB simulation model. Section 5 presents case studies and draws managerial insights. Section 6 summarizes the research and discusses possible future investigations.

2 Methodology

The objective of this research is to model human-robot collaboration in bricklaying with an AB modeling approach. To achieve the objective, AnyLogic© (version 8.5.0) is used as a simulation platform. A six-step methodology is utilized (Figure 1), which contains system analysis, model scope determination, simulation environment determination, agent property definition, data collection and scenario application.

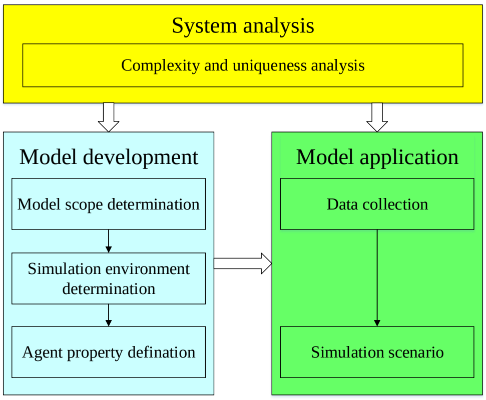

Figure 1. Overview of the research methodology

At the very beginning, the human-robot collaboration system in construction is analysed. Its complexity and uniqueness comparing to other collaboration systems are further stressed, which is the foundation of all the rest steps. In model development, model scope is first determined. Robot agents, worker agents, brick agents, and recorder agents are incorporated. A real project in Beijing is used as the simulation environment. Acting behaviors are captured to define the agents' property. Then, agents can act spontaneously in the experiments. The model is further applied to a case study to test its applicability and draw managerial insights. Data collection should be done at first to determine parameters in the model. Considering the practical applications of bricklaying robots are still limited, the parameters cannot directly be acquired from real bricklaying robots. To address this, the parameters are based on theoretical and empirical evidence, including previous papers and video records. However, it is important to mention that the parameters can be easily adjusted to other values when needed. Considering the randomness in experiments, the simulation scenario is simulated three times and outputs are set to the average value.

3 Analysis for human-robot collaboration systems in construction

3.1 Collaboration system

Collaboration systems are classified by participants. In construction, collaboration systems between human-human, human-device, robot-robot and human-robot are common (Figure 2). Human-human and robot-robot collaboration refers to the collaboration among workers and machines respectively. The difference between human-device collaboration and human-robot collaboration is that human conducts a mission by manipulating a device (i.e. infrared cameras in bridge inspection[12]) while human and robots can work on different tasks side by side[13].

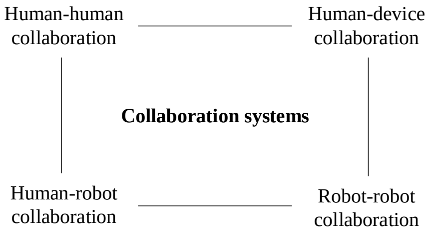

Figure 2. Classification of collaboration systems

Several communication modes are involved in collaboration systems[13] (Table 1). These modes are originally used in human-robot collaboration, but they can be generalized to other collaboration systems as well. Therefore, agents are used to represent the participants, corresponding to the AB approach.

3.2 Complexity and uniqueness of human-robot collaboration system

3.2.1 Traditional collaboration system

Traditional collaboration systems between human-human, robot-robot and human-device are involved in simulation scenarios of previous papers. Table 2 summarized the scenario, collaboration type, communication mode of representative works. For example, in bridge inspection process[12], on one hand, preparation and inspection are conducted in sequence by technicians. Technicians use voice to communicate, which is considered a form of RCI. On the other hand, technicians move with the devices in the inspection process, and since technicians need to set or program the devices first, the communication mode is ME.

It can be concluded that traditional collaboration systems only involves a simple communication mode, either RCI or ME. This is reasonable since humans only need to communicate by voice; robot-robot system as a fully automated system only needs electronic signals to send messages; while device as a passive object only need to be programed.

3.2.2 Human-robot collaboration system

Comparing to traditional collaboration systems, human-robot collaboration is complex and unique in the following three aspects. All three aspects will be further illustrated in Section 4. (1)Simultaneously involving multiple communication modes: since many robots in construction is not fully automated, they still need to be installed, programmed or manipulated (ME, TL) like devices; however, robots have much higher autonomy and independence as a collaborator rather than a passive tool, which provide possibility for more communication modes (RCI, DPI). (2)Safety requirement: for extremely complicated and distributed environment like construction site, it will be very hard to set up fence to separate workers and robots. Since human workers are exposed to robots, human-robot collaboration system needs some safety requirements such as safety distance[14]. Safety issue is seldom considered in traditional collaboration systems. (3) Different characteristics between participants: the two participants, human and robot, have different characteristics. For example, human workers will forget or feel tired, but robots will not. This is unique as well. For human-device collaboration, when humans are tired, the efficiency of device will also be effected as it is manipulated by humans.

Table 1. Communication modes in collaboration systems[13]

Communication mode	Description
Direct physical interaction (DPI)	One agent’s body contact with another in order to perform a task
Remote contactless interaction (RCI)	Agents contact by interfaces (e.g. voice, camera)
Teleoperation(TL)	Workers directly drive a machine with interface
Message exchange(ME)	Information is exchange using digital signals transmitted through physical button

Table 2. Traditional collaboration systems in previous work

Paper	Scenario	Collaboration type	Communication mode
Seo et al.[9]	Bricklaying	Human-human	RCI
Abdelkhalek et al.[12]	Bridge inspection	Human-human	RCI
Zhe et al.[15]	Pump maintenance	Human-human	RCI
Jabri et al. [11]	Earthmoving	Robot-robot	RCI
Yassin et al. [16]	3D printing reinforced concrete	Robot-robot	RCI
Abdelkhalek et al.[12]	Bridge inspection	Human-device	ME
Jung et al.[10]	Lift system	Human-device	ME

4 AB model development for human-robot collaboration

After having an understanding of the complexity and uniqueness of human-robot collaboration system, this section provides an AB model to simulate this process.

4.1 Model scope

Model scope determines the content of agents. Four kinds of agents are involved in this model, robot agents, worker agents, brick agents and recorder agents. The first two agents will work together to fulfil masonry tasks. Four agent states are introduced to capture the working condition of both robots and workers: (1) working state refers to an agent working on a given mission; (2) idle state refers to agent being in idle without missions; (3) moving state refers to workers moving robots or robots being moved; (4) operating state refers to workers and robots doing preparatory works. Bricks are considered as passive agents for robots and workers to manipulate. Besides, in order to record the agent state at any time, a kind of dummy agent, recorder, is introduced to the model. Each recorder agent has one corresponding robot agent or worker agent. It will record the state and the corresponding time when the state has changed.

4.2 Simulation environment

The simulation environment is the construction site where agents are acting and interacting with each other. In this research, a typical residential project in Beijing is used to provide references to the design of the simulation environment. Several assumptions are made to simplify the original layout of the construction site without losing generalization. One of the buildings in the layout is picked as the construction object. The corner of the site is assumed to be Long-term Store Place to deposit construction materials, such as bricks. A small place near the building is considered as Temporary Store Place for workers' convenience. A rectangle area that envelopes the building is assumed to be Work Zone. Besides, a small rectangle place near Temporary Store Place is set to be Robot Store Place. The simplified layout of the simulation environment is shown in Figure 3. It is then imported to the simulation model in Anylogic© using real-world plotting scale to ensure the reliability.

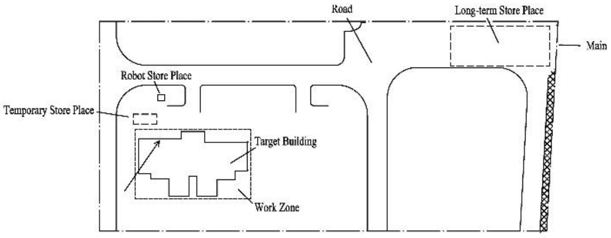

Figure 3. The simulation environment of the model

At the beginning, all bricks are deposited in the Long-term Store Place. The robot is placed in the Robot Store Place, while all the workers are randomly placed in Work Zone. In this research, we mainly focus on the situation with one robot. It is assumed that three workers are needed to move the robot. Therefore, the simulation environment contains 3 worker agents and 1 robot agent.

4.3 Agent properties

In AB models, agents have two types of properties, attributes and variables, to regulate their performance[17]. Attributes are fixed properties, while variables may change in the process.

4.3.1 Robot agent

The main job for robot agents is to construct brick walls. Conventionally, brick walls function as infilled walls that locate between columns. Two dummy nodes, start node and end node, are extracted to represent the endpoints of each wall. The set of all nodes, Node Set (NS), is introduced to record all the start nodes and end nodes. It represents all the construction tasks for the bricklaying robot. One attribute, Number of Nodes (NN) and one variable, Number of Completed Nodes (NCN), are applied correspondingly to capture the number of all nodes and completed nodes in NS. Another attribute, Number of Layers (NL), is introduced to determine the number of layers in each wall.

The robot agent will pass through four stages during the whole construction process. (1): Robot agents start waiting for workers at Robot Store Place, so it is classified as idle state. (2): After moved and installed by workers, the robot is working in Work Zone, and is classified as working state. Although there are several types of bricklaying robot existing in industry or academic [2, 18-23], most robots share the same process of laying one brick. Therefore, SAM100 is chosen as an example to model the laying process. For SAM100[24, 25], the whole process can be summarized into the iteration of two procedures, moving to target position and bricklaying. Bricklaying is a generalized process that contains plastering on the surface, grabbing one brick and laying it on the mortar. Two attributes, Moving Velocity in Working (MVW) and Brick Laying Duration (BLD) are critical in this stage. The first attribute captures the velocity as robots moving to the target position, and the second attribute captures the duration for the bricklaying process. When one layer is finished, the robot will return to the start node. For safety reason, it is assumed that the robot will not start the next layer until the worker responsible for extra mortar removing (introduced in the next section) finishes this layer. (3): After all layers are finished, the robot will automatically move back to the start node and stop operating. It is classified as idle state. Meanwhile, the start node and the end node for this wall will be labeled as "Complete" and NCN will increase by two. (4): Because several bricklaying robots has a pipe to deliver mortar[25], it is assumed that the mortar is always sufficient. However, robots probably will still run out of bricks that are stored inside. When this happens, the robot will pass to Stage 4 and stop operating, therefore the state will change into idle state. The attribute, Robot Storage Capacity (RSC), is applied to determine the maximum number of bricks that can be stored inside the robot. When the bricks are supplemented, the robot will start operating again and continue the previous task.

4.3.2 Worker agent

In this model, workers are responsible for three kinds of tasks in the whole process. First, workers need to carry the robot to target locations, called Robot Moving and Installing (RMI). Second, considering when robots squeeze a brick on the mortar, the robot arm will also push some mortar beyond the below brick's edges[23], this extra mortar is supposed to be removed by one human worker. This task is called extra mortar removing (EMR). Third, when robots run out of bricks in their storage, one worker is responsible to supplement bricks[26]. This task is called Brick Supplement (BS). For the three worker agents in the model, one is responsible for BS and RMI (called the BS worker), one is responsible for EMR and RMI (called the EMR worker), and the last one only need to participates in RMI (called the RMI worker).

RMI task can be divided into two parts. (1): At the very beginning, workers first move to Robot Store Place. Their moving speed is determined by the parameter Walking Velocity (WV). Some preparation works need to be done before they move the robot. Then, workers will carry the robot to Node 1. Another attribute, Robot Moving Velocity (RMV), is introduced to capture this moving speed when carrying loads. Then, workers need to install it on the work site. These two processes, determined by Preparation Duration (PD) and Installation Duration (ID), belong to operating state. (2): When the robot finishes the bricklaying work for one wall, workers will judge whether there are other unconstructed walls. If so, they will move the robot to the next unfinished node in NS. Otherwise, workers will move the robot back to Robot Store Place.

EMR task is the iteration of moving to target brick and removing extra mortar on the brick. Since the worker is not carrying loads, it is assumed that the moving speed is WV as well. An attribute, Mortar Removing Duration (MRD), is introduced to determine the time for the worker to remove mortar on one brick. To ensure that the EMR worker has a safe distance with the robot, it is assumed an at least 10 bricks length separation distance.

Since the EMR worker is beside the robot, he will inform the BS worker when the robot runs out of bricks and stops operating. Then, the worker will go to Temporary Store Place or Long-term Store Place to supplement bricks, depending on the number of bricks at Temporary Store Place. If it is larger than RSC, he will grab, move and add these bricks to the robot. Otherwise, the BS worker will first transport five times RSC bricks from Long-term Storage Place and drop them to the Temporary Storage Place. Three time-related attributes, Grabbing Duration (GD), Dropping Duration (DD), and Supplement Duration (SD) are introduced to determine the duration the BS worker needs to grab, drop and supplement RSC number of bricks. Besides, Carrying Velocity (CV) is introduced to decide the moving velocity for the BS worker when transporting bricks. Besides just waiting for the information from the EMR worker, it is assumed the BS worker will check the number of remaining bricks periodically. If the BS worker finds that bricks in the robot are less than Supplement Limit (SL), he will start the supplement process directly. Check Interval (CI) is introduced to determine the checking frequency.

Two ergonomic behaviors are incorporated.

(1) Forgetting: Because the BS worker may repeat checking many times a day, he is very possible to forget some checks. To capture the forgetting behavior, the variable Forgetting Possibility (FP) is introduced. FP is determined by the following equation[15]:

$$FP = e^{-0.01CI} \tag{1}$$

(2) Muscle fatigue: In bricklaying process, several tasks have physical work load on masons [27], which leads to muscle fatigue. To address this, we reference a dynamic fatigue model proposed by Seo et al. [9]. A worker will take a voluntary rest when his current level of muscle strength is lower than the physical demand in the following work element, and will not perform the task until the former is at least 10%MVC higher than the latter. MVC refers to the maximum muscle strength. Relation of current muscle strength and work load is shown in equation (2), and muscle strength in the recovery process can be explained in equation (3).

$$\frac{F_{cem}(t)}{MVC} = e^{-\frac{F_{load}}{MVC}d} \tag{2}$$

$$F_{cem}(t_b) = [1 + r \times (b - a)]F_{cem}(t_a) \tag{3}$$

$F_{cem}(t)$ represents the currently available maximum force at time t. d refers to the duration of the task, and F_{cem} refers to the average physical demand of a work element. Only four work elements that have physical demand are considered based on Seo et al. [9]. The physical demand for extra mortar removing is 0.1%MVC; while the physical demand for grabbing bricks, dropping bricks, and adding bricks to the robot are 0.4%MVC. Besides, r equals 5%MVC per 1 min when F_{cem} is lower than 90%MVC, and equals 0.3%MVC per 1 min otherwise.

4.4 Characteristics of human-robot collaboration in the AB model

This section introduces how the characteristics of human-robot collaboration mentioned in Section 3.2.2 is embedded in the AB model.

Table 3 shows the communication modes related to the bricklaying process. It shows that the human-robot collaboration simultaneously involves three communication modes except TL. These there modes are successfully captured by the proposed model.

Table 3. Involved communication modes in AB model

Communication mode	Scenario
DPI	BS supplements bricks for the robot Workers move the robot
RCI	Communication among workers The Robot waits EMR for next layer
TL	/
ME	Workers install the robot

As mentioned before, the robot will not start laying the next layer until the EMR worker finish the layer; the minimum distance between the robot and the EMR worker is required. These two rules represent the safety requirements. Other requirements can be embedded to the model as well in the same way. Besides, the different characteristics of human and robot are modelled by considering two human factors.

5 Model application and demonstration

5.1 Data collecting

The simulation model is set up based on a range of parameters, including attributes and variables. Attributes are given default values, and variables can be calculated from attributes. Attributes in the model are classified into four types. (1): NS, NN, NL are defined by the construction tasks; (2): PD, ID, MVW, BLD, RSC are related to the robot type; (3): RMV, WV, MRD, GD, DD, SD, CV are determined by the workers' capacity; (4): SL, CI represents the inspection policy. This research aims at providing a modeling approach, without focusing on specific robots, workers or policies. Therefore, the attributes are decided in Table 4 based on theoretical evidence, empirical evidence and necessary assumptions[18, 24, 28]. Triangular distributions with a 20% variance are applied to PD, ID, MRD, GD, DD and SD to capture workers' random performance[29].

Table 4. Default value of attributes

Robot agent		Worker agent	
Attribute	Value	Attribute	Value
PD	10min	RMV	0.33m/s
ID	10min	WV	0.75m/s
MVW	0.2m/s	MRD	5s
BLD	8s	SL	100 bricks
RSC	300 bricks	CI	15min
		GD	30s
		DD	30s
		SD	10s
		CV	0.67m/s

5.2 Case study

This scenario gives a demonstration of the output in order to shed light on a better understanding of the proposed model, while draw useful managerial insights from the output. The construction task for this scenario is the first wall with ten layers, which is labeled with an arrow in Figure 2. Therefore, NS contains two nodes, NN equals two and NL equals ten. Other attributes equal default values.

5.2.1 Recording duration data

The model is capable of recording total and classified construction duration for both robot agents and worker agents. Based on the duration data, the proportion of working time and idle time can be calculated. Duration data for robot agents are shown in Table 5. The construction duration, together with proportion of working time and idle time can serve as an indicator of the productivity of the construction process.

Table 5. Duration data for robot agents

	1	2	3	average
Construction time (h)	5.07	5.10	5.04	5.07
Working time(h)	2.78	2.77	2.77	2.77
Idle time (h)	1.58	1.57	1.54	1.56
Moving time (h)	0.06	0.06	0.06	0.06
Operating time (h)	0.66	1.57	1.54	0.67
Working proportion		/		54.6%
Idle proportion		/		30.8%

5.2.2 Generation of state-to-time variation

Based on the data recorded by recorder agents, figures that show state-to-time variation can be generated. In the figures, different states are labeled with different numbers (2 refers to working state, 1 refers to idle state, 0 refers to operating state, -1 refers to moving state). This grading approach can capture the divergence of states from working state. The state-to-time variation of primary agents, including the robot agent, the BS worker agent and the EMR worker agent are showed in Figure 4.

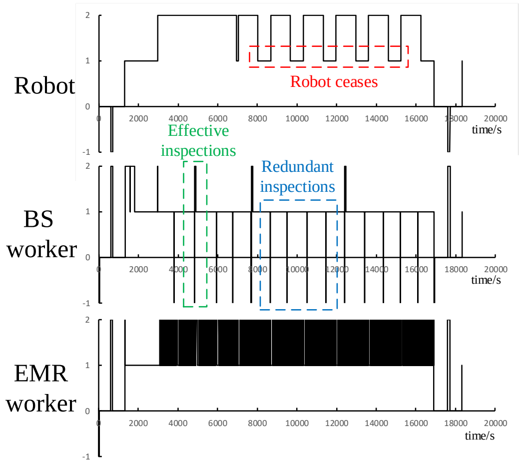

Figure 4. State-to-time variation of main agents

The state-to-time variation clearly shows the working condition of each agent, therefore it is considered to be a good tool to examine the productivity of the process. For example, it stresses the impact of inspection policy on total productivity. Beside effective inspections labeled with the green rectangle, the BS worker has several redundant inspections labeled with the blue rectangle, which infers CI should be adjusted longer than the default value to achieve better effectiveness. Besides, the robot still ceases several times labeled with the red rectangle due to the fatigue of the EMR worker. It is clearly shown in Figure 6 that all the pauses happen after the F_{cem} of the EMR worker reached 0.11, 10%MVC higher than the physical demand of his tasks. Another important managerial insight can be drawn to address this. At the early stage, workers' strengths match well with the robot. However, when the construction is carried forward, workers become incompetent due to muscle fatigue. At this time, some managerial actions (i.e. shifts) should be taken to regain the balance between workers and robots. The proposed model can indicate the best time to shift the EMR worker, which is labeled by red line in Figure 5.

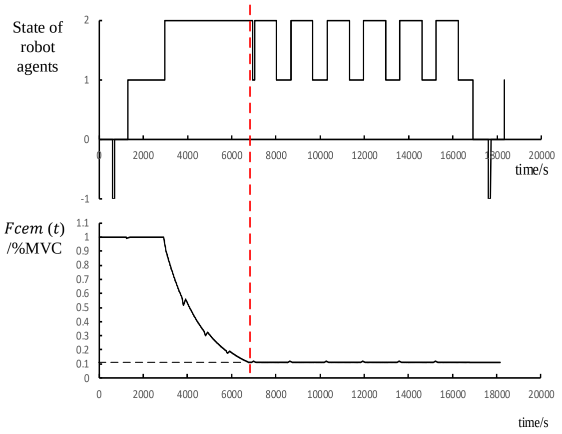

Figure 5. Impact of fatigue on productivity

6 Conclusion

Comparing to collaboration systems between human-human, human-device and robot-robot, human-robot collaboration is complex and unique because it involves multiple communication at the same time; it has special safety requirements; its participants, human and robot, have different characteristics. In this research, an agent-based approach is applied to simulate human-robot collaboration process in typical bricklaying scenarios, in order to provide a bottom-up approach to help understand and further optimize this complicated process.

The proposed model fully integrates the behaviors of both workers, robots and their interaction. The effect of muscle fatigue and forgetting is incorporated as human factors to further emphasize the differences between robots and workers. The AB model is capable of recording total and four types of classified construction duration corresponding to the four states, and is able to capture state-to-time variation. Development of the simulation model is based on a range of parameters to capture the quality of both workers and robots, which is further based on theoretical and empirical evidence, including previous papers and video records. The result confirms the potential of AB modeling for analyzing human-robot collaboration process in construction. The results also draw some managerial insights: (1) inspection policy can be adjusted to achieve a higher effectiveness; (2) shifts in workers are highly recommended to retain the strength balance between workers and robots to maximize the productivity, since muscle fatigue will greatly hamper workers' capacity.

Further research can be conducted to improve and utilize the proposed model. Although the proposed model reflects the coexistence of different communication modes, it will be very meaningful to abstractly model the four communication modes, which can guide the establishment of future simulation models related to human-robot collaboration. Besides, currently only forgetting and muscle fatigue are considered in the model. However, other human factors (i.e. communication errors etc.) and ergonomic behaviors (i.e. muscle fatigue increases the forgetting possibility etc.) can be incorporated. Furthermore, many parameter values in this research are not based on actual robots due to the limited practical application. As construction robots become more prevalent, parameters can be adjusted to actual values.

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