Enabling human-robot collaboration in unstructured construction environment through sharing control: Classification, Challenges, and Future Trends

Guohao Wang[1,*], Changrui Zhu[2], Honghu Chu[1,3], Abdul-Majeed Mahamadu[1] , Vijay M. Pawar[1]

[1]Bartlett School of Sustainable Construction, University College London, United Kingdom
[2]Computer Science, University College London, United Kingdom
[3]College of Civil Engineering, University of Hunan, China

*ucbvanb@ucl.ac.uk

Abstract -

Robots hold great potential for enhancing efficiency, quality, and safety in construction, yet the unstructured and dynamic nature of construction sites limits the feasibility of full automation. Human-robot collaboration (HRC) offers a solution by integrating human expertise with robotic precision to improve adaptability. However, there remains a significant gap in understanding the systematic integration of human and robotic intelligence, particularly in dynamic control sharing. This study addresses this gap through a systematic review of shared control in HRC within unstructured environments, reflecting on its application to construction. A two-layer classification framework is proposed, encompassing "human-in-the-loop" (HITL) and "human-on-the-loop" (HOTL) systems, further divided into five subcategories. Key challenges and future research directions are also identified, providing actionable insights for designing and optimizing HRC systems in complex construction scenarios.

Keywords -

Robotic construction; Human-robot collaboration; Control sharing; Unstructured construction environment

1 Introduction

The construction industry, which contributes approximately 13% of global GDP, continues to face persistent challenges related to safety and labor shortages. In the UK, construction sector accounted for 51 worker fatalities in 2023, representing 37% of all workplace deaths [1], alongside a shortfall of over 150,000 skilled workers jeopardizing housing plans [2]. Robotics presents a promising avenue for mitigating workforce deficits and undertaking hazardous tasks. However, the inherently unstructured and dynamic nature of construction sites—characterized by irregular components and unpredictable environmental conditions—demands a high degree of adaptability. This complexity underscores the difficulty of achieving fully autonomous robotic operations in construction, highlighting the need for intelligent systems capable of navigating uncertainties and adjusting dynamically [3].

Humans' agility and expertise are crucial for managing uncertainties in unstructured environments, making human-robot collaboration (HRC) a viable approach for deploying construction robots. Although originally developed for industrial settings, HRC has expanded into fields such as surgery and military operations, while its application in construction remains in an early stage. Recent reviews have examined HRC in construction, focusing on robot autonomy [3], worker skill transfer methods [4], multidimensional taxonomy frameworks [5], and applications scenarios [6], laying the foundation for advancements in this field. Nevertheless, it remains unclear how the integration of human operators' intelligence and robotic autonomy is achieved in unstructured construction environments. In this study, we focus primarily on human-robot collaboration systems under teleoperation scenarios. Within this context, as the robot is the primary entity executing tasks, human-robot collaboration can also be referred to as shared control of the robot. A limited understanding of shared control constrains HRC system design, restricts autonomy, heightens risks, reduces efficiency, and undermines user trust—ultimately impeding adoption in complex construction settings.

To fill the aforementioned knowledge gaps, this study investigates shared control mechanisms of human-robot collaboration systems in an unstructured construction environment. A systematic literature review methodology is employed, involving comprehensive retrieval and rigorous screening to ensure the scientific rigor and reliability. The findings aim to provide theoretical support for the design and optimization of HRC systems in such complex settings. The research questions are formulated as following: (1) What shared control methods have been developed in existing human-robot collaboration systems in unstructured environment? And how can they be systematically classified? (2) What are the key challenges in implementing shared control systems for construction robots operating in unstructured environments? (3) What are the emerging research trends for the advancement of shared control systems in construction robotics?

2 Methodology

This study conducted a systematic literature review following the PRISMA guideline [7]. As instructed in PRISMA flow diagram, there are two steps in PRISMA i.e. studies identification and screening each of which will be introduced in details in this section.

2.1 Identification

In PRISMA, relevant records need to be systematically identified first and then initially filtered out of duplicates and ineligible records using automated tools. To ensure the comprehensiveness of the literature review, we carefully selected search terms as shown in the Figure 1. Specifically, we incorporated a broad range of terms capable of reflecting various human-robot collaboration paradigms that combine human expertise with robot autonomy. It is important to note that these terms do not have standardized definitions, and in some cases they are cross-used. In addition, we selected “robot” and “uav” to cover common types of robots. For built environments, the search strategy included terms describing unstructured environments similar to buildings, ensuring coverage of a wide range of dynamic and changing built environments, including “building”, “architecture”, “infrastructure ”, “unstructured environments”, “changing environments”, “dynamic environments”, and “clutter “.

Through this systematic search, 656 records were initially retrieved. Automated filters were then applied to refine the dataset, restricting it to English publications from 2010 to September 2023 within the engineering and computer science fields to ensure a comprehensive and up-to-date literature review. Finally, 521 records remained after removing duplicates.

2.2 Screening

In this subsection, the screening criteria and rigorously assessment process will be introduced. This study focused on the remotely collaboration between human and real robots within unstructured construction environment. Thus, studies in which only systems with partial shared control and physical robots were included, excluding review papers, fully human-controlled or fully autonomous systems, soft robots, and miniature robots. Additionally, selected studies focused on applications in unstructured, dynamic, and cluttered environments typical of construction engineering, ensuring relevance to complex construction scenarios.

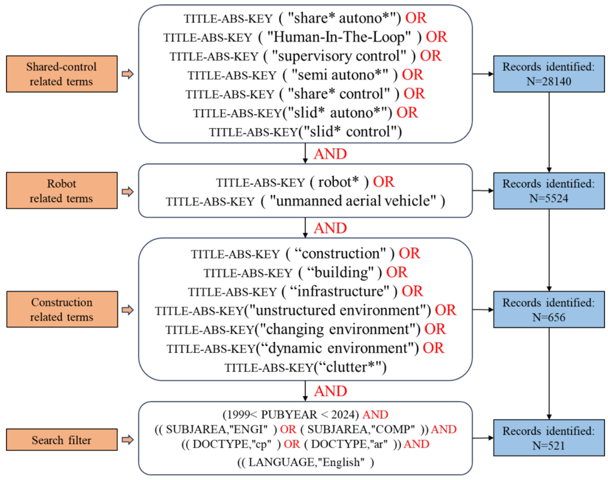


Figure 1. Combination of searching terms

To ensure rigor in the screening process and reduce subjective bias, a literature assessment team consisting of three PhD students was formed. The assessment process consists of three steps: (1) independent assessment of titles, abstracts, and keywords to identify relevant or uncertain studies; (2) independent full-text review of selected articles; and (3) consensus among raters, requiring at least two agreements for inclusion. Before final consensus, each rater followed the above screening criteria without any interference from others. By following the above criteria and process, a total of 65 relevant articles were finally included for detailed review.

3 Bibliometric Analysis

This section analyzes publications on human-robot collaboration based on shared control in unstructured environments, highlighting trends, robot types, and key venues.

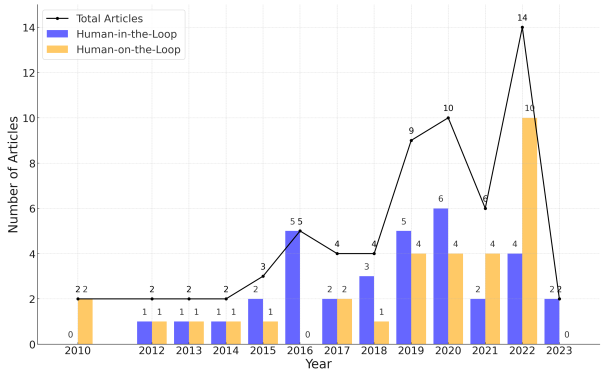


Figure 2. Numbers of publications of each shared control category by year

As shown in Figure 2, the annual publication count of shared control systems has steadily increased, with significant growth since 2016 and a peak in 2022 (14 articles). The trends of ”Human-in-the-Loop” (HITL) and ”Human-on-the-Loop” (HOTL) indicate a shift towards supervisory roles, as HITL research peaked in 2020 while HOTL rapidly expanded in 2022, driven by advancements in AI and the demand for balancing automation and human oversight.

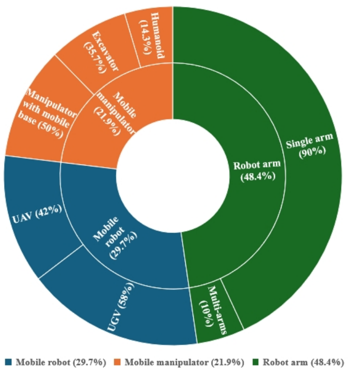


Figure 3. Distribution of robot types

Figure 3 shows that robot arms dominate the field (48.4%), with 90% being single-arm systems, reflecting their maturity in industry. Mobile robots (29.7%), led by UAVs (42%) and UGVs (58%), highlight their versatility, while mobile manipulators (21.9%) showcase rising interest in dynamic environments. Humanoids (4.3%) and excavators (5.7%) remain niche areas.

4 Classification of shared control based human-robot collaboration systems

Based on retrieved studies, a two-layer classification framework of human-robot collaboration systems is proposed in this section based on control sharing mechanisms. Table 1 shows a summary of the classification framework.

4.1 Human-in-the-loop system (HITLs)

Human-in-the-loop (HITL) systems involve the active participation of human operators within the robot’s control loop, where human input is essential to ensure task execution. Depending on the mechanism by which human and robotic control are integrated, HITL systems can be categorized into three subtypes as shown in Figure 4: semi-autonomous human-in-the-loop systems, robot-guided human-in-the-loop systems, and human-instructed human-in-the-loop systems.

4.1.1 Semi-autonomous human-in-the-loop system (SA-HITLs)

SA-HITL refers to a shared control system capable of fusing motion commands from both human operators and autonomous controllers, which are then executed by the robot. In SA-HITL, the operator provides low-level motion commands in a human-in-the-loop manner, while the autonomous controller simultaneously generates motion commands to assist the operator in performing tasks such as obstacle avoidance in unstructured environments. To fuse the commands from both the operator and the autonomous controller, existing studies primarily adopt two methods: (1) degrees of freedom (DOF) allocation and (2) command fusion. In the DOF allocation method, the operator and the autonomous controller independently control different components or DOF of the robotic system. For example, [8] developed a shared control system for motor graders, where human commands control steering and autonomous commands control blade motion. Such studies typically assign certain robot DOFs, often those challenging to automate, to human control, enhancing the system’s adaptability in uncertain environments.

In another type of SA-HITL, operator and robot commands act on the same DOFs and are fused, typically using linear, probabilistic or constraint optimization methods, to generate the final execution command. Adjusting fusion strategies, such as the weights in linear fusion, allows the system to better align with human intentions or objectives of autonomous controller. For example, a linear command fusion strategy was proposed [9] to utilize robot-generated obstacle avoidance commands to mitigate collision risks caused by reduced situational awareness during human teleoperation of robots in cluttered and unknown environments.

4.1.2 Robot-guided human-in-the-loop system (RG-HITLs)

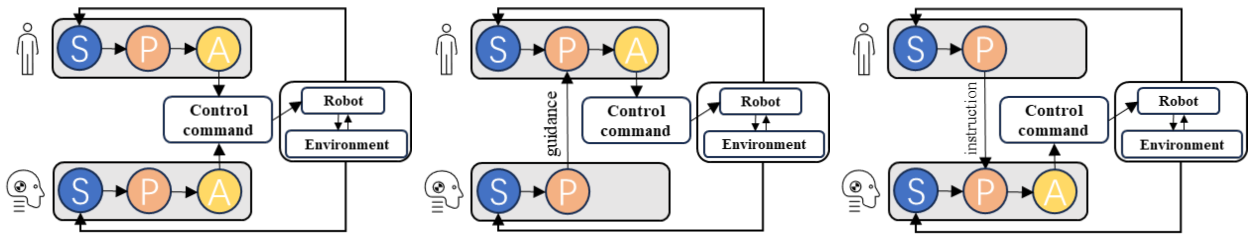
RG-HITL systems enable shared control by guiding, prompting, or constraining the operator’s inputs, without the autonomous controller directly generating commands for the robot’s actuators. This approach allows operators to effectively control the robot while leveraging the autonomous system’s planning and situational awareness. RG-HITL systems can be classified into sensation-based and virtual fixture-based systems.

Sensation-based systems enhance operators’ situational awareness by conveying environmental information to them through multimodal feedback, such as visual [10], auditory [11], or haptic cues [12]. For instance, a UAV haptic interface guided operators in navigating obstacle-laden environments, where tactile feedback not only reduced collision risks but also improved performance in scenarios with limited visibility [13].

Table 1. Classification of shared control based human-robot collaboration systems

Class	Subclass	Human Role	Robot Role	Techniques	Potential HRC applications in construction
HITL	SA-HITL [8, 9]	Provide control commands	Generates control commands, fuses operator commands, and executes.	DOF allocation [8]; Commands fusion [9]	Tasks with redundant robot's DOFs such as grading and rolling
	RG-HITL [10, 11, 12] [13, 14, 15]	Provide control commands with robot's guidance	Provide guidance to operator and executes operator's commands.	Visual[10], auditory [11], and haptic cues[12]; Virtual fixtures [14, 15]	Dynamic tasks requiring accurate control such as Welding or drilling
	HI-HITL [16, 17, 18] [19, 20]	Provide high-level planning instructions	Convert operator's high-level instructions into low-level planning, generate executable control commands, and execute them.	Geometric [16], template-based [19], and demonstration-based motion planning [17]	Tasks requiring high-complexity planning such as grasping structural demolition components
HOTL	HI-HOTL [21, 22, 23]	Supervise robot performance and intervene when necessary	Execute tasks autonomously and await human intervention when needed.	Gesture, haptic[21], or voice-based "take over" mechanisms [22]	Tasks with conditional robot autonomy such as drone-based construction site safety monitoring
	RI-HOTL [24, 25, 26]	Intervene when triggered by robot based on external information	Execute tasks autonomously, monitor system/environment state, and adjust autonomy.	Task failure risk prediction [25, 26], system gain prediction [24]	Tasks with high robot autonomy: drone-based 3D reconstruction of the exterior of buildings

Note: Due to page limitations, identified works for each shared control category cannot be fully indexed. The full list is provided in the appendix A.



(a) SA-HITL (b) RG-HITL (c) HI-HITL

Figure 4. Schematic diagram of three HITL shared control systems

The second type of RG-HITLs is virtual fixture-based, which employs attractors or repulsors to guide or constrain operator inputs. Attractor fixtures create a converging force field, directing the operator's control toward a desired trajectory or target, enhancing precision and simplifying tasks. For example, Adjigble et al. [14] applied attractor-based fixtures in robotic telemanipulation for industrial assembly, enabling stable and accurate peg-in-hole operations even in unstructured environments. Conversely, repulsor fixtures generate a diverging force field to prevent the operator from moving the robot into restricted or unsafe areas. For instance, Gottardi et al. [15] utilized repulsor fixtures in a teleoperated UAV for search-and-rescue missions, helping operators navigate around collapsed structures and debris, thereby reducing collision risks and enhancing safety in disaster response scenarios.

4.1.3 Human-instructed human-in-the-loop system (HI-HITLs)

Human-instructed human-in-the-Loop (HI-HITL) systems are characterized by a distinct interaction model where the operator provides high-level instructions rather than low-level motion commands. These high-level instructions are integrated by the robot's autonomous planner to generate detailed, low-level control commands. By eliminating the need for real-time low-level robot control, with HI-HITLs operators can focus on higher-level planning.

Components on construction sites tend to be irregular in shape and material compared to parts in manufacturing. To achieve robust autonomous gripping requires tedious computation, yet this is a subconscious action for humans. The HI-HITL system can effectively utilize human dexterity and tacit knowledge in grasping irregular objects to compensate for deficiencies in robotic reasoning. For example, existing studies have proposed that operators could instruct robots through (1) setting a target grasping pose [19], (2) selecting from a set of grasping candidates generated by the robot [20], or (3) defining geometric constraints for grasping [16, 17]. In addition to grasping assistance, another type of application for HI-HITL is in guiding mobile robots through complex environments. For example, Jia et al. [18] used a graphical interface enabling operators to modify the robot's cost map by marking non-traversable obstacles that are difficult for the robot to perceive, improving path planning in cluttered environments.

4.2 Human-on-the-loop system (HOTLs)

Unlike the HITL system, the HOTL system places more emphasis on robot autonomy, i.e., the robot has the ability to perform tasks autonomously under ideal circumstances, but retains the authority of the human operator to intervene. Thus HOTL systems have the capability of control authority switching, which is also referred to as sliding control or supervisory autonomy in some contexts. Depending on how control authority switching is triggered, HOTL can be categorized into human-initiated HOTLs and robot-initiated HOTLs. These systems reduce operator workload, ensure reliability and safety, and balance efficiency with adaptability in complex environments by limiting intervention to critical situations.

4.2.1 Human-initiated human-on-the-loop system (HI-HOTLs)

HI-HOTL systems enable operators to "take over" control as needed, often through emergency stop buttons or GUI-based triggers in teleoperation scenarios. Other that these, haptic devices also play a role, allowing intuitive takeovers by detecting operator actions, such as moving the device, as demonstrated by Brosque et al. [21] in collaborative welding tasks. Additionally, systems can transition to operator control based on confidence in predicting the operator's intent, ensuring alignment with human goals.

While the reliability of the HI-HOTL system is ensured by human supervision, it relies on the operator's ability to understand the robot's state, environment and condition accurately and in a timely manner. Traditional approaches typically require operators to continuously monitor sensor data, plans, and environmental information, which can be unintuitive and cognitively demanding. To address this, Song et al. [22] introduced a system using visual-language models to present the robot's perception and motion planning in natural language, enhancing intuitiveness. Additionally, research aims to enable robots to learn from operator interventions, improving autonomy and reducing the need for future takeovers [23].

4.2.2 Robot-initiated human-on-the-loop system (RI-HOTLs)

RI-HOTL systems enable robots to operate autonomously while involving human operators only when necessary. By monitoring their state and environment, robots identify situations requiring intervention, relieving operators from constant monitoring. This further reduces operators' cognitive load and allows them to manage other tasks, improving efficiency and multitasking capabilities.

In existing RI-HOTL systems, the decision to involve human assistance is fundamentally rooted in predictions concerning the environment or task execution. This decision-making process primarily revolves around two key aspects:

1. **Estimating System Gains from Human Assistance:** For instance, hierarchical reinforcement learning has been utilized to predict the potential gains of human intervention, such as improving rescue efficiency and safety in cluttered environments. Here, the robot learns to decide when to involve the human operator to maximize task performance and ensure safety [24].

2. **Assessing Task Failure Risks:** Another approach involves evaluating the risks associated with task failures. For example, in [25], a 3D environmental uncertainities estimation model-based, risk identification and management framework was presented in which the failure probabilities of various type of mobile manipulator's task such as collisions and missed grasping were estimated. Except for utilizing task information, environmental information such as environmental accessibility [26] can also be used to regulate the autonomy of the system.

5 Challenges of deploying shared-control system in unstructured construction environment

In this section, we identify three key challenges associated with the deployment of shared control HRC in an unstructured construction environment.

5.1 Low latency bidirectional communication systems

A stable and low-latency bidirectional communication system is essential for shared control systems. Communication delays can cause command mismatches and feedback distortion, undermining operator control and robot performance [27]. This is particularly critical for SA-HITL, RG-HITL, and HI-HOTL frameworks. In SA-HITL and RG-HITL, operators provide real-time low-level control commands, and latency disrupts synchronization between operator inputs and robot actions. For instance, hydraulic excavators experience efficiency drops to 40–60% of manned operation levels due to communication delays [28]. Similarly, in HI-HOTL systems, where operators monitor and intervene, delays impair situational awareness, as seen in crane operations, which face increased task difficulty and extended completion times [29].

5.2 Intuitive human-robot interaction interface

An intuitive human-robot interaction interface is essential for shared control in construction, as it determines whether a construction worker, without robotics expertise, can accurately interpret the robot's state and remote environment, make appropriate decisions, and efficiently issue control commands with minimal errors. While most existing research on shared control focuses on the fusion mechanisms of human and robot commands, the impact of interaction interface design has received significantly less attention.

HRI interfaces can be categorized into feedback and control interfaces. Feedback interfaces are used to communicate information about the robot, the mission and the environment to the remote operator, and are therefore critical in SA-HITL, RG-HITL and HI-HOTL systems that require real-time operator feedback or supervision. Existing studies have shown that the addition of sensory dimensions such as vision, auditory and haptic can help improve situational awareness under teleoperation [30]. However, other studies have found that providing too much information to operators increases their cognitive load and, in turn, decreases their productivity. For example, relying only on visual modal information when teleoperating an excavator can overload the operator, cause fatigue and poor decisions to operators, and even damage underground utility facilities such as pipes and wires [31]. Therefore, what and how information is presented to the remote operator for different construction tasks and environments still needs a lot of human subject validation. Unlike feedback interfaces, the core challenge of control interfaces for human-robot collaboration in the field of construction engineering lies in the mismatch between limited robotic degrees of freedom and highly flexible human movement. Construction workers often require extensive training to overcome mismatches with field robots during teleoperation, thereby raising the barrier to widespread adoption.

5.3 Building trust between human and robots

Trust between humans and robots reflects the confidence and willingness of humans to rely on or cooperate with robots to accomplish tasks. Without some level of trust, it is difficult to apply any shared control method to a real construction site. Typically, the more autonomous a robot is, the more it needs human trust. For example, the HOTL system has the ability to operate fully autonomously compared to HITL, and therefore also requires more trust from the human supervisor.

To foster trust between humans and construction robots, key questions include: (1) Trust in Specific Autonomy Levels: Which shared control framework is most trusted for a given task and environment? (2) Transparency and Explainability: How can robotic systems improve transparency to enhance operator trust? (3) Impact of Training: Does continuous training increase operator trust and acceptance of higher autonomy?

6 Future trends

In this section, two future research trends identified from related works are introduced which helps to tackle with the above challenges as shown in Figure 5.

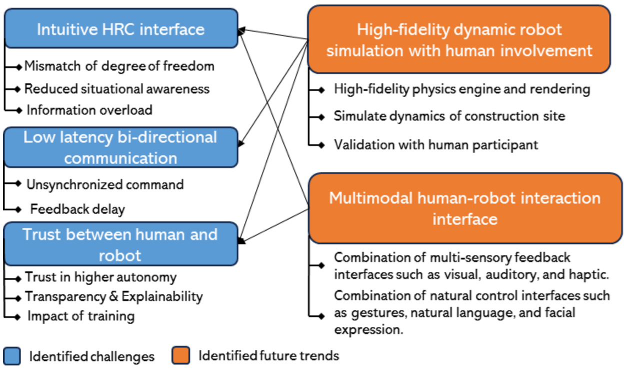


Figure 5. Mapping between identified challenges and future trends

6.1 High-fidelity dynamic robot simulation with human involvement

Compared to traditional static, low-fidelity robot simulations, shared control systems in unstructured construction environments require high-fidelity simulations to reflect the dynamics of the site and the operator's perception of the environment. High-fidelity means that the simulated environment accurately replicates the physical conditions affecting the robot and operator. For example, simulating a drone in a tunnel must account for lighting and airflow, while a robotic crane needs to model the dynamics of a pendulum in a wind or rush-stop situation to address payload swing. Similarly, simulations of inspection robots navigating incomplete structures should include uneven surfaces, temporary scaffolding, and obstacles such as materials or moving people to ensure effective robot adaptation. Future research should prioritize high-precision physics engines and advanced graphics rendering for realistic simulations. Digital twin technology can be used to capture the dynamics of the construction site and integrate real-time data to effectively simulate the ever-changing construction environment.

6.2 Multimodal human-robot interaction interface

Current research on shared control is primarily based on GUI to convey signals to operators in a visual format.

In recent years, auditory and haptic modalities have been shown to enhance remote operator situational awareness [30]. Thus, future research could focus on the integration of multiple sensory modalities, such as vision, auditory, and haptic, to provide remote operators with an immersive experience. For example, by leveraging vision-language models, robots can explain their understanding of the environment and their own actions to operators in natural language [22], while operators can also issue commands to the robots using natural language.

7 Conclusion

This paper reviews shared-control human-robot collaboration systems, focusing on their application in unstructured construction environments. A two-layer classification framework was proposed that categorizes these systems into "Human-in-the-Loop" (HITL) and "Human-on-the-Loop" (HOTL), highlighting varying autonomy levels and human involvement. Bibliometric analysis reveals significant growth, with a shift toward supervisory HOTL roles enabled by advances in autonomy. However, challenges persist, including limited focus on usability, and insufficient exploration of real-world deployment, particularly regarding trust-building, training, and adaptability. Future research should prioritize standardized frameworks, user-centered design, high-fidelity simulations, and multi-modal interaction interface to bridge the gap between theory and practice, accelerating adoption and improving safety, efficiency, and collaboration in construction robotics.

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A List of Identified Works

The full list of identified works can be found here.