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Perceived Challenges to Implementing Heterogeneous Robotic Systems for Construction

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Research Goal

To identify key technological challenges in implementing heterogeneous robotic systems within the construction industry.

Introduction

The construction industry continues to face persistent challenges such as labor shortages, low productivity, and hazardous working conditions. In response, there is growing interest in robotics to improve safety, efficiency, and overall performance for construction tasks. Robotic systems can take over repetitive or dangerous tasks, offering higher precision and reducing the risk of human error. Multi-robot systems (MRS) offer key advantages in contrast—such as data sharing, more dexterity and flexibility, efficient time and energy consumption, and greater operational scalability [1, 2]. These systems can divide complex jobs into smaller sub-tasks and assign them to the most suitable robot, enabling more effective and flexible workflows. In particular, heterogeneous multi-robot teams, which combine different types of robots (e.g., UAVs for site surveying and UGVs for material transport), can perform diverse functions that no single platform could accomplish alone.

Despite these advantages, implementing heterogeneous MRS introduces significant system-level complexity. Each robot must operate reliably on its own while also communicating and coordinating seamlessly with others, despite differences in hardware, software, and functional roles [3]. This requires shared architectures for data exchange, task planning, and real-time control [3]. The challenges become especially pronounced in dynamic and unstructured environments like construction sites, where key functional areas—including site monitoring, task generation and allocation, task execution, and inter-robot communication—each pose unique difficulties.

This study investigates these core challenges associated with deploying heterogeneous multi-robot systems in construction. By gathering insights from academic experts, it aims to identify key technological barriers hindering their effective implementation.

Heterogeneous Robotic System (HRS)

The task generation system interprets site data and environmental context—using AI or LLM-based reasoning—to generate actionable tasks and assign them appropriately across robotic agents.

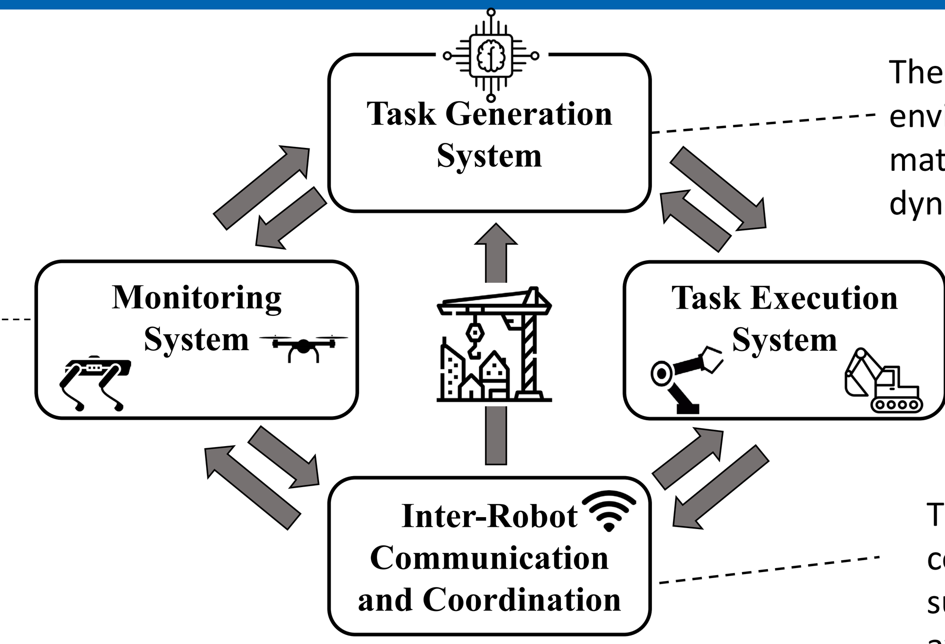

Fig 1. Four elements in the heterogenous robotic system.

The task execution system involves physical interaction with the environment, where robots perform construction activities such as material handling, assembly, or inspection based on predefined or dynamically generated plans.

This system manages data exchange and synchronized collaboration among heterogeneous robots, enabling shared understanding, distributed decision-making, and cooperative task execution on complex construction sites.

The monitoring system enables real-time perception of the construction site using sensors and robotic platforms (e.g., drones), supporting progress tracking, safety assurance, and situational awareness in dynamic environments.

Key Challenges

Monitoring System

Challenge	Description	Ref
Operational Safety (OS)	Continuously detect and react to human presence to avoid collisions and ensure safe interactions in shared spaces.	[4], [5]
Robustness to Environmental Conditions (RE)	Operate reliably despite environmental factors such as dust, water, poor lighting, wind, and ground vibration.	[6], [7]
Energy Constraints (EC)	Short battery life limits operation time; additional sensors and processors further reduce endurance.	[5], [8]
Navigation in Unstructured Environments (NU)	Navigate cluttered, GPS-denied areas by avoiding obstacles and generating safe, adaptive paths.	[8], [9] ,[10]
Connectivity CN)	Wireless communication is often unstable in large, obstructed, or steel-framed construction sites.	[11]

Task Execution System

Challenge	Description	Ref
Expert-Driven Setup (ED)	Require manual configuration or expert programming prior to autonomous task execution.	[12]
Operational Safety (OS)	Performing tasks near humans, equipment, and obstacles demands reliable safety mechanisms to prevent accidents.	[4], [13]
Robustness to Environmental Conditions (RE)	Harsh outdoor factors—such as water, poor lighting, and wind, and vibration—can impair performance and damage components during operation.	[6], [14]
Trajectory Planning (TP)	Motion planning must adapt to dynamic surroundings and consider mechanical limits of different robot platforms.	[15]
Task Verification (TV)	Systems must assess whether tasks meet required specifications, particularly for high-precision or safety-critical operations.	[16]

Task Generation System

Challenge	Description	Ref
Interpretation of Collected Site Data (IC)	Real-time processing of large-scale sensor data is constrained by bandwidth, latency, and on-site hardware limitation	[17]
Semantic Understanding of Construction Context (SU)	Requires deep contextual understanding of the construction site, including sequences, spatial constraints, materials, and hazards.	[18]
Adaptation to Environmental Uncertainty (AE)	Generated tasks must remain valid under changing site conditions, requiring models that can generalize to uncertainty.	[19]
Context-Aware Task Allocation (CA)	Effective task allocation demands awareness of each robot's capabilities, limitations, and current operational status.	[20]

Inter-Robot Communication

Challenge	Description	Ref
Distributed Knowledge Management (DK)	Managing what each robot knows and shares—while avoiding network overload—remains a key systems challenge.	[21], [22]
Heterogeneous1 Control Architectures (HC)	Diverse software stacks and control schemes hinder unified planning and complicate integration of centralized or decentralized coordination.	[21] ,[23]
Resilience to Partial Failure or Dropouts (RP)	The system must maintain stability when one or more robots disconnect or fail during task execution.	[24]
Coordination Overhead with Increasing Team Size (CO)	As the number of robots increases, communication traffic, synchronization delays, and task management complexity grow non-linearly.	[24], [25]

Survey

Overview

- **Objective:**
  - Evaluate the perceived importance of 18 specific challenges in Heterogeneous-Robot Systems (HRS) in construction.
- **Rating Scale:**
  - Use a 5-point Likert scale (1 = Not at all important, 5 = Very important)
- **Structure:**
  - Microsoft Forms
  - Ranking questions to assess the relative importance of challenges within four major system categories.
  - Open-ended responses to capture participants' reasoning and insights.
- **Participants:**
  - Total of 8 respondents (Assistant Professors or Ph.D. candidates specializing in construction robotics).

Results

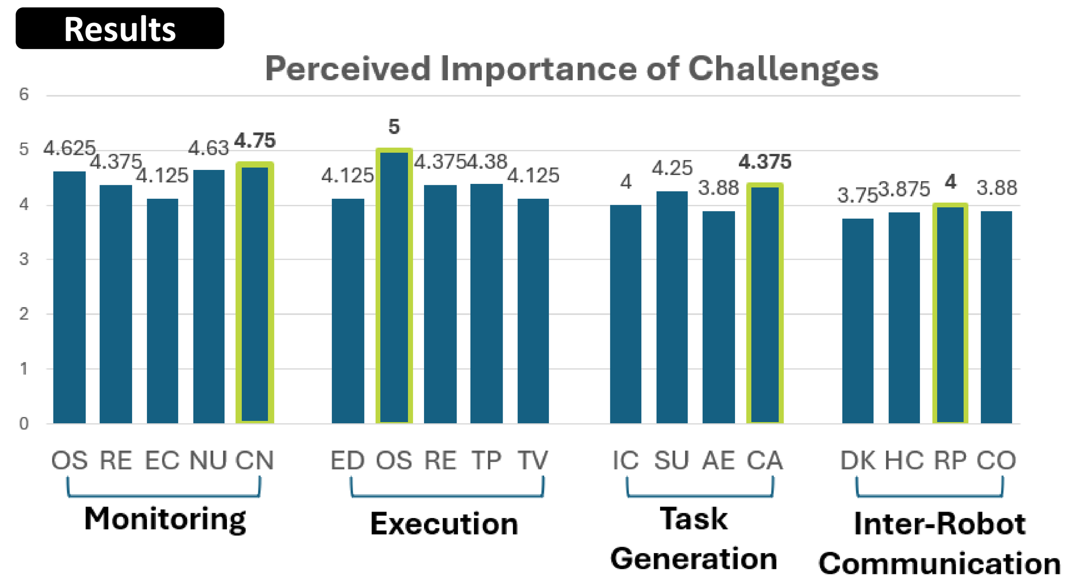

Fig 2. Perceived Importance of Challenges in the HRS in construction.

System Category	Top Challenge	Avg. Score	Remarks
Monitoring	Connectivity (CN)	4.75	Strongest emphasis on robust communication infrastructure.
	Overall System Avg. Score	4.5	Highest perceived importance among all categories.
Execution	Operational Safety (OS)	5	Highest-rated challenge across all systems.
	Overall System Avg. Score	4.4	Second highest system score.
Task Generation	Context-Aware Task Allocation (CA)	4.375	Most important in its category.
	Overall System Avg. Score	4.125	Four factors received one first-place vote each, showing diverse opinions.
Inter-Robot Communication	Resilience to Partial Failures (RP)	4	Heterogeneous Control (HC) was most frequently selected as top challenge.
	Overall System Avg. Score	3.88	Lowest-rated system overall.

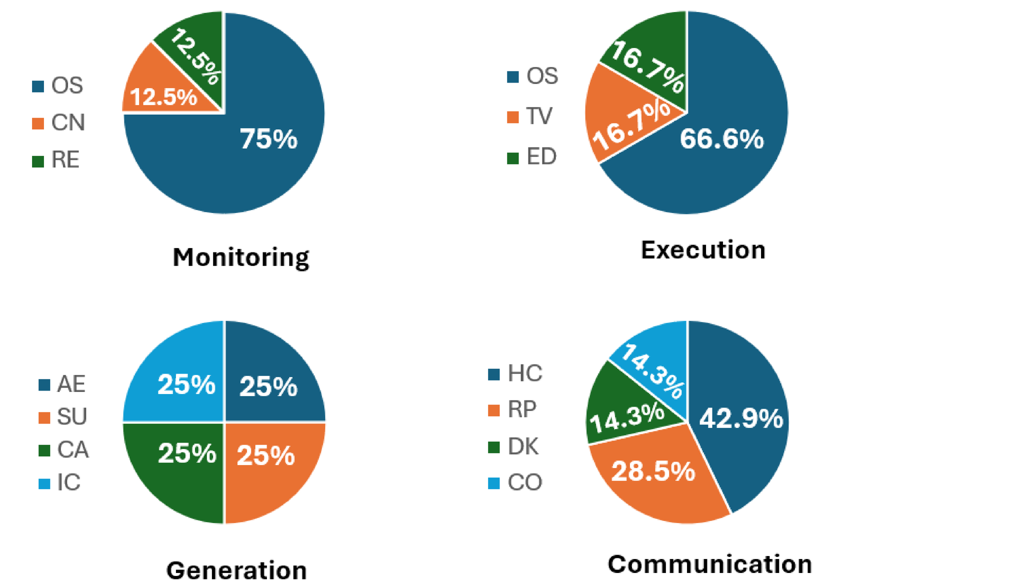

Fig 3. Participant Rankings of Challenge Priorities by System Category

When asked to select the single most important challenge across all categories, six out of eight participants (75%) chose *Operational Safety (OS)* in the Monitoring system and Task Execution. The remaining two participants identified inter-robot communication issues, including *Distributed Knowledge Management* and *Heterogeneous Control Architecture*, as the most critical.

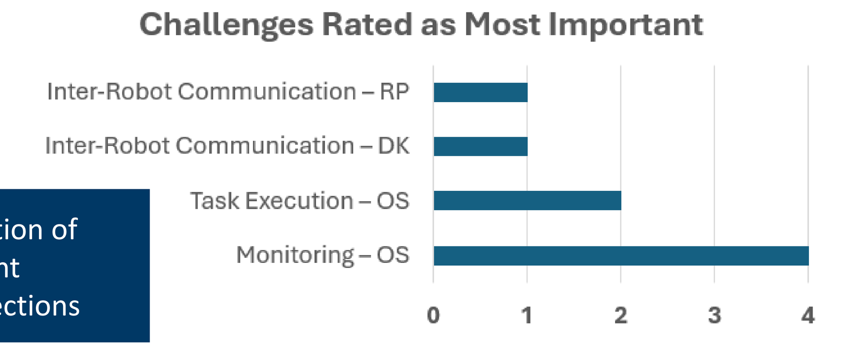

Fig 4. Distribution of Most Important Challenge Selections

Conclusion

This study explored the perceived challenges in implementing Heterogeneous Robotic Systems (HRS) within the construction industry, based on expert feedback. Operational Safety consistently emerged as the most critical concern, particularly in Monitoring and Execution systems. This highlights the significant risks associated with human–robot and robot–environment interaction on dynamic and often hazardous construction sites. In contrast, expert opinions on Task Generation and Inter-Robot Communication were more diverse, reflecting a range of perspectives on which capabilities are most important in these systems. This suggests the need for further investigation to better understand overarching priorities across the HRS framework.

As a next step, future work will involve conducting a systematic literature review to comprehensively map existing technological gaps, along with expanding the survey to a broader pool of participants. This will allow for the generation of more statistically grounded insights into the perceived barriers and inform a clearer research roadmap for advancing HRS in construction.

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