Research on a Robotic Natural Language Intelligent Decision-Making Framework Based on Large Language Models, Thinking Chain Reasoning, and Multi-Agent Collaboration

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Abstract. With the rapid advancement of large language models in semantic understanding and reasoning generation, robots are gradually becoming more intelligent in language-driven decision-making in office settings. However, they still face challenges in areas such as command ambiguity, concurrent task scheduling, and environmental adaptability. To this end, this study, drawing on the work of a national key research and development program, constructed a natural language intelligent decision-making framework that integrates large language models, thought chain reasoning, and multi-agent collaboration. This framework uses semantic reasoning to capture user intent and integrates real-time perception information to achieve efficient multi-robot scheduling. The research proposed an innovative mechanism in the method design that can automatically generate autonomous tasks from human-computer dialogue. This mechanism effectively reduces the interference caused by language uncertainty to the system operation by closely integrating language semantic parsing with task planning. It has been verified in multi-scenario datasets and real application environments, demonstrating its stability and adaptability in complex contexts. Based on this, this study developed a multi-agent reasoning assistant with environmental perception, task planning and autonomous reflection functions, enabling it to achieve unified decision-making and execution at both the virtual and physical levels, thereby significantly enhancing the flexibility and collaboration of cross-scenario task processing. This achievement not only verifies the feasibility of multimodal information fusion and heterogeneous robot collaboration, but also provides a brand-new technical path and practical value for the promotion and application of intelligent service robots in office scenarios.

1. Introduction

With the continuous accumulation of breakthroughs in artificial intelligence in semantic parsing, knowledge deduction, and autonomous decision-making, service robots have gradually evolved into

the core execution units in complex human-computer interaction systems. In the practical application process, robots not only need to accurately understand and parse natural language instructions in diversified scenarios such as office work, medical care and logistics, but also must maintain stable and efficient operation in the face of multiple tasks occurring simultaneously, continuously changing environmental conditions and close collaboration among multiple agents. This makes it an urgent research focus to establish a stable and efficient mapping relationship between the semantic layer and the action layer. Although existing technologies such as positioning, modeling and environmental perception can support the operation of robots to a certain extent, natural language itself has the characteristics of high ambiguity and dependence on context, which often leads to understanding deviations or judgment errors when robots process user instructions, thereby causing a decrease in execution efficiency, an increase in resource consumption, and even conflicts in task allocation and coordination. This situation clearly indicates that the traditional control mode driven solely by explicit instructions can no longer meet the practical application requirements in complex environments.

Although the continuous evolution of multimodal perception and environmental modeling provides robots with increasingly rich external information input, how to deeply integrate these low-level perception data with high-level semantic reasoning capabilities, enabling robots to make flexible and robust decisions in environments with strong constraints of uncertainty and real-time performance, remains an important bottleneck restricting the improvement of intelligence levels. Large-scale language models have demonstrated significant advantages in cross-scenario semantic transfer and complex logical reasoning. These models have gradually developed strong logical consistency and semantic interpretation capabilities through chain thinking deduction and self-reflection mechanisms, enabling robots to precisely extract potential task goals in natural interactions and transform them into practical execution plans. It has injected new impetus and opportunities into the development of intelligent service robots. However, existing methods are often limited to simulation environments or virtual platforms, lacking sufficient adaptability and robustness verification for multimodal perception input, heterogeneous platform collaboration, and real-time control constraints in real physical environments. Therefore, how to deeply integrate the semantic understanding and reasoning advantages of large models with the embodied perception and control capabilities of robots, and achieve the rational scheduling and efficient execution of complex tasks through multi-agent collaboration, remains the key to further development in this field. Against this backdrop, this study proposes a natural language intelligent decision-making framework that integrates a large language model, thought chain reasoning, and multi-agent collaboration. This framework accurately identifies users' underlying intentions through high-level semantic reasoning, combines environmental perception information with robot status to enable task generation and dynamic scheduling. Furthermore, it leverages the division of labor and collaboration among multiple agents to achieve unified execution of multiple tasks in complex office scenarios. This not only advances theoretical exploration of the language-perception-action closed-loop mechanism but also provides a new path for the practical implementation of service robotic systems in real-world environments.

2. Overview of Related Literature

In modern robotics research, natural language-driven intelligent decision-making and execution capabilities have become a core topic in embodied intelligence and service robotics. Numerous scholars have systematically explored, using diverse approaches, how to enhance robots' ability to efficiently complete tasks in complex environments. M Sun's research demonstrates that vision-language navigation tasks require robots to observe the environment and interpret natural language

commands, then effectively fuse and match multimodal information from vision, speech, and environmental sensors to generate a reasonable action sequence to complete the task[1]. He also notes that traditional approaches relying on imitation learning or reinforcement learning struggle to maintain stability in dynamic environments due to low data utilization efficiency and policy distribution shifts. Therefore, modeling navigation action policies as conditional denoising diffusion processes can significantly optimize the learning of state-action pairs, thereby improving the accuracy and robustness of navigation tasks. S Sagar proposes that in high-risk and complex decision-making scenarios, the lack of interpretability of black-box neural networks makes it difficult for engineers and regulators to fully understand the underlying decision-making[2]. Therefore, by constructing an explanation method based on human-understandable high-level concepts, matching neural network activation patterns with visual concepts and assigning uncertainty scores, this method provides an intuitive and verifiable a posteriori diagnostic tool for robot decisions. The method has been validated in both simulation and real-world environments to improve decision reliability and enhance user trust. The continuous advancement of artificial intelligence technology has enabled robots to emulate human cognitive and decision-making capabilities in natural language understanding, image recognition, and complex task planning. R. H. pointed out that by continuously optimizing system performance through machine learning and deep learning, intelligent agents can demonstrate remarkable efficiency and adaptability in multi-task environments[3]. However, this also brings social risks such as changes in employment structure, decision-making bias, and potential abuse. F. Wang proposed that by building a collaborative behavioral knowledge model between robots and users, it is possible to systematically parse ambiguous or ambiguous information in natural language, enabling robots to generate reasonable operational strategies based on understanding user intent[4]. He emphasized that structured representation of behavioral knowledge can provide theoretical and practical support for the implementation of efficient and scalable natural language interaction systems. Z. Wang demonstrated that the vision-language-action model can directly map camera images and natural language task instructions into robot control actions, significantly improving robot decision-making efficiency and the human-robot interaction experience in complex task environments[5]. However, its data-driven nature and lack of interpretability pose challenges to its effectiveness and robustness. To this end, the proposed LADEV platform automatically generates simulation environments through a language-driven approach, enabling efficient testing and reliable evaluation of the vision-language-action model, providing a practical tool for subsequent optimization of robot control strategies. In the research of service robots and question-answering robots, the integration of knowledge reasoning and human-computer interaction has also shown significant value. LV Gómez proposed that a service robot system integrating knowledge management, command parsing, decision generation, and language interaction modules can efficiently understand natural language commands and complete complex tasks[6]. It also demonstrates higher task completion efficiency than the average human when processing incomplete or uncertain commands. C Yuan pointed out that intelligent question-answering robots based on natural language processing suffer from robustness issues such as incomplete semantic slots, insufficient filtering of sensitive words, and irrational matching algorithms[7]. He verified the potential for system failures or abnormal responses by simulating user error input and proposed improvement strategies to enhance system stability. R Gao proposed that, through a high-level task planning method based on a large language model, a mobile single-arm humanoid robot can autonomously complete the continuous transition from high-level decision planning to low-level action execution after receiving natural language commands, achieving sequential operation of complex tasks indoors[8]. Sub-module and overall performance testing was completed on a real robot platform, verifying the effectiveness of the method in long-term collaboration and complex task processing scenarios. Significant progress has been made in

multimodal information fusion, high-level task planning, natural language understanding, enhanced explainability, collaborative behavior modeling, and system robustness. However, gaps remain in multi-agent collaboration, dynamic environment adaptation, and long-term task continuity. This provides a clear research direction and technical foundation for building a natural language intelligent decision-making framework that combines large language models, thought chain reasoning, and multi-agent collaboration.

3. Task Allocation and Natural Language Command Parsing Optimization

In modern multi-zone office environments, robotic natural language intelligent decision-making systems face the challenge of highly dynamic and complex task allocation. Researchers abstracted the office space into a collection of multiple functional zones, each containing several resident individuals and their spatial coordinates. These coordinates are accurately mapped using a two-dimensional semantic map, enabling the correspondence between individual identities and navigational targets. This also reflects potential connections between individuals based on department, project, or job responsibilities. A collaborative group of multiple service robots is deployed within each zone, and a dynamically updated task sequence is maintained for each robot to record and execute natural language instructions received from personnel. These instructions typically involve operations such as document signing, item delivery, or cross-regional collaboration. The system must parse natural language instructions into structured navigation tasks and identify the zones and potential cross-regional dependencies involved in the tasks to ensure the rationality and efficiency of task allocation. During task allocation, the system dynamically evaluates each task by comprehensively analyzing real-time environmental information, personnel location, and robot status. The robot status includes not only the current location and motion capabilities, but also the execution time of the remaining tasks in the current task sequence and the increased load of the tasks to be assigned. The system optimizes the allocation by calculating the total time required for each robot to complete the new task, ensuring that the task is assigned to the robot with the shortest time and minimizing the task completion time globally while avoiding task accumulation and cross-regional delays. For robot R_j, the estimated total time t_{R_j} to complete task K_i can be expressed as formula (1).

$$t_{R_j} = t_{current} + \sum_{k=1}^{N_i} t_k \tag{1}$$

$t_{current}$ is the robot's estimated completion time for the remaining tasks in the current task sequence, N_i is the number of navigation points required in task K_i, and t_k is the estimated time it takes for the robot to reach each navigation point and complete the operation. The system assigns the task to the robot R_{min} that minimizes t_{R_j}, as shown in Equation (2).

$$R_{min} = arg \min_{R_j \in R_F} t_{R_j} \tag{2}$$

Natural language command parsing forms the core of the framework. Leveraging the reasoning capabilities of a large language model and contextual learning techniques, the system transforms unstructured text into an executable list of navigation targets. Through semantic mapping, it maps human identities and target coordinates to spatial information executable by the robot. Subsequently, the navigation task assignment module generates an optimization strategy based on the task objectives, robot status, and environmental constraints, assigning tasks to the most suitable robot and updating the task sequence in real time to ensure a reasonable execution order. During the execution phase, the robot strictly follows the updated sequence to complete the assigned task. Its motion trajectory and operation time are dynamically adjusted based on the location of the resident human and spatial constraints, enabling efficient collaboration in a cross-regional, multi-tasking

concurrent environment. This intelligent decision-making framework seamlessly integrates natural language understanding, spatial semantic mapping, task duration prediction, and multi-robot collaboration strategies to achieve closed-loop management of the entire task generation, allocation, and execution process. It not only dynamically adapts to changes in tasks and environments, but also effectively addresses complex issues such as cross-regional scheduling, multi-tasking concurrency, and limited resources. It provides an efficient and robust solution for multi-agent collaboration in office scenarios and lays the theoretical and methodological foundation for future expansion into intelligent task scheduling with large-scale, multimodal input, and complex environments.
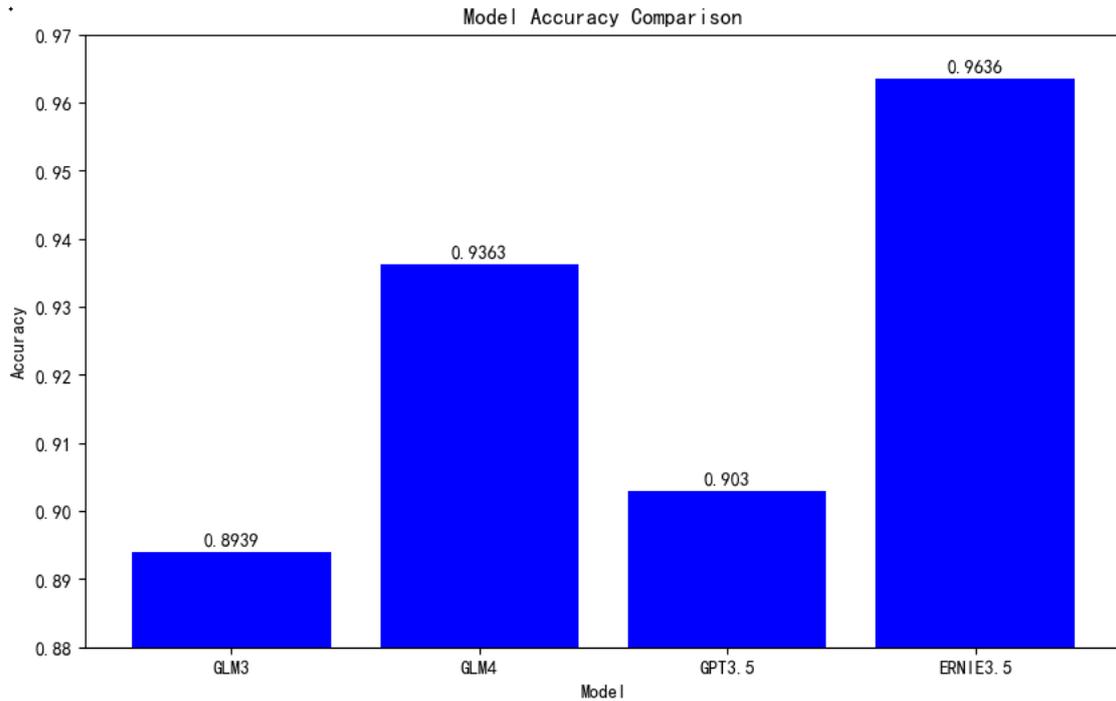

Figure 1. Comparison of the accuracy of different large language models in natural language instruction parsing tasks.

Based on natural language corpora for robotic task execution, this study screened and normalized instruction text to avoid significant duplication of semantics and content, while retaining complex expressions that reflect cross-domain interactions. This ensured that the data covered real-world scenarios. In terms of corpus format design, the study aligned natural language descriptions with task triggers, enabling colloquial expressions to be converted into action sequences that matched environmental coordinates. This served as the basis for evaluating the language model's reasoning and generation capabilities.

To ensure experimental stability and comparability, the prompts clearly defined task constraints and environmental settings, while maintaining a low sampling temperature to reduce random fluctuations. Accuracy was ultimately measured by comparing the consistency of the model-generated action sequences with the target sequences. The experimental results in Figure 1 demonstrate that different language models performed at a high level overall on this task. Some models demonstrated strengths in parsing complex semantics and generating stable sequences. Some updated versions also demonstrated improved comprehension and generation capabilities after iterative optimization. The overall stability of the accuracy demonstrates that, through appropriate prompt design and output constraints, the general model demonstrates good reliability in mapping instruction parsing to execution logic.

4. Dialogue-Based Autonomous Navigation Task Generation

In this study, researchers aim to explore how to enable service robots to autonomously identify tasks and generate executable navigation paths in complex multi-person conversational environments. This allows robots to understand potential task requirements from group conversations and complete tasks such as item delivery, document handover, and cross-regional collaboration without explicit human instructions. In real-world scenarios, robots face multiple challenges, including ambiguous language, redundant or irrelevant conversational interference, varying task priorities, and complex spatial layouts. These factors can significantly impact the accuracy and efficiency of task planning. Therefore, the system must closely integrate natural language understanding with spatial location information. By conducting layer-by-layer analysis of multi-round dialogue content at the semantic level and conducting a comprehensive assessment in combination with the spatial relationships presented by the environmental topological structure, robots can gradually extract reasonable and executable action goals in dynamic interaction and generate logically tight and continuous task sequences on this basis. To overcome the transformation bottleneck between natural language and specific actions, this study constructs a two-stage generation framework centered on chain reasoning, relying on the advantages of large language models in semantic understanding and logical deduction, and integrating the environmental information carried by two-dimensional semantic maps, thereby achieving the goal of effectively mapping natural language into specific action sequences.

In the first stage of the framework, the system guides the large language model to conduct detailed semantic analysis of group conversations by introducing prompt words and context examples, transforming unstructured natural language into clear and logically rigorous task planning, thereby ensuring that the robot can accurately identify item categories, target locations, and execution sequences related to the task. Integrate the task planning generated in the previous stage with the coordinate information and distance relationship in the environment to construct an optimal navigation path that can be directly executed, enabling the robot to complete tasks in an optimized sequence in an environment where multiple tasks are intertwined and multiple agents are running in parallel. During the execution process, robots dynamically handle spatial constraints and interaction requirements, thereby maintaining the stability and efficiency of the overall operation, enabling them to independently complete item transportation and achieve cross-subject collaboration in complex office environments.

To verify the effectiveness of this autonomous navigation task generation method, this study specially designed a simulated dialogue environment based on office scenarios and combined the generation potential of large language models with small sample guidance technology in the experiment to construct a set of high-quality test dialogue data. These dialogues cover a variety of office task types, including item delivery, borrowing and returning operations, and cross-space collaboration. Each piece of data has been strictly manually screened to ensure that the language expression has clear semantic readability, the task logic has reasonable hierarchy, and the context presentation is as close as possible to the real office environment. In the process of dialogue design in this study, the language styles and communication habits of different participants were deliberately introduced, enabling the robot to accurately capture the core task information and generate feasible action plans based on it, even when facing multi-round interactions with complex semantics and a lot of redundancy. The research gradually guides the model to generate dialogue topics highly relevant to specific scenarios and builds multi-round interactive communication processes based on these topics. This not only demonstrates the diversity of task requirements but also truly presents the environmental constraints and interaction requirements that robots face when navigating and transporting items among multiple locations, providing more realistic experimental

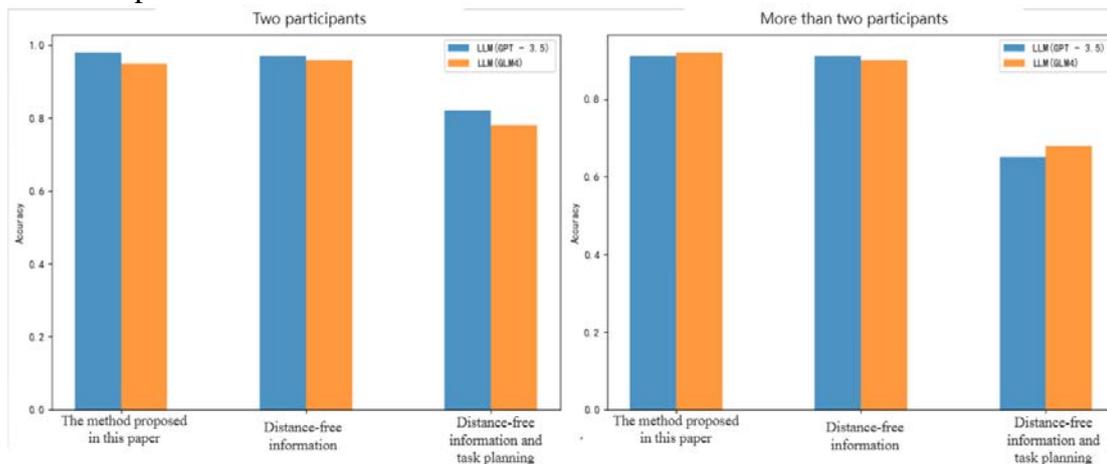conditions for the performance verification of the model.

Figure 2: Comparison of the accuracy of different methods in generating autonomous navigation tasks based on multiple rounds of dialogue.

In this study, when experimentally verifying the generated data, the accuracy of the proposed two-step thought chain method in generating navigation sequences in various scenarios was systematically evaluated through comparative experiments and ablation experiments. The research results of this method show that it can significantly enhance the robot's ability to generate tasks in multi-participant dialogues. Its performance is also far superior to methods that rely on template mechanisms or randomly select strategies in terms of the reliability and stability of task execution, thereby providing more robust and efficient technical support for task generation in complex dialogue interactions. The results also confirm the importance of the task planning step for generation accuracy (see Figure 2). The experimental results show that the robot can combine conversation content, task planning, and environmental coordinates to generate logically sound navigation sequences. Even in the face of complex multi-turn conversations and potential task interference, it can still efficiently plan paths and complete tasks. This provides theoretical and methodological support for future expansion to intelligent task scheduling in larger-scale, multimodal, and dynamic office environments.

5. System Implementation and Verification of the Multi-Agent Reasoning Framework PPDR4X

5.1 Working Mechanism of the PPDR4X Framework and Agent Collaboration

This study abstracts the office environment as a spatial collection composed of multiple independent locations, each with a unique identifier and several human members arranged in the environment. Each member is located in a specific position and holds a unique set of personal items. This design enables intelligent assistants to accurately identify items and their spatial relationships when performing tasks. When a member requests a task, the intelligent assistant must coordinate and execute a series of actions based on a comprehensive assessment of the overall environmental status, the member's location, and the ownership relationship of the items. These actions include going to public facilities to complete service operations such as fetching or picking up meals, while passing or receiving items among different members and ensuring that the task progress is synchronized and tracked by sending information to relevant members, thereby ensuring that cross-location multi-item tasks are completed in an efficient and logically reasonable sequence and

maintaining the feasibility and consistency of the overall operation. This study designed a multi-agent active reasoning framework PPDR4X driven by large models for the efficient management of complex tasks. This framework consists of a perception agent, a planning agent, a decision-making agent and a reflection agent. Each agent relies on a unified large-scale language model for cognitive reasoning and generates targeted task actions through carefully designed prompt words. The shared storage unit in the framework is responsible for recording the long-term environmental status, short-term task information, user instructions, and dialogue content, enabling each agent to fully understand the task context and flexibly respond to dynamic environmental changes. The perception agent generates fine-grained descriptions of the local environment and tasks by analyzing the storage units, providing a basis for the planning agent to formulate high-level action plans. The planning agent converts these descriptions into specific and executable decision instructions, while the decision agent performs virtual operations or dispatses robots to complete physical tasks according to the high-level plan, and at the same time follows the logical constraints of the tasks and the operation sequence to ensure the rationality of the actions. After the task execution is completed, the reflective agent assesses the actual results, updates the incremental information to the storage unit, and generates feedback judgments to optimize the subsequent planning and decision-making processes, thereby forming a complete closed-loop task management mechanism to achieve efficient autonomous operation and multi-agent collaboration of intelligent assistants in complex office environments. This enables the intelligent assistant to maintain flexibility, adaptability, and efficiency in complex task scenarios involving multiple participants and objects, while effectively reducing the risk of misoperation and improving the accuracy and efficiency of task completion.
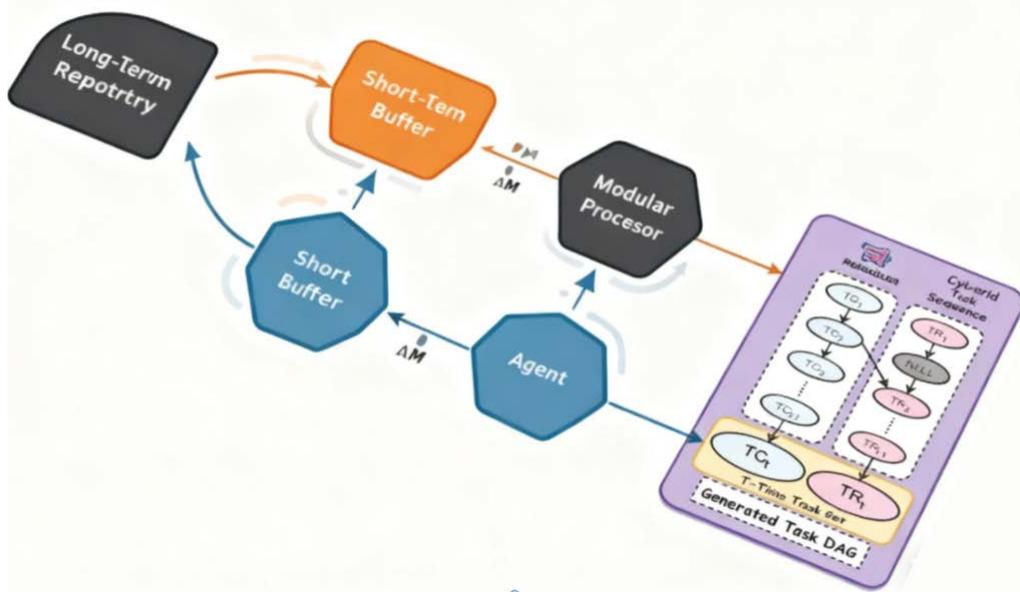

Figure 3 PPDR4X Multi-Agent Active Reasoning Framework

In this study, a simulated office environment based on a semantic map was constructed, encompassing over twenty independent locations, including workstations and public facilities, to fully validate the intelligent assistant's comprehensive capabilities in multi-task, multi-role, and multi-location environments. Furthermore, a natural language instruction dataset highly aligned with the experimental scenario was compiled based on a survey of hundreds of user behaviors and needs. This dataset includes static basic instructions and instruction variants generated due to changes in personnel status, along with executable labels. This allows the system to automatically determine that tasks are unexecutable when key personnel are absent or resources are unavailable,

ensuring that instruction execution is consistent with real-world conditions. Based on this, the research team designed comparative experiments, testing the PPDR4X framework against existing baseline methods under the same large-scale language model conditions to evaluate their performance in processing complex instruction sequences, cross-task operations, and dynamic environmental changes. Experimental results (Figure 4) show that PPDR4X significantly outperforms other methods across key metrics, including success rate, task completion rate, action redundancy, and both virtual and real-world task accuracy. It maintains high completion efficiency and reduces action redundancy in highly complex tasks. Furthermore, through multi-agent collaboration, it effectively integrates long-term and short-term memory information, enabling reliable decision-making and task optimization in dynamic environments.
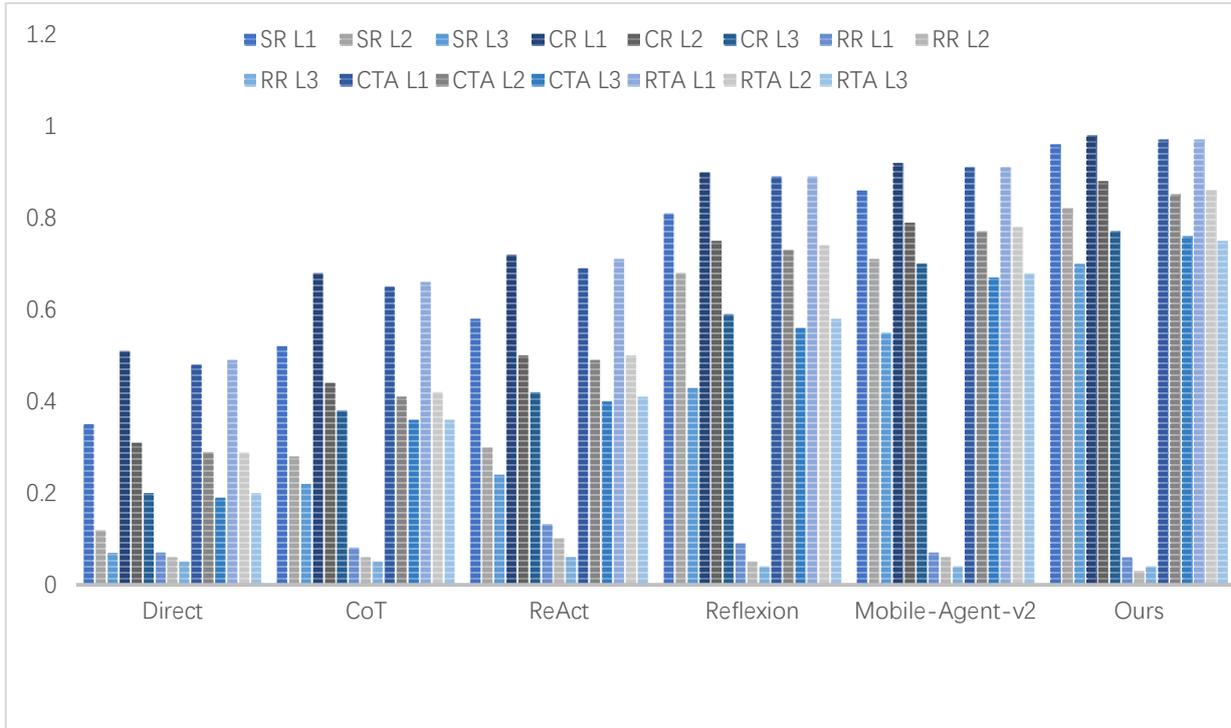

Figure 4 Performance comparison of the PPDR4X framework and baseline methods across multiple metrics.

Ablation experiments further reveal the core role of each agent in the overall framework. When the perception agent is removed, the success and completion rates of high-complexity tasks decrease significantly, demonstrating its irreplaceable role in environmental perception and information integration. When the planning agent is missing, the network and real-world task accuracy of medium-complexity tasks decrease significantly, demonstrating the key role of high-level planning in guiding action selection and responding to dynamic environmental changes. When the reflection agent is removed, the overall task success rate decreases significantly, indicating that it helps the system identify potential errors, correct biases, and enhance its ability to handle uncertainty in multi-participant collaborative tasks. Comprehensive experimental results demonstrate that the PPDR4X framework can effectively integrate virtual and real-world task information in complex environments, achieving efficient, accurate, and flexible intelligent decision-making, fully demonstrating the significant advantages of the multi-agent active collaboration architecture in task execution efficiency, accuracy, and environmental adaptability.

5.2 Integrated Experimental Platform Construction and Multi-Environment Performance Evaluation

This study constructed a highly integrated experimental platform to comprehensively validate the operational effectiveness of a robotic natural language intelligent decision-making framework combining a large language model, thought chain reasoning, and multi-agent collaboration in complex real-world scenarios. The platform dynamically displays robot states, motion trajectories, action summaries, and the reasoning steps of the large language model. It also records human-machine interaction information for in-depth analysis, providing traceable data support for system performance and interaction logic. The platform frontend utilizes modern web technologies to implement a real-time visualization interface and periodically retrieves data updates from the backend database. Caching and trajectory sparse sampling strategies are employed to rationally allocate memory and computing resources, ensuring continuous and stable operation in high-throughput environments. The backend standardizes and encapsulates task execution information and robot states and stores them in a unified format. This enables the frontend to efficiently access and display the multidimensional data generated during complex task execution, ensuring the integrity and consistency of data generation, transmission, and presentation. In the human-computer interaction module, the system assigns a unique social media account to each robot, enabling it to receive and interpret natural language commands from users. All interaction records are stored in a database for subsequent analysis and research. The front-end interface displays user identity, command content, task associations, and timestamps in real time, clearly reflecting the robot's entire process of parsing, understanding, and executing commands. Participants can also directly issue commands or simulate operations through the front-end to verify the system's understanding and response efficiency in continuous conversation and real-time task scenarios, providing intuitive support for the framework's stability and interactivity in practical applications. In this study, two types of mobile robots were tested in the physical robot experiment. The first type of robot is equipped with autonomous navigation and storage functions. It combines depth sensors, industrial control computing units, and multi-sensor mobile chassis, and is capable of independently completing tasks such as environmental mapping, path planning, obstacle avoidance, and intelligent navigation. The second type of robot is equipped with a six-degree-of-freedom mechanical arm, which can precisely grasp and transport various objects during movement. The system has established an advanced function library for the robot, encapsulating common actions into directly callable interfaces, enabling large language models to focus on high-level decision-making without dealing with low-level navigation and action operations, thereby significantly enhancing the framework's fault tolerance and execution stability in complex task environments. A series of experiments conducted in real scenarios have shown that this framework demonstrates significant advantages in task allocation, navigation, and multi-agent collaboration. The dynamic task allocation experiment shows that the framework can intelligently schedule tasks based on the correlation between the robot status and task requirements, thereby effectively shortening the average completion time, which is superior to the random allocation mode and the single robot execution mode. The autonomous navigation experiment shows that the robot can complete multi-point movement tasks under the guidance of continuous dialogue and adjust the task objective in real time through the finite state machine mechanism, thereby improving the coherence of actions and the overall execution efficiency. The multi-agent active reasoning experiment further verified that the robot can actively capture collaborative opportunities while passively responding to instructions, and respond to environmental changes and task diversity by scheduling other robots or seeking human assistance, thereby achieving efficient completion of complex tasks. Extended experiments also demonstrate the framework's excellent generalization and scalability in

heterogeneous robot groups and multimodal perception, making it robust across diverse task types and real-world scenarios. This demonstrates the practical application value of natural language intelligent decision-making systems in robot collaboration.

6. Conclusions and Outlook

This study systematically explored the ability of service robots to achieve intelligent decision-making through natural language in complex and dynamic environments. A multi-agent collaborative framework based on a large language model was proposed. This framework seamlessly integrates dynamic task allocation, autonomous navigation task generation, and proactive intelligent assistants, enabling robots to achieve efficient decision-making in parsing user commands, perceiving environmental states, and collaborating with multiple agents. Experimental results show that the robots can extract implicit task information from continuous conversations, plan appropriate paths based on integrated environmental data, and automatically adjust existing decisions in the face of unexpected changes, significantly improving task completion efficiency and system stability. Although the framework demonstrates a high level of intelligence in task execution, it still faces challenges when handling long-duration tasks, including limited contextual information, potential loss of critical data due to multi-tasking, and insufficient multimodal perception. Therefore, future research should further integrate multi-source information, such as vision and touch, with the large language model to optimize memory information management and task relevance analysis. This will improve the robot's understanding, decision-making accuracy, and execution efficiency in complex and dynamic scenarios. Furthermore, it should enhance human-robot interaction capabilities, enabling the robot to more accurately understand user intent and proactively generate action plans, enabling efficient collaboration with humans.

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