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Hybrid Human/Robot Team Establishment using E-CARGO and Role-Based Collaboration

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***Abstract*— This paper clarifies the requirements of a hybrid team including both humans and robots, then analyzes and confirms that the Role-Based Collaboration (RBC) methodology and the Environments - Classes, Agents, Roles, Groups, and Objects (E-CARGO) model can meet the requirement and assist in establishing such teams. Following this assessment, this paper proposes to use E-CARGO/RBC in building human/robot teams. Simulations and experiments are used to verify the proposed method.**

Keywords—RBC, E-CARGO, Hybrid Human/Robot Team.

I. INTRODUCTION

As robotics advances, robots become more intelligent and skillful. In 2023, Boston Dynamics declared their new autonomous robots that can be highly intelligent in response to environmental changes [https://bostondynamics.com/]. These advanced robotic systems are transforming the way we envision team dynamics in crisis situations. It is a determined and accomplishable task for us to establish a team including humans and intelligent robots for future missions, such as earthquake rescue, hurricane recovery, and other crisis responses.

Due to the diverse array of critical elements in these applications, achieving collaboration and consensus among agents within the robot team can rapidly evolve into a complex challenge. This becomes exceedingly difficult when facing a range of hardware options, battery longevity, sizes, uncertainties, trust considerations, and robot functionalities in a dynamic environment influenced by numerous dependent or interconnected factors [2]. As the robots operate within this dynamic environment, they must efficiently adapt their context-sensitive behaviors to align with the environment's state, a process tightly linked to the agent's type and mutual trust. The cooperation between self-governing robots and humans leads to the establishment of hybrid human/robot teams, which introduce new prerequisites, novel challenges, and innovative solutions to real-world issues. When many dissimilar and autonomous robots are assembled into a team to achieve a mission, the accurate assignment of tasks to each robot, alongside the assessment of their performance before action and the subsequent optimization of process roles, is critical. Attaining optimal task assignments and optimizing process roles can prevent failures and enhance operational efficiency as the robots carry out their mission.

E-CARGO (Environments - Classes, Agents, Roles, Groups, and Objects) [20-22, 28, 30-42] is a valuable tool for scientists and engineers seeking to formalize complex, abstract problems. This model has undergone thorough verification by successfully formalizing and solving numerous non-trivial problems within complex systems requiring collaborative efforts. An illustrative example of its effectiveness is evident in Group Role Assignment (GRA). E-CARGO empowers the application of the Role-Based Collaboration (RBC) method, enabling the resolution of a wide array of real-world challenges, even in dynamic and adaptive contexts. E-CARGO/RBC emerges as a solution that aligns with the prerequisites for establishing hybrid human/robot teams, ushering in a new era of collaborative problem-solving.

In this paper, we examine the requirement of hybrid human/robot teams, describe RBC and its model E-CARGO, clarify how E-CARGO/RBC meets the requirements of a hybrid team, discuss related team design issues, and present initial simulations and experiments.

II. SCENARIO AND REQUIREMENTS OF ROBOT TEAM

Ann, the CEO of Company X, which is responsible to provide services for crisis responses. Someday, a hurricane happens at City Y and leads to a disaster of human life and community resources. Ann immediately contacts the government and expresses her interest and ability to help in the disaster recovery, and then signs a contract valued at millions of dollars. She asks Bob, the CTO of company X, to establish a team including 50 robots and 10 people to accomplish these tasks regulated by the contract. Considering the catastrophic situation, Bob quickly sets up the fundamental requirements of the team [25] (Table I) for him to manage and accomplish the mission. These functional requirements should be carefully defined and tailored to the specific application and objectives of the robot team to ensure its effectiveness and successful operation. The following sections describe what we can do to help Bob accomplish his tasks.

TABLE I. THE REQUIREMENTS OF A HYBRID TEAM

Items	Meanings
Communication [25, 34]	Humans and robots should be able to communicate with each other to share information and coordinate their actions effectively.
Consensual decision making [25]	A team needs to take action in a consistent way. It refers to a process in which individuals or groups work together to reach agreements or make choices that are acceptable to all parties involved. Such decision making may be local

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	or global in nature, but every step of decision making should be in consensus.
Roles [21-22, 25, 28, 30-42]	To enable teamwork, the team must set out a clearly defined set of required responsibilities and rights (roles). Each member should be assigned specific roles that leverage individuals' preferences, abilities, skills, and appropriateness.
Sensing and Perception [4, 5, 9, 16]	Team members should be equipped with sensors such as cameras, LiDAR, or proximity sensors to perceive their surroundings. They should be able to detect and recognize objects, people, or specific features in their environment.
Goals [25]	Each collaboration should have a result, i.e., a product, a state, an achievement, or an accomplishment, which represents the goal of the team. Such a goal should be shared by all the members. Optimization of resource utilization is one such goals, such as sensor data processing, communication bandwidth, and computational resources.
Leadership [8, 11, 25]	A leader performs a special role within a community. Leadership requires a strong self-driven personality that can foster a sense of trust and loyalty. The player of the role leader in the proposed hybrid team should be human.
Management [1, 25, 34]	The management of team components and human-robot interactions contributes to the high-performance operation of the hybrid team.
Sharing [25, 34]	Resources, information, and assessments are among the many things that can be shared. This activity requires effective administration to avoid or minimize conflict. Robots should share sensory data and fuse information from multiple sources to enhance their perception and decision-making abilities. They should have mechanisms for aggregating and analyzing data collectively.
Task Execution [25, 34, 42]	Every task should be executed by a member. Team members should be capable of performing designated tasks, which may involve manipulation, assembly, or transportation of objects. They should be able to synchronize their actions to achieve a common goal.
Trust [2, 23, 25, 26]	Trust represents a specific degree of confidence placed in an individual both prior to and during the execution of actions. It encompasses attributes of both a quality and a relational nature. Trust incorporates elements such as credibility, quality, reputation, reliability, validity, utility, robustness, and the rate of false alarms. Trust is a dynamic concept, capable of being established, developed, and undermined. It can manifest as enduring, stable, temporary, or evolving over time.
Human-Robot Interaction [4, 5, 9, 16]	If robots interact with humans, they should possess natural language processing or gesture recognition capabilities to understand and respond to human commands or queries. User-friendly interfaces may be necessary.
Adaptability [28, 30, 38, 39]	The team and robots should have the ability to adapt to changing conditions and learn from their experiences to improve performance over time. The team should be scalable to accommodate changes in the number of robots or humans, allowing for easy expansion or reduction as needed. Redundancy is also required.
Role players [20-22, 28, 30-42]	Participants are visible components that perform tasks or roles. They are essential and necessary for collaboration. Energy Management should be accomplished for both humans and robots. The team should efficiently manage their energy resources to maximize operational uptime. Charging or refueling stations should be considered if applicable. Robots should be able to sense autonomously within their environment, avoiding obstacles and reaching specified destinations. They should possess localization capabilities to determine their position accurately.

III. E-CARGO AND ROLE-BASED COLLABORATION

The E-CARGO/RBC model [20-22, 28, 30-42] meets the requirements of hybrid teams by defining essential components and providing the required mechanisms of a complex system. E-CARGO is a general composition model to express the components of a complex system, and RBC forms a process model for a complex to operate. E-CARGO/RBC establishes a methodology involving a set of well-defined concepts, models, and algorithms to facilitate collaboration analysis, design and implementation. RBC drives the development of E-CARGO. E-CARGO clarifies more details in collaboration.

Using E-CARGO/RBC [54, 60, 68], a complex system including a hybrid human/robot team, is expressed as a 9-tuple $\Sigma ::= <\mathcal{C}, \mathcal{O}, \mathcal{A}, \mathcal{M}, \mathcal{R}, \mathcal{E}, \mathcal{G}, s_0, \mathcal{H}>$, where each upper case symbol expresses a finite set to express a component of a complex sytem, and s_0 means the initial state of the system. A system starts from s_0 and progresses according to the RBC flowchart (Fig. 1), i.e., including the process of role(s) ($\mathcal{R}$) negotiation, agent(s) ($\mathcal{A}$) evaluation, and role assignment, playing, and transfer. The RBC chart helps organize groups ($\mathcal{G}$) work well on their environments ($\mathcal{E}$), which is formed by classes ($\mathcal{C}$) of objects ($\mathcal{O}$), and supports the formal analysis, design, implementation, development, and maintenance of a system and a team.

TABLE II THE MANAGEMENT LEVEL OF A TEAM

Symbol	Meaning	Level	Explanation
m [34, 42]	The number of agents	1	The manager only knows the # of agents in the team.
n [34, 42]	The number of roles	2	The manager knows how many roles are needed.
L [34, 42]	A role requirement n-vector	3	The manager knows the # agents needed for each role.
Q [34, 42]	A qualification $m\times n$ matrix	4	The manager knows how well each agent works on each role.
T [34, 42]	The assignment $m\times n$ matrix	5	The manager knows the optimized assignments.
W [34, 42]	The role weight n-vector	6	The manager has ideas about the importance of roles.
A^c [32, 34]	The agent conflict $m\times m$ matrix	7	The manager takes care of potential agent conflicts.
A^{cc} [36]	The agent conflict/cooperation $m\times m$ matrix	8	The manager considers both conflicts/cooperation between agents.
C^f [41]	The conflict / cooperation $(m\times n)\times(m\times n)$ matrix	9	The manager considers conflicts/cooperations between <agent, role>s.
P_a [22]	The manager's preference m- vector	10	The manager uses his/her preferences in assignment.
θ_a [1-3]	Process role Stream of states	11	The process role entails modeling the agents' contextual behavior using a stochastic process.
τ_a [1-3]	Trust A vector with length of m-1	12	A trust vector τ_a represents trust levels from agent "a" to all other agents. The trust density lies between 0 and 1.

More specifically, we use the symbols in Table II to help specify a complex system. Table II also informs the management level of a team if the manager is aware of the meanings and facts of the corresponding symbols. In addition, we use symbols i and j to express the indexes of agents and roles, respectively. Therefore, $Q[i, j] \in [0,1]$ expresses the qualification of agent i on role j, and $T[i, j] \in$

$\{0,1\}$ expresses whether agent i is assigned to role j, i.e., 1 means assigned and 0 no.

Role negotiation produces a specification of how many roles are required, how each role is specified, how many agents are required for each role, and how many agents for each role can accommodate. Role negotiation can be divided into more detailed steps including resource integration, agent categorization, role awareness, and role specification.

Based on the outputs of the role negotiation process, agent evaluation produces an $m \times n$ matrix Q, each of the elements informs the qualification value of an agent on a role.

With the support of agent evaluation, optimized role assignment can be accomplished by GRA, which can be defined as follows:

Given agent set $\mathcal{A}$, role set $\mathcal{R}$, Q, and L, the GRA problem [33, 41] is to obtain

$$max\ \sigma = \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} Q[i,j] \times T[i,j]$$

subject to

$$T[i,j] \in \{0,1\}\ (0 \le i < m, 0 \le j < n), \tag{1}$$

$$\sum_{i=0}^{m-1} T[i,j] = L[j]\ (0 \le j < n), \tag{2}$$

$$\sum_{j=0}^{n-1} T[i,j] \le 1\ (0 \le i < m), \tag{3}$$

where expression (1) shows the 0-1constraint, (2) informs that enough agents are required for each role, and (3) means that an agent can be idle and assigned to one role at a time.

We have presented a pragmatic resolution to GRA [42] by customizing it to the Kuhn-Munkres algorithm. Our continuous endeavors have resulted in the development of models and solutions for a multitude of intricate scenarios. Leveraging the robust optimization platform, IBM ILOG CPLEX Optimization Package (CPLEX) [https://www.ibm.com/products/ilog-cplex-optimization-studio], we can tackle more intricate problem sets, such as Group Role Assignment with Constraints (GRA+) [36] and Group Role Assignment with Multiple Objectives (GRA++) [31, 37], within acceptable timeframes.

All the GRA+ and GRA++ problems are based on the structure of GRA by adding more math structures and constraints [30, 35, 36]. GRA, including GRA+ and GRA++, establishes the foundation for building a role engine.

We can match the components and principles of E-CARGO/RBC to the team's requirements as follows, where the *italic* terms are formally defined in E-CARGO/RBC [30-42], and the underlined terms are the requirements: 1) E-CARGO/RBC uses *roles* [30-42] to provide the direct requirement of roles. Roles represent positions, tasks, rights, duties, and responsibilities, confine the accessibility of objects, and facilitate interactions and communications among humans, robots, and between humans and robots. 2) E-CARGO/RBC uses role negotiation, *agent evaluation* [34] , *GRA* [34, 42] and process role optimization [1] to represent the processes of decision making and consensus. 3) E-CARGO/RBC uses special *roles* [30-42] and *relations* [34] among roles to express leadership, i.e., assigning the leadership role to a human in a hybrid team and a highly autonomous robot in a pure robot team. 4) E-CARGO/RBC provides substantial symbols and components (*Table II*) to support the management of of a team. 5) E-CARGO/RBC uses *roles* [30-42] and *environments* [30-42] to support sharing, including resource, data, information, and knowledge sharing. 6) E-CARGO/RBC uses *agents* [30-42] to express the autonomous individuals, i.e., the direct requirement role players, in a team, who are capable of optimizing and accomplishing tasks independently, i.e., task execution. 7) E-CARGO/RBC employs *roles* [30-42], role *relationships* [30-42], *process roles* [1-3], and agents, alongside agent evaluation, to portray trust. 7) In E-CARGO/RBC, an *upper role* [34] or a better *evaluation* [35] is the goal of team members. The goal of a group is the maximization of *group performance* [42], which can be tuned and constrained based on special requirements. 8) In E-CARGO/RBC, the *RBC process* [32, 34] inherently reflects the adaptive properties of the team, allowing different kinds of *adaptivity*. 9) Within E-CARGO/RBC, the optimization of process roles involves the utilization of stochastic processes and consensus-based Bayesian inference. This combination is employed to model the contextual behavior of agents and to facilitate trustworthy decision-making [1, 2].

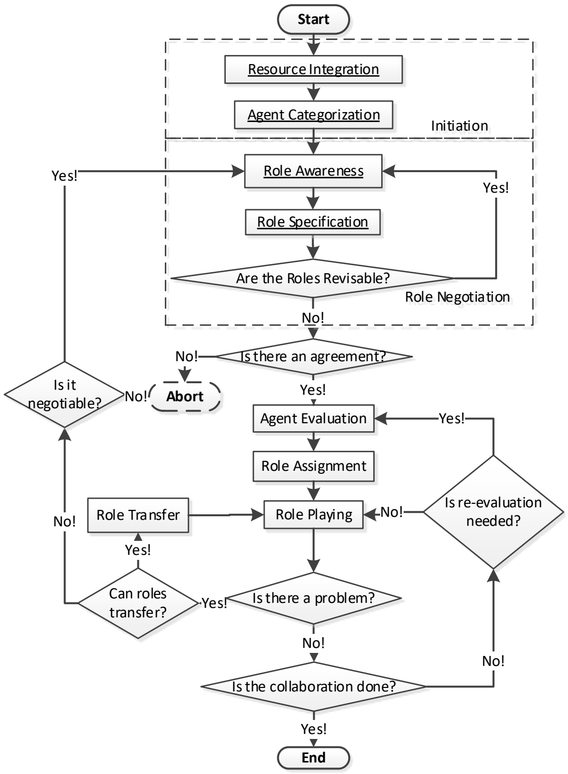


Fig. 1 Revised Process of RBC [32-34].

Beyond the above, E-CARGO/RBC uses 1) *classes* of *objects* to express passive and accessible entities in the real-world; 2) *groups* to represent a system, an organization, or a community, which is the major target of management. The goal of E-CARGO/RBC is to make a group into a team, i.e., a well-organized group; 3) *environments* and *messages* establish connections, facilitate interactions, resolve conflicts, and enable coordination, cooperation, and collaboration among members; 4) *group states* [28, 30, 39], the timely values of the system components, represent the dynamics of an adaptive system that responds to changes; and 5) *human users* to express human agents. 6) Utilizing a stochastic process to model the process role enables agents' behavior optimization in dynamic environments [1, 2].

Also, we assume the robots in a hybrid team possess the functions of sensing and perception. This assumption is acceptable according to the current robotics technology.

IV. DESIGN ISSUES

The RBC process (Fig. 1) [32-34] follows an iterative and adaptable approach, aligning well with the requisites of a hybrid team consisting of both humans and robots. This process also integrates hybrid management and control methodologies[1-3]. Specifically, it employs centralized decision-making for achieving optimal team performance based on historical evaluation values. Meanwhile, task execution is decentralized, involving both robots and humans who can make localized decisions in response to their immediate circumstances and surroundings. Centralized initialization and training contribute to optimization, as the central computer possesses comprehensive team information, incorporating data from individual robots and humans. Simultaneously, local decision-making by individuals can influence subsequent central decisions. If an agent determines that the situation doesn't permit an immediate decision, they can relay this to the central management, potentially triggering new central decision-making.

The RBC process also provides possibilities to take advantage of special robots and humans due to the dynamic changes of the environment including the ground states and weather. For example, if it is too windy, then UAVs are not good choices for executing transportation tasks; or if the road conditions become bad, trucks and cars are not good agents for performing transportation.

The central management is implemented as a role engine [38, 42], which incorporates the E-CARGO model and related algorithms including GRA+ and GRA++, dynamically matchmakes roles and agents, makes the whole team be in a balanced and steady state, and forms a sustainable system. The sustainability of the team comes from the feedback mechanisms of the RBC process.

As for role assignments, the central management, or the role engine dynamically revises roles required in the team mission, evaluates all the agents' current performance at playing different roles, and assigns appropriate roles to agents in time. Such assigned roles are normally interface roles, which specify more on what to do. More detailed and concrete process specifications on how to do will be determined by the assigned agents. The roles in assignment are depicted through the contextual behavior of the agent and called *interface roles*. *A process role* will be described by a stochastic process of an agent. Furthermore, a trust vector is in place to showcase the extent of trust between the specific agent and other agents.

After using GRA+ or GRA++ to assign roles to each agent, the agents will use their process roles, which specify more about how to do, to map the assigned interface roles to accomplish the designated tasks.

In RBC, the group performance is a simple sum of the selected agent's performance value on specific roles. The goal is to optimize the role assignment using GRA [41], GRA+ [35], and GRA++ [30, 36]. As an abstract indicator, group performance and evaluations match numerous factors that express robots' and humans' properties.

To provide optimized team performance, role negotiation and agent evaluation are initiated dynamically based on the requirements of the system including feedback communicated from the individual role players, i.e., the agents in cooperation.

In [1], a hybrid control role engine is implemented where the central unit handles role negotiation and GRA, while decentralized role playing utilizes a consensus-based Bayesian inference to model agents' contextual behavior and optimization. This same approach is subsequently employed for fault-resilient systems and trust management in [2-3].

V. SIMULATIONS AND EXPERIMENTS

We tested our approach in a situation including four robots going from arbitrary initial positions to unlabeled destinations (Fig. 2). In such a simulation, we established a hybrid team including the role engine operator and the robots.

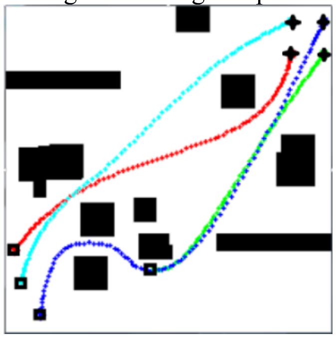


Fig. 2 The initial process roles were obtained through GRA for a scenario involving four agents navigating to unlabeled star points.[1].

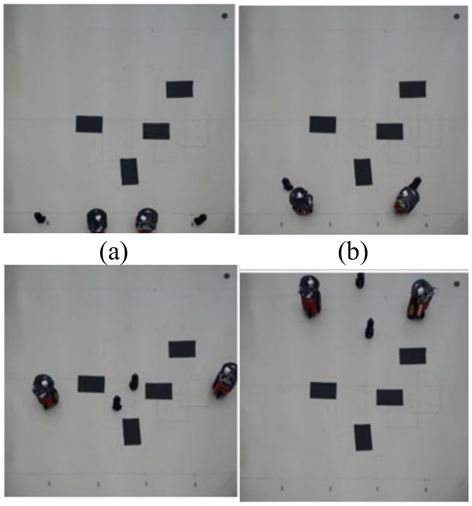
At the outset, the mission is defined, and the central computer is informed about the final locations. Four distinct roles (corresponding to destination points) are specified. For our simulation, we consider four robots as agents and evaluate the cost associated with each process role. We establish a Q matrix and use GRA [41] to allocate roles among the 4 agents.

In this simulation, we amalgamate interface roles and process roles. Each process role is defined as an optimized trajectory to the destination location, employing the Gaussian process [1-3]. We assign these optimized trajectories to the respective process roles. Each agent (robot) then follows its assigned role, which, in this case, is the pre-defined trajectory. Throughout the task, every robot autonomously avoids local collisions through decentralized decision-making, all while maintaining its trajectory toward the destination location.

We also verify that the approach is effective in a real-world setting. The experiment is designed to command four robots to move and establish a diamond formation in a cluttered environment with static obstacles. As in the simulation, the destinations are not initially assigned to the robots. Two different-sized pairs of robots are used: the Pioneer 3DX mobile measuring 33cm^3 and the TurtleBot3 Burger measuring 16cm^3 as shown in Fig. 3. The user of the centralized role engine is considered as a member of the hybrid team.

(a)Pioneer 3DX mobile robot (b) TurtleBot3 Burger

Fig. 3 The robot models used in the practical experiment (Fig. 4) [1].



(a) (b)

(c) (d)

Fig. 4 (A) Robots start. (B) Turtlebots move in front of the Pioneers, while avoiding collisions, to take efficient paths through the obstacles as in (C). (D) Robots reach the desired formation.

This experiment was executed using Robot Operating System (ROS), initially on the Gazebo simulation platform [https://gazebosim.org/home], and then conducted in a real-world environment. It was conducted in the Advanced Control and Mechatronics (ACM) lab at Dalhousie University.

In the experiment (Fig. 4), the robots are assigned the roles and process roles and play the roles, i.e., the centrally calculated trajectories. The results show that the E-CARGO/RBC method can assign suitable roles for different robots to successfully complete a formation task in a cluttered environment. In this experiment, agents operate autonomously while maintaining consensus with the central unit. Additionally, a human assumes a supervisory role, overseeing high-level tasks, monitoring task progress, and intervening when failures occur [1, 3].

VI. RELATED WORK

Not much research has been done from the perspective of hybrid human/robot teams due to the lack of models and appropriate methodologies. However, there are many research activities in teamwork [4-10, 12-15, 17-19, 24, 27, 29], and human-robot collaboration (HRC) [4, 5, 9, 16].

In teamwork research, the performance of teams is a well-accepted research topic in psychology [4-8] and remains a challenge for organizers and managers hitherto. The term "team performance" is taken for granted by many investigations without clear definitions and specifications. Team performance is assumed in most of the literature to refer to the quality of a team to accomplish the designated task [6]. Pursuing optimal expected team performance prior to execution is not a trivial aim [17], since it is difficult to know the performance of a team before the teamwork is completed. Efficiency and effectiveness are widely used metrics for inspecting the performance of a team [18, 19]. Such metrics need investigators to design quantitative methods to specify and calculate team performance. Therefore, developing methodologies to quantify team performance is valuable and rewarding. Providing methods to model team performance is also required. In [7], a methodology for managing robot teams is proposed to manage robots to execute team tasks. Their work dynamically changes the robots' roles to accommodate cooperation requirements during the progress of the robot team.

In HRC, Angleraud et al. [4] propose a system architecture to support robot collaboration, which enables a human to coordinate when and which robot actions are executed. Baratta et al. [5] surveyed the HRC work from the perspective of industry 4.0. De Simone et al. [9] identify how the operator's work is affected by HRC by a scoping review, analyze the collaboration between humans and robots, and present critical factors influencing the performance of collaborative operators. Inkulu et al. [16] describe various HRC techniques and their applicability to various manufacturing methods, along with key challenges.

From the above related work, we may understand the originality and the significance of this paper.

VII. CONCLUSIONS

This paper presents a novel method to establish a well-organized hybrid team including both humans and robots. This approach applies the well-designed E-CARGO/RBC model and uses a role engine to be the central management for the team, taking advantages of both distributed task executions and globally optimized team decision making. Such a method can keep a team perform well through adaptive processes.

The proposed method is verified initially by simulations and experiments by testing the centralized role assignment and distributed role playing. More simulations and experiments are required in the aspects of adaptive processes including dynamic role assignment.

Future work includes implementing a real hybrid team including dynamic environment changes, which will validate the proposed method with more strong and solid evidence.

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