Human-Robot Teaming: Concepts and Components for Design

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Abstract In the past, robots were used primarily as "tools for humans." As robotics technology has advanced, however, robots have increasingly become capable of assisting humans as partners, or peers, working together to accomplish joint work. This new relationship creates a new host of interdependencies and teamwork questions that need to be addressed in order for human-robot teams to be effective. In this paper, we define communication, coordination, and collaboration as the cornerstones for human-robot teamwork. We then describe the components of teaming, including agent abilities, taskwork, metrics, and peer-to-peer interactions. Our purpose is to enable system designers to understand the factors that influence teamwork and how to structure human-robot teams to facilitate effective teaming.

1 Introduction

The role of robots in human-robot (HR) teams has begun to shift from an extension tool to a peer-like teammate that is able to assist with and complete joint tasks [8, 13]. Human-robot teams are groupings of humans and robotic systems who com-

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municate, coordinate and collaborate together to perform a joint activity [8, 14]. The role of robots as teammates in human teams will allow for more collaboration and performance on joint activities. For example, robots in space exploration environments are placed in a variety of applications where humans cannot operate alone and require assistance [2, 13, 14]. Research geared towards studying the effect this newer perspective has on teaming design and approaches in Human-Robot Interaction (HRI) will be beneficial.

As NASA moves toward future deep space missions, taskwork will be given to human-robot teams for mission safety and success [13, 14]. Longer space missions are more dangerous to humans as astronauts must operate autonomously from ground. Astronauts are limited by time and physical constraints and will need to rely on robot systems to assist in joint tasks that require both agents to be involved. To effectively complete joint activities, however, requires an understanding of how interdependencies between team members affect the execution of tasks. Creating and structuring an effective team and assigning work to each agent in the team is imperative to mission success and proper task execution [31].

Developing HRI by focusing on team performance for joint activities is imperative to developing better systems. Systems must evaluate the changing capabilities of each team member and their distinct roles in the team composition. While previous research and surveys of HRI describe different methodologies on developing human-robot systems, there is still a lack of convergence on HR teaming design.

This paper surveys various ways to build and construct HR teams. The goal of this survey is to provide system designers better insight into HR teaming, particularly regarding methods that can be used for HR team design. We first elaborate on the background of teams and prior research in HR teaming. Next, we describe how designers should consider taskwork, agent abilities, design metrics, and dependencies when composing HR teams. Lastly, we discuss open issues in HR teaming that warrant additional research.

2 Motivation

The central concept behind this paper is the concept of a team —interdependent members who share a common goal, have common ground, and trust in between them [13, 14, 15]. Teams are structurally organized include members who have their expertise and background; each member brings their own skills and background to the team. Teamwork is a fluid, context-dependent activity. Teamwork is composed of a variety of factors; the combination and effective of which can greatly affect the structure of teamwork [10]. High-performing teams operate with dynamic skillsets, including anticipation and prediction, to handle more complicated scenarios and workflow [24, 28]. While teamwork might seem to be an obvious detail in HRI design, system's designers must consider a variety of factors that affect the structure of teamwork from team compositions to the resulting dependencies.

Neither HR team design nor effective ways of measuring its success have been well defined in the literature. Prior research in developing human-robot teams has been widely vetted from human factors perspective [30]. Moreover, there has been little to no translation of HR teaming theory into real-world application. To close the gap between theory and practice, system designers need to develop effective teamwork designs, methods, and protocols.

Creating effective HR teams is challenging because robotic capabilities are continually advancing —leading to better physical abilities, cognition, and awareness. Despite these advances, we expect that robots will always have limitations, particularly when faced with anomalies, edge cases, and corner cases. Humanoid robot appearances can disillusion humans as they appear human-like but lack human capabilities [23]. Humans face difficulty in creating mental models of robots and managing their expectations for their robot companion's behavior and performance. Robots struggle to recognize human intent, which causes incorrect or poorly timed responses, as well as slow and jittery interaction. These issues result in an unnatural and inefficient teamwork with high human workload [23, 14]. Future HR teams need to consider robots as trustworthy team members despite their limits.

Given the difficulties of creating human-robot teams, it is clear placing a well-designed robot with a human to complete a task is not enough to ensure good teamwork and task execution. Design for HR teams must understand the context of human-robot relationships and the dependencies that form as they work together [25]. In joint activity, understanding interdependencies between team members will reinforce better human-machine systems design decisions [25]. Future HR teams will need to understand how teammates can communication, coordinate, and collaborate effectively for mission success.

3 The Components of Teamwork

3.1 Communication

Communication is the expression or exchange of information between two (or more) parties [5, 18, 37]. For example, robots requesting help communicate: 1) getting attention, 2) alerting that help is needed, and 3) requesting help [5]. Any robotic cue provides pertinent information about its state and current action. While humanoid robots have a larger breath of communication means, non-humanoid robots are more goal driven and require more planning to take human collaborators into consideration [5]. Even robots that are capable of speech or text (on screen) lose the subtlety, tone, and context of human speech.

Communication can extend between various pairings in teams, between robots through a shared network, or to humans through various means. To do the latter, they require more signal types to be more informative and develop richer intuition. Signals are very limited in content (up to a few bits), but they are capable of conveying awareness, intent, and state. Numerous mechanisms support this by combining redundancy with emphasis through auditory, gaze, gesture, and motion. Signals can involve lights, sounds, haptic feedback, and more depending on the system. Language is highly extensive and conveys a high level of detail, however, whether language is specific or general is dependent on task, domain and other factors [5].

3.2 Coordination

Coordination is the harmonious functioning of the group or ensuring that two or more people or groups can work together properly throughout the mission [12, 37]. It requires integration of activities and responsibilities for resources to be used efficiently [23]. Coordination requires cooperating with foresight and planning to set, organize, and monitor activity. Effective coordination requires 1) Common Ground, where mutual knowledge supports joint activity, 2) Directability, assessing and modifying individual actions within a joint activity, and 3) Intepredictability, being able to predict what others will do [23, 25]. These traits are more measurable and support the goal of teammates that can do work together successfully.

3.3 Collaboration

Collaboration is a joint activity involving two (or more) parties working collectively to achieve a common goal. [23, 25, 9]. Joint work requires multiple members working together to achieve a shared objective and is dependent on communication and coordination. Members share of knowledge, intention, and goals between themselves —like two agents working together to build a bookshelf. Collaborative tasks can be tightly or loosely coupled, as well as planned or spontaneous [20, 40, 23]. In tightly coupled work, each member's actions depends on each other. In loosely coupled work, members engage in complementary actions towards a common goal. The difference between planned and spontaneous work is acutely dependent on the environment, situation, task, and more. In scavenger hunt (a collaborative task), teammates have a common goal (find all items) but do so separately.

4 Considerations for Designing Human-Robot Teams

It is essential to consider a variety of factors to design an effective HR team. These include the pitfalls that HR teams designers should keep in mind pitfalls HR teams can fall into, the task work scope for the team to complete, limitations of and support for team members, metrics for evaluating teams, and how to facilitate effective teamwork. These following sections discuss the importance of these considerations for taskwork, team composition, and structuring teamwork. Fig 1 shows these factors outside the team and between the agents. The context of the mission, the environment the team is in, and the tasks to complete are external factors that impact the design of a team to fully capable of completing the work. Humans and robots have varying abilities, and the depedencies that arise between these agents as team members creates interdependencies within the team. Human-robot teams must have excellent communication, coordination, and collaboration in order to work effectively together amongst these factors of influence.

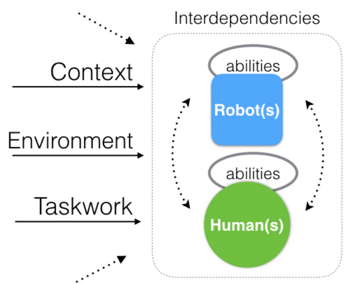

Fig. 1 Factors that are influences on Human-Robot Teaming from external to internal within a team.

4.1 Pitfalls for Human-Robot Teams

A variety of macro and micro factors like the human(s), robot(s), remote users, controls, environments, and task context, affect the relationships between team members and the resulting teamwork. [36].

Barriers of Communication High time delays in communication or even team members' inability to understand each other can cause collapses in teamwork. Barriers are a result of unintuitive or improper modes of communication when processing human attention, predicting actions, and understanding intent from others [35].

Inefficient Collaboration Team members with different goals work divergently result in delays in task completion and poor quality of work. Users who fail to check for qualifying capabilities or lack training and proficiency cause improper handoffs or transfer of control between users [36].

Poor Coordination A mismatch of individual abilities can cause poor cooperation when trying to coordinate activity, especially in cases where team members have gaps in their capabilities or uncomplimentary skills. A poor team composition results in a lack of trust between the members that can be detrimental to the coordination. [31].

Bad Leadership A leader lacking leadership can steer a team into disarray. In imperfect scenarios, an inadequate leader may struggle to redirect the team or adjust the taskwork goals.

Lack of Management Adjacent to bad leadership is poor management, which can cause teams to become confused or lose sight of the work to be done. Managing the team also requires managing the team's environment, continuously planning, and ensuring that the team is on track.

Workload Issues Task demands, temporal demands, and task structure cause workload issues [22]. The complexity of the mission and the consequences of its failure need to be considered while designing HR teams. The task constraints and pressure, task interruptions and ill-defined tasks are setbacks that can confused team members [22].

Forgetting Environmental Factors Visibility, complexity, uncertainty and stressors factor in team interactions with the environment and each other [22]. Failure to consider the context-dependent factors result in teaming that is unprepared to work in its environment.

4.2 Taskwork for Teams

Taskwork is a key component of HR team design consideration as it is the breakdown of work teams need to complete to achieve their goal. Taskwork is also situational and context-dependent; the flow of teamwork and operator workload is dependent on it [22, 40]. Taskwork can determine how teams should be structured and put together; completing it requires varying levels of user performance, fault management, multiple team members, and for some tasks, multitasking. Scheduling and dependencies on other system components also constrain how taskwork can be assigned and managed. The type of taskwork and its criticality are important to review. For example, the individual actions exploring planetary surfaces vary and depend on the density of route waypoints, hazards, and obstructions. Properly valuing taskwork's complexity and fully scoping will lay out the groundwork for designing an HR Team to complete it [40, 22, 25].

4.3 The Structure of Teams

The structure, or composition, of an HR team, helps construct effective teamwork and is determined by the physical makeup of a team, as well as each individual's abilities [39, 40]. Team structure involves finding the proper team size to fit the mission goals and teammates who have complimentary skill sets to coordinate and collaborate effectively. The ratio of humans to robots is also important to consider, be it homogeneous (human-only, robot-only) or heterogeneous (mix of humans and robots) [39]. Team composition shapes interactions that vary based on the ratio from one human, one robot; one human, robot team; one human, multiple robots; human team, one robot; multiple humans, one robot; human team, robot team; human team, multiple robots; and multiple humans, robot team [40].

4.3.1 Agent Abilities and Team Abilities

Each agent's abilities and the overall team capabilities should compliment each other. Robot abilities are based on factors of the work they are given and their capabilities depend on the concept of capacity [25].

> Capacity is the total set of inherent things (e.g., knowledge, skills, abilities, and resources) that an entity requires to competently perform an activity individually. (p.47)

This concept of capacity implies a limit to a robot's capacity –specifically, their ability to extend their capabilities beyond engineered abilities and to possessing a certain level of autonomy or cognition. Autonomy for robots has been previously defined from a variety of perspective, from teleoperation to 'full autonomy'. Desai wrote the resulting interaction between HR teams is dependent on this level of robot autonomy [6]. Goodrich defines autonomy as the measure of neglect a system can take —the more autonomous, the fewer interactions [18, 19, 20]. Brum's sliding scale of autonomy was a large step in the understanding robot autonomy is not simply a single discrete mode, but adjustable depending on circumstances [3]. While there are many varieties of robot autonomy, it is clear that successful HR teams take shifting context-dependent autonomy into consideration for team design[18, 14].

Autonomy is a relative concept and a robot's autonomy should be defined respective to another system's autonomy [25]. One step further is recognizing autonomy is a function of the team's capacity together, not just a robot's cognition agents alone. We frame Team Autonomy to be an HR team's capability to operate as a single unit. HR team designers should understand this parallel concept of autonomy from a robot's shifting autonomy and the overall Team Autonomy.

4.4 Measuring Human-Robot Team Performance

Metrics are central to good design as they describe how to measure team design [32]. Metrics for team performance can be considered qualitative or quantitative, but identifying the best metrics is essential to assess effective teamwork. Working effectively as a team is benchmarked not only on the success of completing the mission but also the quality of teamwork.

Evaluating HR teams can be from a 1) high-performance perspective, through quantitative analysis and formal methods, 2) user perspective, through the usability, overall effectiveness, and satisfaction, or 3) team perspective through fluidity, team workload, or interaction between team members[29, 41]. Quantitative metrics measure efficiency and productivity by time to complete tasks, idle time for each member, and the total mission time [1]. Qualitative metrics assess social measures, team flexibility, adaptability, and robustness or resilience to errors in the environment. Several authors with different perspectives have identified metrics to measuring HRI through task, common, or interaction metrics [1, 32]. Steinfeld and Fong compare three common metrics that emphasize the HR team and interactions [32].

System performance This group is comprised of *quantitative performance* which evaluates effectiveness (% of mission completed) and efficiency (time taken to complete a task), *subjective ratings*, where indirect and direct factors impact effectiveness and *mixed-initiative utilization*, which includes the effort to regulate the control and interaction efforts had between robots and humans through interruptions, requests for help, etc [32].

Operator performance This focuses on the system operator, considering *situational awareness* which impacts decision-making, performance and handling dynamic tasks, *workload*, which assesses multidimensional workload balancing techniques and operator stress, and *mental model accuracy*, which tracks how much the interface affects user performance [32].

Robot performance This examines *self awareness*, which is a degree by which a robot could assess itself through knowing its capacities, monitoring itself through tasks, and recovering from faults, *human awareness*, which is how a robot may be able to perceive humans and predict and read human behaviors, and *autonomy*, whereby a robot can function as a unit comparatively to a measure [32].

While these common metrics assess the components of a team, they do not identify a team metric. System performance describes how to quantitatively assess the overall system, but does not consider the interaction that can be measured amongst the team members. From a task perspective, Steinfeld and Fong continue to dive into "task metrics" which cover the span of robot capabilities and provide a more granular taxonomy on appropriate metrics for specific robot task performance (navigation, perception, management, manipulation, and social) [32]. Shah et. al describes quantitative cognitive and physical interaction metrics that can be gleaned from instances of active communication, coordination and collaboration within an HR team[1].

Physical Interaction metrics Physical interaction can be easily taken from systems through various metrics such as response time, availability, proximity of physical interaction, and duration of physical interaction

Cognitive Interaction metrics Cognitive interaction is more difficult to measure but depends highly on the system used to evaluate HRI. These metrics include information exchange and assessment, decision and action selection, inherent lag, and command specifications as primary metrics to capture.

Freedy et. al's *Collaborative Mixed-Initiative System* describe qualitative measurements allow for team assessment through evaluating how teammates predict each other's actions, collaborate together and develop trust between members[15].

1. Measures of Performance: These measures are observable and come from the operators' task skills, strategies, steps or procedures used to accomplish tasks.

These consists of human team, UV control, and human/robot team processes. The HR team process consists specifically of shared mental models, human to robot ratio, level of trust, behavior acceptance and observability, human-robot coordination, and mixed initiative efficiency[15]
2. Measures of Effectiveness: These measures note the 'goodness' of the quality and execution of tasks but depend on environment and luck. This condenses down into mission and team behavioral effectiveness (collective conformity, latency, decision quality, and comparative performance amongst teams) [15].

The metrics above have distinct and different focuses on components of HRI and HR teaming. These differences and similarities are captured in the Table 2. HR teaming should use metrics that capture both the perspective of the team while balancing quantitative and qualitative metrics.

Metric	Individuals	Team	Quantitative	Qualitative
Common Metrics	●	●	●	●
Task Metrics	●		●	●
Interaction Metrics		●	●	
Mixed Initative Measures of Performance		●	●	●
Mixed Initiative Measures of Effectiveness		●	●	●

Fig. 2 Comparison of four metrics as team or individual focused, and quantitative vs. qualitative.

5 Structuring Effective Teamwork

This section brings together the previous investigation in workload and agent capabilities to demonstrate how to structure teams. Teaming is a dynamic structure where changing agent roles, task definition and requirements, environment context and circumstances affect how the team does work. The structure of the team affects when (pre, during, post), where, and how robots do their work.

First, system designers need to consider the roles each member will play and any occurring interdependencies as team members work together. Fong's collaborative control points to the importance of humans as collaborators instead of controllers [11]. Scholtz et al. notes five roles that humans take on when interacting with robots: supervisor, operator, teammate(peer), mechanic, and bystander [30]. Members' roles may shift as circumstances change, which reshapes the team structure and dynamics. Interactions change depending on the roles humans and robots take on in a team; these greatly impact how to foster teamwork effectively [30, 40]. A natural progression as humans and robots work closely is the occurrence of interdependence [20, 25]. Interdependencies and relationships structure teamwork from influences of the external (environment, taskwork, and context) forces, and the internal (abilities, capabilities) [25].

> interdependence describes the set of complementary relationships that two or more parties rely on to manage requires (hard) or opportunistic (soft) dependencies in joint activity. (p.47)

With that in mind, teamwork can be structured in the following ways:

1. **A "Play"** or sequence structure assigns work to users to follow the "play" (i.e. military plays, football plays). These types of plans are pre-thought out and simply need to be carried out with some room for mild adaptation given a non-nominal circumstance [16]. Plays provide a breakdown of the task into several appropriate metrics like time to complete and task allocation, offering a full blo-byblow description. This level is detail can fit certain types of task where the mission may be very specific and distinct. Overall, a play can be a strategy but if too constrained, it is not flexible to handle variances in scenarios.
2. **Function Allocation (FA)** first decides the work to be done then allocates that work to the agents in the system [38]. FA asks the questions who can do what task and describes how to make that decision; it determines the best fit for a user to a task before or during real-life execution. FA can be evaluated through modeling and simulation to vet a series of work allocations, using varying analytics to assess the best distributions of tasks. This process can be methodical, and has opportunity to use formal modeling tools to quantitatively analyze results. This type of work is best for evaluating teams when early-in-design to fully explore the potential combinations of teamwork.
3. **Bidding** allows agents bid on clearly delineated tasks [7]. Agents are responsible for task allocation and bid considering their availability, skill set, and time to complete the task. Team designers determine winners from variety of measures based on preference and appropriateness. This structure works well for teams with agents that have specific abilities and bidding measures are clearly defined.
4. **Interdependencies** implies both robot autonomy and the interface should be designed together to manage dependencies [25]. Given taskwork and team capabilities, work is assigned effectively for joint activities through interdependence requirements (observability, predictability, and directability) [11, 25]. Human-robot teams must be able to observe and understand their teammates actions, predict their teammates next moves, and direct each other to do work [27]. Teams cognition is key here in order to have the same shared mental model to facilitate communication and coordination [33].

The following examples of HR team scenarios show various types of team structures, ratios of humans to robots, and use cases of teams in a space exploration application. These structures demonstrate the breadth of work HR can accomplish [4, 14]. In Fig 3, we show these four examples as the team works through the workload and the changing dynamics of the team.

1. **Robotic Scouting** involves a human remotely controlling a rover to scout planetary surfaces for scientific and technical progress. In this example, there is a

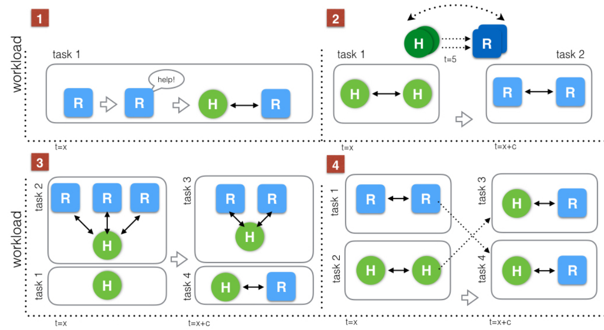

Fig. 3 Four different types of team structures that are possible build from a variety of factors.

1:1 communication line between the human and robot. The work is completed before humans take action as a precursor to human workload. Additionally, the robot can work alone but needs to have strong capabilities in maneuvering and fault recovering from environmental factors. These two members must have good coordination and communication to efficiently explore and inform the most impactful information [14].

a. **Ex. 1** For a single task, a robot works in solitary scouting mission until it requests for human help or alert it has completed the task. The robot requests for help on a task and requires human intervention to work closely on a joint task. It interacts through communicating its progression through the task and completes the task 1:1 with the human thereafter. The robot here would require high capacity for communication, coordination, and collaboration.

2. **Robotic Followup** involves humans working first, then robots following up after to further investigate and finish the task. There may be a transfer of control between the humans and robots collaborating loosely together to finish the subsequent work. Teaming here revolves around coordinating this transfer and a follow-up of completing the task, see Fig. 3 [14].

   a. **Ex. 2** Two humans complete task 1 and communicate with the two-robot team the remainder of the task. The robot team then complete task 2. At the transition phase, communication of the remainder of the task and coordination in shifting authority of the task will impact the mission success and metrics.

3. **Multiple Astrobees with Crew**, up to three Astrobees are capable of flying through the International Space Station and assist astronauts on board with research activities. Members can remotely direct the bees to do specific actions (like navigation), or command them through a series of sequences (similarly to 'plays') to work directly with the crew [4]. Work between astronauts and Astrobees ranges from tightly compacted to more dispersed, see Fig. 3.

   a. **Ex. 3** Shifting abilities and dynamic task requirements can alter groupings within a team of two humans and three robots [8]. At t = x, one human is working with three bees and another human is working alone. At some time t = x+c (where c is the time it takes to complete tasks 1 and 2), one of the robot bees moves to the other human to take on task 4 together while the remaining bees stay to finish task 3. Here the successful coordination and collaboration allows the flexibility of the bee to traverse between human teammates and take on different team tasks.

4. **Planetary Exploration** with HR teams may be far off in the future but understanding the implications of close-knit teamwork on team success is important for homologous real life scenarios. Fong et. al. provides several real-life examples of closely coupled HR teams co-located and responsible for a multitude of joint tasks [14]. These robots are highly dexterous and capable of assorted collaborative tasks. They are remotely controlled or somewhat autonomous and have strong skills in communication through voice and gesture recognition. Their capabilities enable collaboration between HR teammates and provide insight for culminating interdependencies from close conduct.
   a. **Ex. 4** At t = x, a robot team and a human team work loosely coupled on tasks 1 and 2 respectively. At t = x+c, the teams shift partners into two single HR teams and work on the tasks 3 and 4 in tightly coupled teams. Here, teamwork is highly dynamic and the modification of teams is necessary to coordinate effectively. [8] Robots and humans need complimentary skillsets and adapt to new scenarios and unpredictable contexts easily.

6 Future of Human-Robot Teaming

This paper discusses varies factors that impact building effective teamwork in HR teams by investigating the components of teaming of taskwork, capabilities, dependencies. However, future work can continue to provide insight on this topic by exploring the effect of communication, coordination, and collaboration on team performance. As the need for effective HR teams grows, analyzing these design considerations will allow for these heterogeneous teams to advance from a team perspective. Agent capabilities, taskwork breakdowns, metrics for valuable measurements, team autonomy and teamwork structuring are all areas that have room to expand our understanding of HR teaming. The goal of this paper is to highlight that designing for human-robot teams is important for effective teamwork. Building successful teams goes beyond considerations for individuals and extends to the team's combined capabilities and deepening our knowledge of team member relationships. Designing teams where robots are not tools, but peers, is a start to designing effective teamwork and structuring future HR teams to be more successful in their endeavors.

Acknowledgements This work was supported by a grant from the NASA Human Research Program #NNX17AB08G. Partial support was provided by a DARPA/NASA effort to model and predict workload in human-machine systems.

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