A Working Framework for Human–Robot Teamwork

Sangseok You
School of Information
University of Michigan
Ann Arbor, MI, USA
sangyou@umich.edu

Lionel Robert
School of Information
University of Michigan
Ann Arbor, MI, USA
lprobert@umich.edu

Abstract
Despite the established volume of literature on human–robot interaction, the ways in which humans and robots work together as a team have been relatively understudied. This paper proposes a working framework for human–robot teams as a theoretical guide, based on IMOI (Inputs-Mediators-Outputs-Inputs) framework for teamwork in human teams. The proposed framework describes the developmental process of human–robot teams, in which different characteristics regarding humans and robots produce team outcomes through various mediators within organizational contexts.

Author Keywords
Framework, human–robot teamwork, robots in groups, teams working with robots, collaboration, teams

ACM Classification Keywords
H.5.2 [User Interfaces and Presentation (e.g., HCI)]: Theory and Methods; H.1.2 [Models and Principles]: User/Machine Systems – human factors.

Introduction
Robots are increasingly becoming a central part of teamwork [18]. For instance, search-and-rescue teams employ remote-control robots to help respond to emergencies [3]. Teams of construction workers use remote-control robots to tear down concrete walls [21]. The use of robots in the context of teamwork has the potential to transform teamwork by introducing new dynamics between humans and robots [6,22].

The importance of this topic suggests the need to develop a theoretical framework directed at better understanding teamwork with robots. A theoretical framework can help identify factors that enable or hinder the effectiveness of human–robot teams. The identification of such factors is crucial for two reasons: (1) to achieve theoretical progress in the field of teamwork with robots and (2) to gain a practical understanding of promoting outcomes in such teams.

This position paper proposes a research framework that integrates the literature on teamwork and human–robot interaction (Figure 1). This framework attempts to capture the dynamic, adaptive, and developmental nature of human–robot teams. In doing so, this framework incorporates the inputs, mediators, and outputs of human–robot teams with an iterative

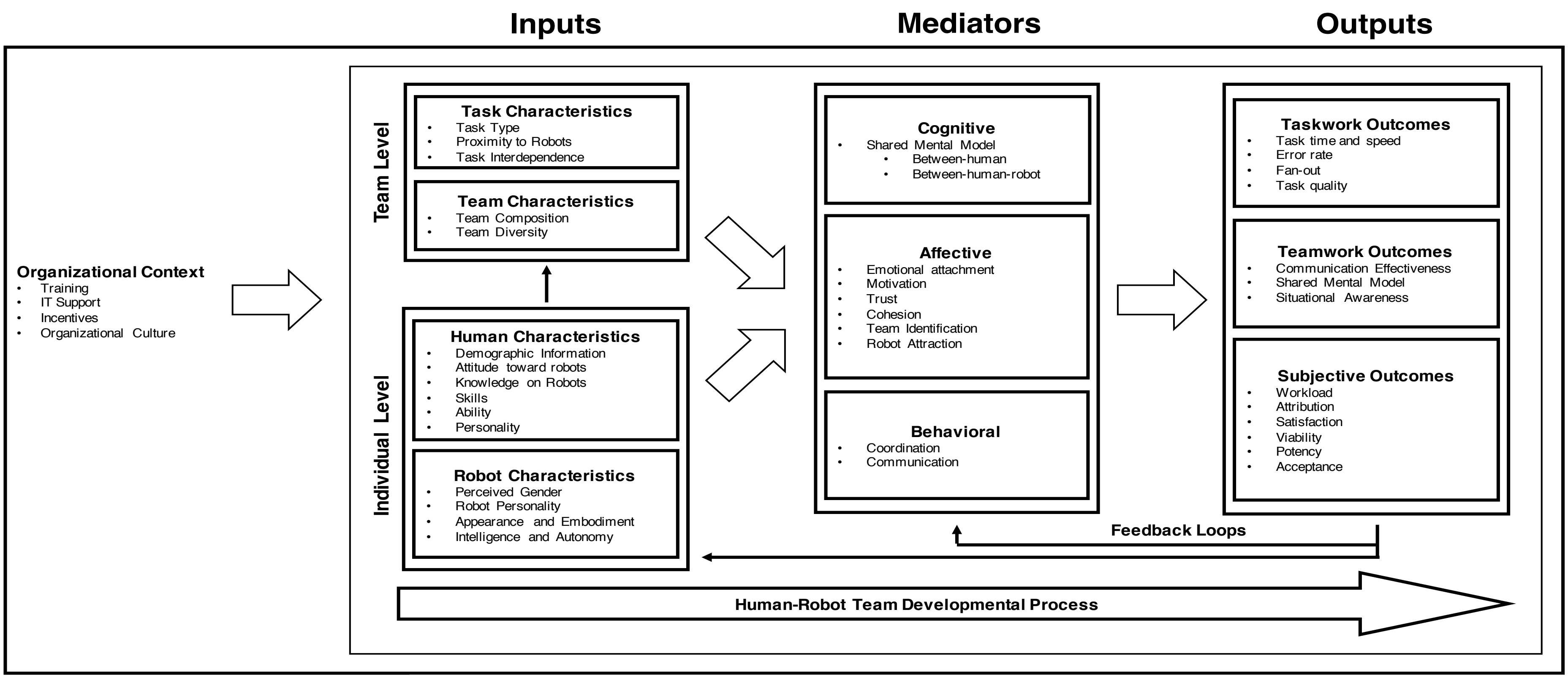

Figure 1 A working framework of human-robot teamwork

process of feedback loops. We believe this framework is an initial step that will motivate further theoretical development and empirical validation.

A Working Framework

Our framework is based on previous frameworks of teamwork, where inputs, mediators, and outputs are identified as key elements in team's life cycle (see [13] for a review). Constructs in the inputs influence emergent states of teamwork with robots (i.e. mediators), eventually producing outputs. Our model is based on IMOI (inputs-mediators-outputs-inputs) framework by [7] to represent the cyclic nature of human–robot teams with feedback loops from outputs to subsequent inputs and mediators during the team life cycle.

Inputs

The inputs represent resources and properties available to teams [10]. This includes multiple levels from the individual level, including characteristics of individual team members and robots, and the team level, including team composition and job characteristics. The team-level inputs are influenced by the individual-level inputs and are shown by the solid line from individual level to team level on the left side of Figure 1.

Our framework includes the combination of both robot and human characteristics that can manifest unique team compositions and structures in human–robot teamwork. Robots in teams can be perceived to possess humanlike attributes such as gender, ethnicity, knowledge, ability, and personality [1,11]. This is because people often ascribe agency to robots and treat them as social entities [6]. For instance, a human–robot team can be considered homogeneous when a robot is perceived to have the same ethnic attributes as other team members [12]. Therefore, our framework puts the same emphasis on robot characteristics as it does human characteristics when it comes to the makeup of team-level characteristics.

Proposition 1: Individual-level characteristics of robots and humans can influence team-level characteristics of human–robot teams.

Our framework depicts inputs influencing subsequent mediators and eventually outputs. This relationship can occur at both the team and the individual levels. For example, at the team level, task interdependence is critical to communication and coordination between humans and robots during teamwork [9]. Task interdependence between humans and robots is proved to help achieve better mental models on task and team performance [15]. Also, at the individual level research suggests that individuals positively evaluate robots that are perceived to have similar personality and social identities such as ethnicity [1,5].

Inputs at the team level can influence mediators and outcomes at the individual level. For instance, the composition of a human–robot team may determine the level of individual motivation and satisfaction of its team members. In teams that involve multiple human team members, individual effectiveness may be a function of both team-level inputs and individual-level inputs [7,23].

Proposition 2: Inputs influence mediators and subsequent outputs in human–robot teams.
Proposition 3: The influence of team-level inputs can occur at the individual and team levels.

Mediators

Mediators are emergent processes or states through which the effects of inputs are manifested. For individuals, mediators are often attitudes and beliefs. For teams and groups, they are typically processes that result from the interactions necessary for combining different inputs [14]. Mediators can also be viewed as an output of the team's input.

Mediators of human–robot teams can be present between humans, and between humans and robots. For example, shared mental models are important cognitive mediators. Accurate mental models usually promote team performance and reduce cognitive load [16]. Shared mental models can exist between humans and robots [15], as well as between humans [16]. In first-responder teams, team members are often scattered across locations [3,9]. Communication among humans and robots is required to maintain accurate shared mental models of the situation [3].

Emotional attachment is a mediator, defined as an affective reaction toward robots or other humans [4]. When team members are emotionally attached to their robots, they are likely to be more motivated to perform tasks with the robots and perceive the work with the robots to be more rewarding [4,19]. However, emotional attachment can also deter teams from deploying robots to risky situations [4]. As behavioral mediators, it is shown that effective communication and coordination are important to improve team outcomes with [2] and without robots [10].

Proposition 4: Cognitive, affective, and behavioral mediators influence outputs.

Team-level mediators can also influence individual-level outputs. Team trust can influence the relationship between individual trust and individual performance [8]. It is also possible that mediators such as team cohesion and communication can influence whether team members want to remain on the team.

Proposition 5: The influence of team-level mediators can occur at the individual and team levels.

Outputs

Outputs have three categories: *taskwork, teamwork*, and *perceptual outcomes*. In human–robot teams, taskwork can include the task time, solution quality, and error rate, while teamwork can include communication efficiency and effectiveness, awareness, and coordination. Perceptual outcomes are attitudinal and emotional reactions, such as satisfaction.

Our framework attempts to capture the role of time. The original IPO (input-process-output) model has been criticized for focusing only on a linear path from inputs through outcomes. However, most teams undergo developmental processes and feedback loops as they mature [13]. This means that mediators and outputs can influence subsequent inputs and mediators through feedback loops (shown by solid lines on the right side of Figure 1). In other words, time matters, and we should expect past interactions to play a key role in the future interactions of human–robot teams.

As an example, time matters in the role of task knowledge and skill. For instance, a human–robot team could have little task knowledge (inputs), which could influence its shared mental models (mediators) and ultimately its initial performance (outputs). When a human–robot team repeats the task, the team becomes better, which influences mediators and the outputs of future tasks. However, the influence of previous outputs can be more influential than feedback from previous mediators. Mediators are often subject to change based on a team's previous performances and experiences. Inputs, including specifications of robots and individual traits, tend to be static and less dynamic.

Proposition 6: There are feedback loops, in which mediators and outputs influence subsequent mediators and inputs in a cyclic manner.

Last, the organizational context influences inputs, mediators, and outputs associated with human–robot teams. Teams are often embedded in a larger organizational context. Organizations help determine both the operation and management of human–robot teams. Organizations provide the resources to facilitate teamwork. For instance, organizations can provide training and support to human–robot teams [10]. Consistent training and support from the organization can be critical, particularly for human–robot teams [23]. Team members are likely to build strong social relationships with their robots through prolonged interactions throughout the team life cycle.

Proposition 7: Organizational contexts of human–robot teams can influence their inputs, mediators, and outputs by providing positive conditions.

Discussion

There are three advantages of this framework. First, it acknowledges different compositions of human–robot teams beyond one robot and one human. Given that many human–robot teams consist of multiple robots and their operators, both human–human and human–robot collaboration should be examined to better understand how these teams achieve their goals in synergistic ways. Our framework not only incorporates the different individual and robot characteristics but also various compositions among the characteristics of robots and humans. This includes *collaboration*, as a joint action between and among humans and robots, to jointly accomplish a shared goal [2].

Second, the framework suggests individual, team-level, and multilevel relationships. Most research focuses on the individual level — often ignoring the team context. Our framework describes how team characteristics influence individual mediators and outputs. A multilevel approach is essential to investigate impacts of the team level on the individual level [17,20].

Third, our framework considers the role of time by including feedback loops. It is possible to investigate how different team compositions convert to outputs through mediators. Many researchers have treated such variables as attraction and attachment toward a robot as an end-point of human–robot interaction, mainly for predicting individual adoption of social robots. However, human–robot teams often repeat similar tasks and interact with robots assigned to them during the team life cycle. In this case, previous performance can alter a team's perception toward its robots and the ways mediators influence interactions.

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