Team Synchrony in Human-Autonomy Teaming

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3 authors:

Mustafa Demir
Arizona State University

Nathan J. McNeese
Clemson University

Nancy J Cooke
Arizona State University

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Mustafa Demir[1], Nathan J. McNeese[1] and Nancy J. Cooke[1]

[1] Department of Human Systems Engineering, Arizona State University, Mesa, Arizona, United States of America
{mdemir, nmcneese, ncooke}@asu.edu

Abstract. In Human-Autonomy Teaming (HAT), the development of a highly autonomous agent as a team member is difficult. Similar to human-human teaming, there are multiple dimensions of social behaviors that occur during HAT that must be accounted for within the development of the agent or system. One of these dimensions is team synchrony. In general, team synchrony is, when two systems (or two individuals in a team) are synchronized, resulting in their recurrences being dependent on each other. In order for a human-autonomy team to be synchronous the agent must communicate effectively (i.e., synchronize effectively) with its human team members. Thus, in this paper we present a conceptual discussion on what team synchrony is, how it occurs, and how to better develop it in HAT. To ground our discussion, we use our recent studies in which we empirically looked at team behaviors and team synchrony of HAT.

Keywords: Human-Autonomy Teaming · Synthetic Agent · Teamwork · Synchrony

1 Introduction

Teams are complex, adaptive, and dynamic social systems that are driven by interactions among the team members [1]. A complex system's behavior emerges as a result of self-organization among the interacting parts of which the system is comprised [2]. Therefore, teams are the self-organizing results of individuals cooperating with each other, over time, towards team-level goals. According to this perspective, teamwork can be described in terms of the interactions among team members and between team members and their environment [3], [4].

Over the last couple of decades, with recent technological enhancements, teaming has changed. Increasingly, human team members work involves interactions with highly automated systems (e.g., synthetic agents and robots) with a trend toward autonomy taking on the role of a teammate [5]. Traditionally, teaming consisted of only human-human teams, but advancements in robotics and advanced machine learning have led the way for Human–Autonomy Teaming (HAT). This has led to a research interest in HAT [6]. Autonomy may be advantageous for teams in terms of reducing workload, but it can also adversely increase the cognitive demands on human teammates due to the autonomy's limited verbal behavior [6]–[8]. In addition, humans are familiar with interacting with other humans (i.e., human-human teaming) in this type of dynamic environment. Therefore, in HAT, the development of a highly autonomous agent as a team member is difficult. Similar to human-human teaming, there are multiple dimensions of social behaviors that occur during HAT that must be accounted for within the development of the agent or system.

One of these dimensions is team synchrony. In general, team synchrony is, when two systems (or two individuals in a team) are synchronized, resulting in their recurring behaviors being dependent on each other [9]. In order for a team to be effectively synchronous, the agent must communicate and coordinate effectively with its human team members. Given the importance of team synchrony in human-human teaming, it is important to conceptually outline the role of team synchrony in HAT.

In our most recent experiment, we used a full-fledged synthetic teammate as a team member that was able to communicate and coordinate with other human teammates [10]. Based on our experiments, we have identified multiple empirical findings that we feel are important for advancing HAT, but more specifically team synchrony during HAT. These conceptual understandings based on empiricism help to identify what team synchrony means within the context of HAT, and how to empirically study team synchrony in HAT. Thus, at a high level, we discuss whether synchrony in human-human teaming can be transferable to human-autonomy teaming (HAT). Included is a discussion on what team synchrony is, how it occurs, and how to better develop it in HAT. To ground our discussion, we will use our recent studies in which we empirically looked at team behaviors and team synchrony of HAT.

2 Human-Autonomy Teaming

Human team members works increasingly involves interaction with highly automated systems (e.g., synthetic agents or robots) in highly dynamic environments, such as Command-and-Control or surgical rooms. This increasing role of highly automated systems as a team member has started a paradigm shift from human-human teaming to HAT. Autonomy is an independent system of human control [11], and it can be defined as systems that can function—at least partially in a self-directed manner—outside of the sorts of situations that they were designed for by using some intelligence-based capabilities [12].

There are several studies which have examined the use of autonomy or intelligent systems as a teammate [13]–[17]. For instance, one of these studies [14] considers intelligent systems as teammates, equivalent in status to humans, and therefore, they define 'team' as an "actor-agent community" (p.35), and in their study, they underline that intelligent systems may take the initiative and give orders to fellow teammates. Another study [15], again considers this actor-agent community as a HAT and define it as "the dynamic, interdependent coupling between one or more human operators and one or more automated systems requiring collaboration and coordination to achieve successful task completion" (p. B64). Therefore, without outside intervention, an autonomous system can independently achieve goals and maintain good performance in highly dynamic environments by interacting with other humans or other agents [12], [18], [19]. Although these studies consider autonomy as a team member, one of the studies conducted by [20] underlines that the autonomous system's lack of intelligence is a large obstacle on its path to becoming a team member, and they also suggest ten steps to solve these obstacles.

Even if autonomy is advantageous for teams in terms of reducing the workload, it can also increase the cognitive demands that are placed on human teammates, because the autonomy has limited interaction behaviors. Thus, understanding dynamic interaction in HAT and how it differs from human-human teams needs to be taken more seriously in team science.

3 Synthetic Teammate Project

3.1 Synthetic Teammate

One goal of the synthetic teammate project is to create a synthetic teammate capable of human-like behavior in order to interact with other human team members. In the study, one of the team members was a synthetic teammate developed using the ACT-R cognitive modeling architecture [21], which is composed of five components [10]: 1) language analysis to accommodate a variety of English constructions, 2) language generation to choose possible utterances, 3) dialog modelling to recognize when communication is obligatory, 4) situation modelling for situation awareness, and 5) agent-environment interaction to fly an Unmanned Aerial Vehicle (UAV) between destinations.

At the beginning of the study, participants were informed that one of their teammates, i.e., the pilot, was a synthetic teammate and that it had limited communication capabilities. Therefore, in order to interact (i.e., communicate and coordinate) with the synthetic teammate effectively, the human team members needed to send messages in a constructive way - without any cryptic language or misspellings.

3.2 Synthetic Task Environment and Experiment

In the synthetic Unmanned Aerial System (UAS) environment, heterogeneous teams of three members (i.e., pilot, navigator, and photographer) are required to take good photos of critical target waypoints during simulated missions by interacting with each other via text-chat. In this task, three special-kinds of communication-coordination events can occur during the missions: Information-Negotiation-Feedback (INF) [22]. The interaction among team members at critical target waypoints is as follows: (1) the navigator produces a dynamic flight plan with speed and altitude restrictions of waypoints, and sends this *information* to the pilot; (2) the pilot controls the UAV in terms of heading, altitude and airspeed, and then *negotiates* with the photographer about altitude and airspeed; (3) the photographer adjusts camera settings based on the current altitude and airspeed, and photographs ground targets, and after that sends *feedback* to other team members [23] (see Fig. 1).

In this task, there were three heterogeneous team members that communicated via a text-based communications system. In addition to that there were three conditions (by manipulating the pilot role): 1) the Synthetic - the synthetic teammate was the pilot; 2) the Control - an inexperienced human participant was a pilot; and 3) the Experimenter - one of the experimenters, who was experienced with the task, was the pilot.

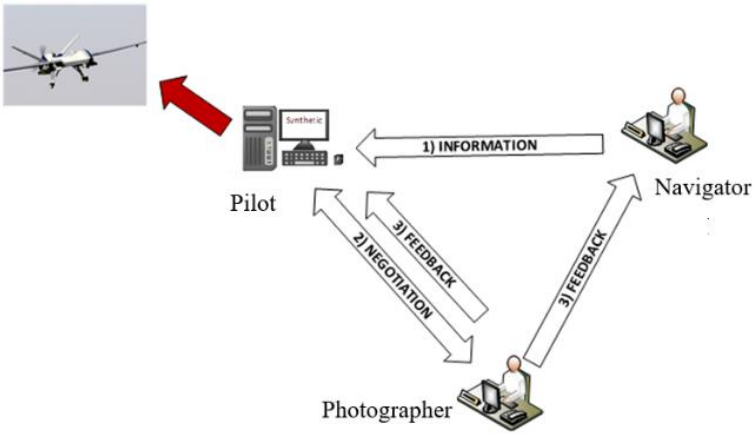

Fig. 1. Team Coordination (Information-Negotiation-Feedback) in HAT (Modified from [7]).

4 Team Synchrony

4.1 What Is Team Synchrony?

Synchrony/ synchronization is a complex dynamical process "wherein more than one dynamical systems are coupled or forced (periodically or noisy) in order to realize a collective or synchronous behavior" [24], [9, p. 160]. In this case, synchronization can be considered from two perspectives: (1) synchronization is a "process fundamental for the embodied grounding of *communication"* [25]; and *coordination*, which is the core aspect of synchronization, is behavioral synchronization among two or more individuals in space and time and, thus, those behavioral patterns can be represented as intentional, dynamic patterns [1]. Synchronization occurs when a unit of individuals, interacting over time, jointly engage in behavioral and affective monitoring. This serves an adaptive function that works by creating equality among the groups' neural, affective, and behavioral patterns [25].

In teams (which are adaptive, dynamic, and complex systems), individual team members are structural elements which temporarily act as one unit; this is also known as "synergy." [26]. Synergy is a team-level process that results in coherent, emergent team behaviors through the interactions of the individual team members. Therefore, we can view spatial-temporal synchronization between team members within a team as a functional synergy [26].

It is also important to explain how the heterogeneous team members' actions during the task can be synchronized within the team behaviors. In order to capture synchronization (which is the basis for team behaviors) among team members, we must first understand how repeated interactions among team members can scale to team behaviors [26].

4.2 Measuring Team Synchrony via Team Communication

Team communication is a subset of team synchrony. Therefore, communication as a purposeful social interaction is one of the ways to explain team synchronization, because it is a cognitive process in which representations are shared among the individuals [25]. One of the measurement methods for synchrony is recurrence plots. When two systems are synchronized then their recurrences are dependent on each other.

Recurrence Plots (RP) was originally introduced by [27] in order to visualize complex system dynamics, i.e., the behavior of trajectories of dynamical systems in phase space [28], [29]. After it was shown to be a strong predictor of data that captures key features of nonlinear systems, recurrence analysis emerged as a sophisticated way to illustrate system properties. For instance, a recurrence plot can be constructed to represent the dynamics of a single system across a delaminated period of time; from such a plot, researchers can develop metrics to represent properties of the system. This extension of the recurrence plot is called Recurrence Quantification Analysis (RQA).

Later on, extensions of RQA were put forward to look at more than one system and their dynamics: a bivariate version of RQA called Cross Recurrence Plots (CRP) and its analysis Cross Recurrence Quantification Analysis (CRQA), and, likewise, a multivariate version of RQA called Joint Recurrence Plots (JRP) and also its analysis Joint Recurrence Quantification Analysis (JRQA). By comparing the states of two different systems, CRPs reveal dependencies between the systems and show the progressions of two different phase space trajectories. Researchers can benefit from CRP by using it to discover recurrent structures between the behaviors of two individuals (be they in a single or multivariate state space) without having to make assumptions about data structure [30].

Another extension of RQA is JRQA (a nonlinear data analysis method) which is a mix of RQA and CRQA. This analysis is especially useful for assessing synchronization between interacting systems or assessing the systems that can jointly influence one another. In this method, first, the recurrences of the systems are plotted separately, then, the two separate recurrence matrices are combined to find times of simultaneous recurrence [29].

4.3 Using Joint Recurrence Plots to Examine Team Synchrony

One of the approaches for investigating team interaction patterns and their change over time involves looking at communication flow using JRQA that quantifies how many recurrences (and their length) are present by phase space trajectory in a dynamical system [31]. Within the team concept, JRQA can be applied to examine how and why several teams differ from one another in their dynamics. Accordingly, it shows the degree to which team members synchronize their activities during their interaction via text or voice communication.

In the synthetic teammate project, we applied JRQA on each of the UAV missions' communication dataset (time-series data sets), and extracted several measures. The following two measures are commonly used for our reports: Recurrence Rate – RR (ratio of all recurrent points in the upper triangle to size of recurrence plots), and Determinism – Det (ratio of all diagonally adjacent recurrent points to all recurrent points in the upper triangle) [31]. The Determinism measure, on joint recurrence plots, states of the system's epochs of similar time evaluation are the diagonal lines [32]. From this definition, chaotic (i.e., unpredictable) processes will have no (or very short) diagonals, whereas predictable (i.e., deterministic) processes will have longer diagonals and fewer single, isolated recurrence points [31]. This determinism ratio can take values between 0% (no repeats in the time series) and 100% (i.e., the time series repeats perfectly) (see Fig. 2). For instance, Fig. 2 shows three teams' joint recurrence plots from the synthetic, control, and experimenter conditions. These three examples of joint recurrence plots demonstrate three different synergies among three heterogeneous team members (i.e., navigator, pilot, and photographer) during the UAV task. In Fig. 2, the synthetic team shows more predictable team communication behavior with longer diagonals (Determinism: 69%) than the control (Determinism: 34%) and experimenter teams (Determinism: 38%). Fig. 2 also indicates that the synthetic team also had a higher Recurrence Rate (RR= 38%) than the control (RR= 16%) and the experimenter teams (RR= 22%; see Fig. 2). In this example, the synthetic team had more synchrony than the other two teams. However, having more synchrony within the team does not equate to having higher team performance. In this example, the synthetic team's performance score was lower than that of the other two teams. Therefore, an argument can be made that the quality and effectiveness of the synchrony is more important than the quantity or frequency of synchrony.

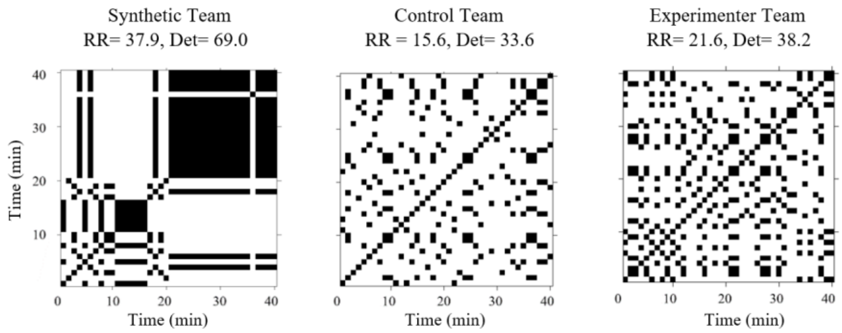

Fig. 2. Example Joint Recurrence Plots from three UAV teams' interactions (length 40 minutes)

5 Team Synchrony with an Autonomous Synthetic Agent

Team communication and coordination are subsets of team synchrony within the perspective of previous scholars' study [1], [25], [26]. To assess whether teams are effectively synchronous or not, we can look at the team interaction (i.e., communication and coordination) in two ways: from the human team member who interacts with an autonomous agent and from the autonomous agent that interacts with human team members.

An autonomous agent's interaction with its team members and task environment is crucial for good team performance in a dynamical task environment. The recent studies conducted for the synthetic teammate project [6], [7], [33] underline the importance of team communication behaviors and, in turn, team coordination. From the human team members' perspective, one of those studies indicated that adding a faux-synthetic teammate (played by a human) as a team member changed the human team members' communication behavior [33], and they exerted more control on the "synthetic team member". Later, another study [6] showed that due to the nature of limited communication behaviors of the synthetic teammate, it is required that human team members need to communicate with the synthetic teammate in stricter ways that it would find interpretable (i.e., no cryptic or misspelled language) or else resulted in intricacies in coordination that might have led to a failed mission. Another empirical study [7] showed that, even when human team members communicated properly with synthetic agent, it did not improve their team performance because of limited interaction capabilities within the team.

This limited interaction capability of the synthetic agent, and in turn among the team members in the HAT, lead to poor team adaptation in the dynamic environment, especially during roadblocks. Findings from one of the studies [8] highlights that the anticipation of other team members' behaviors and information requirements in synthetic teams was lower than the all-human teams. Therefore, developing team interaction mechanisms within HAT is needed for effective team situation awareness and in turn team performance [8].

Overall these recent findings from our studies address the limited team synchrony within HATs, because of poor temporal-spatial synchrony in behavior among the team members (which is distinct from coordination). In order to overcome the autonomous agent's communication and coordination limitations, the synthetic agent needs to have interaction patterns that are synchronous with humans in both temporal and spatial states in terms of *what* (communication), *when* (coordination), and *how* (communication and coordination) [6], [25]. This will also help to improve the synthetic agent's poor team situational awareness. To maintain effective team synchrony in a HAT requires continuous joint behavioral interactions among the team members by establishing neural, affective, and behavioral patterns. Thus, the initial state of effective team synchrony in a HAT starts with its subsets: effective communication and effective coordination among the team members.

6 Conclusion

As we continue to advance teaming from human-human to HAT there are many critical aspects of teaming that must be considered both during the conceptualization and application of HAT. Two such considerations are team communication and team coordination, culminating in the concept of team synchronization. If we are to create and motivate effective HAT, we must understand the impact of team synchrony and plan for improving synchronous aspects of communication and coordination. In this paper, we have presented both a conceptual understanding of the importance of team synchrony during HAT and provided details on how to study team synchrony in a HAT context.

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