Common Ground and Autonomy: Two Critical Dimensions of a Machine Teammate

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Abstract. We propose common ground and autonomy are the two critical dimensions necessary for intelligent machine agents to make the transition from tool to teammate. Existing models delineate a number of teammate characteristics. We explore how these teammate characteristics can be distilled into common ground and autonomy and suggest research steps to test our proposal.

Keywords: Human-machine teaming · Autonomy · Human-autonomy teaming · Trust · Sensemaking · Common ground

1 Introduction

Technological advances are improving the tools designed to assist humans in complex task domains. As the capabilities of these systems improve, machines can begin to transition from tools to teammates. To guide this transition, the human factors community has begun to identify the characteristics needed for a machine to function as a teammate. For example, Klein, Woods, Bradshaw, Hoffman and Feltovich [1] identified ten characteristics necessary for making automation a team player. More recently, Lyons, Mahoney, Wynne and Roebke [2] identified seven factors that cause a machine to be viewed as a teammate. We propose these characteristics, along with others identified as important for the design of human-machine teaming (HMT), are more than what is necessary to design an effective system. They introduce too many dimensions to track. Instead, we propose there are two high-level dimensions necessary for the design of effective teams: (Establishing and Maintaining) Common Ground, and Autonomy.

2 Common Ground

2.1 What Is Common Ground?

One of the most important factors to consider when designing machine teammates is how to establish and maintain common ground. According to Baber et al. [3], common ground is the knowledge and assumptions that agents share and know that they share. Common ground includes shared knowledge of the roles and functions of the team

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members, skills and competencies both individually and for the team as a whole, goals of the participants (individually and as a team), and awareness of each team member's concerns [4]. It is important to note that common ground does not imply team members have a complete shared awareness. Understanding does not need to be total; it needs to be sufficient for the specific task [3]. The type of information and level of detail necessary for common ground depends on the goals of the task.

2.2 Benefits of Common Ground

The ability to establish and maintain common ground with a teammate provides several advantages. First, common ground lowers coordination costs between teammates [5]. Coordination cost is the cost associated with keeping the team functioning as a coordinated unit. Low coordination costs save resources, so the team can focus more energy on the mission. Coordination cost can increase if a teammate's communication is unnecessary. For example, a teammate may provide detailed directions or explanations not realizing that the other party either does not need or already has the information. Coordination cost can also increase if a teammate uses vague or abbreviated language that does not sufficiently communicate his or her message in the initial attempt. This initial unsuccessful attempt at communication will likely lead to additional exchanges between team members for clarification [4]. Each party's ability to maintain shared awareness affects the likelihood that they will over- or under-estimate what information needs to be shared.

Common ground allows teammates to predict each other's behavior [1]. Machine teammate predictability is important because it helps the human calibrate trust and appropriately rely on the technology [6, 7]. Additionally, teammates can predict each other's future needs, proactively provide appropriate resources, minimizing coordination costs [8].

Common ground facilitates task interdependence. Task interdependence exists when the human and machine work on different aspects of the same task, and task components are allocated according to each's unique strengths [2]. In HMT, task interdependence can exist without common ground, but achieving this interdependence places greater burden on the human to allocate, direct, and monitor task execution. Common ground provides the human and machine with a shared understanding of the task that needs to be accomplished and the relative strengths and weaknesses of each. Armed with this shared awareness, the team can demonstrate task interdependence with less direction from the human.

Common ground makes teams more robust. Robustness is the team's ability to adapt to changes in the environment; it is one of several factors impacting HMT resiliency [9]. When new insights shift the focus of an analysis or environmental factors require an adjustment to the plan, common ground provides the ability to adapt. Adaptation may involve reprioritizing tasks, one teammate providing backup to another, or simply redirecting each other's attention [1]. A team on common ground can more effectively and efficiently adjust to changes that may otherwise lead to a break down in team performance.

2.3 Common Ground Breakdown

Common ground poses a major challenge for HMT; not only is it critical for effective team work, it is in a regular state of decay [4]. Common ground breakdowns occur when there are differences in understanding and the team members are unaware of these differences or unmotivated to resolve them [1]. Lack of shared understanding can be based on differences in reasoning, data synthesis and analysis, and/or access to information. Changes in the task environment can spur differences. Perhaps one team member notices the change and adjusts although another teammate does not. Or both teammates may interpret a change differently, resulting in different mental models of the situation. Differences in understanding can also stem from different goals. This type of breakdown is common if the team leader fails to clearly state the team's or individual members' goals.

A breakdown in common ground occurs when the differences in understanding are coupled with ignorance of these differences [4]. Unaware of the differences in goals or understanding, team members will continue to behave under the assumption that common ground exists. Consequently, behaviors will be out of sync and may hurt team performance. The breakdown can only be restored when asynchronous behavior is identified and remedied. Unfortunately, it is typically salient events such as errors that alert team members to the breakdown. Generally, teams lacking experience working together are more susceptible to breakdowns in common ground [4].

2.4 Maintaining Common Ground

Communication. Teams should practice common ground maintenance as a default activity in an attempt to identify breakdowns before they hurt performance [4]. One way to maintain common ground is through communication. Designing technology that is capable of a rich dialog with the human teammate is important for the perception of machines to transition from tools to teammates [2]. Machine teammates must be able to communicate their status, including task progress and future intentions. Additionally, the machine teammate should direct the human's attention to important information. For example, if the machine detects a change in an investigation, it should make the analyst aware before common ground begins to decay. A rich communication dialog also includes the machine's ability to receive and interpret verbal and nonverbal signals from the user [1]. When receiving a message, the machine should both acknowledge receipt and communicate its understanding of the message to help prevent common ground breakdowns [4].

Design for common ground and communication must account for coordination cost. Although the capability for a rich dialog is important, designing for a smooth interaction is also important. Communication with the machine teammate imposes a cost on the team. If establishing and maintaining common ground carries too great a coordination cost, the human may stop attempting to establish common ground. HMT is especially vulnerable to this threat when under time pressure, or experiencing high task load, duress, or fatigue. Designers must consider the amount, form, and granularity of information that is exchanged between the human and machine. A machine requiring a large amount of detailed information in a format unfamiliar to the human places a high burden on the human. Similarly, a machine communicating at inappropriate times using unnecessary details or unfamiliar jargon increases the difficulty of maintaining common ground.

One way designers might be able to lower coordination costs while still maintaining common ground is to leverage cognitive artifacts. Cognitive artifacts are physical or digital representations such as lists, schedules, and analytic visualizations that reflect the thoughts and goals of the creator [10]. These representations are compact representations enabling efficient coordination [11]. These artifacts may be at least partially comprised of symbols and visualizations that depart from traditional linguistic communication. It is important to note that common ground maintenance is not always verbal [3]. In some cases, it may be more natural and efficient for a human to rely on cognitive artifacts when coordinating with the machine teammate. For example, one can imagine an interactive visualization that allows both the human and machine to manipulate the artifact as they coordinate and build a shared understanding. Designers should strive to develop machines that can detect the human's artifacts and correctly translate them into meaning for the machine. Placing some coordination burden on the machine will reduce coordination costs for the human and maximize the likelihood that the user will work to maintain common ground with the technology. Perhaps interactive machine learning could be employed to fine tune the machine's understanding of the human's cognitive artifacts over time [12].

Another technique for keeping coordination costs low is to use language and concepts that are familiar to the user [13]. Unfamiliar information creates confusion and requires additional explanation. Miller's [14] human-computer etiquette concept highlights the importance of familiarity during human-machine communication. According to [14], etiquette in complex task environments is behavior consistent with the norms, expectations, and terminology used by the team. An AI that behaves in a way familiar to the user helps reduce coordination costs and improves HMT performance.

Monitoring. In addition to engaging in regular communication, the human-machine team must also continually monitor itself for signs of common ground decay [4]. The goal of vigilant monitoring is to detect decay *before* it leads to performance errors or a complete breakdown. Monitoring involves attending to the teammate's behavior, the operational environment, and one's own performance. For a machine to function as a teammate, it must monitor the human's behavior and cognitive state for signs of a common ground breakdown. If the human is behaving in a manner inconsistent with the machine's expectations, this inconsistency could reflect a change in the human's goals, analysis of the situation, or access to information unavailable to the machine [3]. Inconsistent behavior may be a sign of early common ground decay. Additionally, the operational environment should be monitored for changes. Changes in mission or investigation make the team vulnerable to common ground decay. Finally, a machine teammate must be aware of decline in its own performance. If the machine's performance is slipping, the human may not be aware of it, and this lack of awareness could lead to a breakdown in common ground.

2.5 Trust

As we build more adaptable, intelligent tools, they become less predictable [1]. This lack of predictability can result in a loss of trust [6, 15]. Common ground may be one way to protect against teammate unpredictability. A machine attempting to maintain common ground is more transparent about its actions. The human is able to build a shared understanding of the task while also gaining insight into the system's functioning. Common ground increases machine transparency, which in turn allows the human to calibrate his/her trust in the technology [16].

While building and maintaining common ground can eliminate under-trust due to unpredictability, common ground breakdowns can lead to over-trust. When a breakdown occurs, the human may be unaware that goals and knowledge are no longer shared with the machine. The human incorrectly trusts the machine to continue behaving consistently with his/her own situation understanding. Restoring common ground can repair trust. However, trust in a teammate is multifaceted. In the case of restoring common ground after a breakdown, the human will likely consider both the machine's ability to perform the task as well as its ability to maintain common ground. These are two separate abilities, and trust in one does not automatically generalize to the other. The human's loss of trust in the machine's ability to maintain common ground may lead to underutilization of the tool.

3 Autonomy

The second critical dimension for HMT is autonomy. Autonomy is a machine's ability to function independently of the human. Machines with little autonomy require explicit direction from the human; highly autonomous machines require little direction. This continuum is captured in Parasuraman, Sheridan, and Wickens, levels of automation concept [17]. There are ten levels of automation, from a machine that offers no assistance (level 1) to a machine that behaves completely independently disregarding any human direction or intervention (level 10).

Machines that establish and maintain common ground without autonomy have a clear understanding of shared goals and tasks but are completely dependent on the human's direction. These machines neither take initiative nor adapt performance to changes in demands unless specifically directed by the human. The burden is on the human to provide clear instructions to the machines at all times. On the other end of the continuum, level 10 automation [17] would also not be suitable for a machine teammate. Good team performance requires the machine be adaptable to the preferences and needs of its human teammate.

3.1 Dynamic Leadership

Sufficient autonomy renders the machine and the human equally responsible for task performance. However, leadership and responsibility may shift depending on the unique strengths of each teammate and the changing demands of their tasks. This interaction is referred to as dynamic leadership [18]. In light of the need for shifting roles and responsibilities, perhaps the most ideal configuration is a machine that is adaptable and/or adaptive to the level of autonomy appropriate for the situation [18]. For example, in certain environments the machine may have access to better quality information than the human and may need to assert a high level of autonomy to ensure optimal task performance. In environments where the machine's capabilities are more limited, it would be ideal for the machine to recognize its own limitations and reduce its own level of autonomy.

3.2 Agency

Autonomy allows machines to exhibit agency by observing and acting on their environment [18]. The ability to take action independently of the human's specific direction allows the machine the freedom to engage in good teammate behavior. For example, the machine can help redirect the human's attention to important changes in the mission and provide backup if the human's performance is degrading. A machine with a high autonomy may be afforded the freedom to correct the human's errors or suggest changes to an existing plan that it deems problematic. According to Lyons et al. [2], humans' perception of a machine's agency influences the extent to which it is viewed as a teammate. Haslam's [19] model of dehumanization identifies agency as one of several characteristic separating humans from machines.

3.3 Trust

Trust is the willingness to be vulnerable to another party when that party cannot be controlled or monitored [20]. Low-autonomy machines can and must be controlled, rendering trust less relevant in the HMT relationship. Instead of trust, humans establish and maintain confidence in the technology through control. Organizational controls (e.g., strict policies and procedures) instill confidence that team members will behave in predictable ways [21]. Similarly, humans may rely on their control over low-autonomy machines to establish confidence in the technology. The ability to direct the specific actions of a machine enables predictable behavior patterns that instill confidence.

As a machine's autonomy increases, the human's level of control over the machine decreases. The absence of control increases the human's vulnerability, placing a greater demand on the importance of trust in the machine. For highly autonomous machines, the human's trust in the technology may play a more significant role in predicting the human's confidence and reliance on the technology.

4 Relationship Between Common Ground and Autonomy

We propose that for a machine to be a teammate it must behave both *autonomously* while striving to *establish and maintain common ground* with its human partner. Machines lacking in either dimension will place additional burdens on the human to manage the HMT. Machines demonstrating a high degree of autonomy without attempting to maintain common ground perform tasks independently; however, they lack awareness of the human's goals and actions. Additionally, these machines are not attempting to communicate their goals, progress, or reasoning with the human. The burden is therefore on the humans to closely monitor these machines and correct their actions if necessary. Machines that establish and maintain common ground but lack autonomy have shared knowledge of the goals, responsibilities, and task demands. However, these machines do not take initiative or adapt their performance and must be directed by the human. The burden is on the human to provide clear instructions at all times. Both cases are examples of poor teamwork. Both examples over-burden the human with team management, diverting resources that could be devoted to task goals.

4.1 Trust Calibration and Risk

Both common ground and autonomy impact the likelihood and severity of machine error, two major components of risk [22]. We propose that as a machine's autonomy increases, the level of risk increases. The machine has more freedom to initiate activities, and it assumes greater responsibility for the team's performance. We also assert that common ground can impact risk via trust calibration. A lack of common ground can lead to a miscalibration of trust in a machine. This miscalibration can, in turn, lead to inappropriate reliance on the technology and degrade HMT performance [6].

For designers interested in developing machines with high levels of autonomy, the impact of autonomy on risk can be mitigated by developing a machine that strives to establish and maintain common ground. Machines that are ineffective at maintaining common ground and are highly autonomous pose the biggest risk to performance. The human has less control over the machine's actions and his/her inability to maintain common ground with the machine makes trust calibration very challenging and (see Fig. 1).

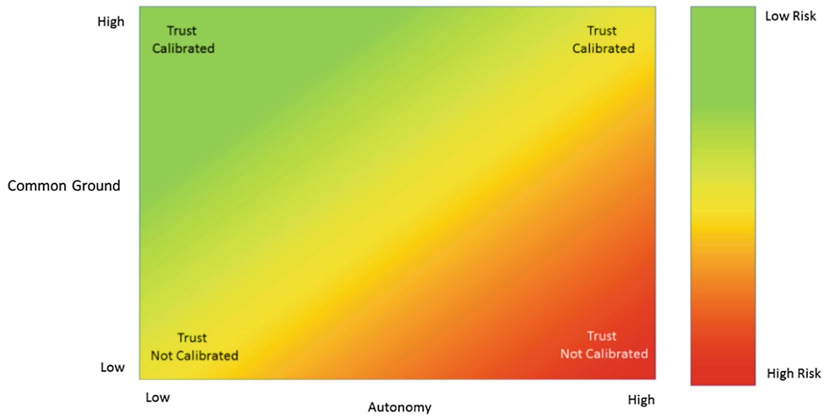

Fig. 1. Conceptual model of risk levels in HMT. The degree of risk (color coded) varies as a function of the two critical dimensions, Autonomy and Common Ground.

5 Models and Characteristics of Human-Machine Teams

We are not the first group to attempt to identify the dimensions critical for transforming computational agents into teammates. A number of models and frameworks have been proposed for HMT. These can be found across the literatures addressing "human-machine teaming", "human-autonomy teaming", "human-robot teaming", and related topics. Regardless of the physical form factor for the computational agents, each model suggests important characteristics[1] to consider in the design of a good teammate. We summarize three of these models in Table 1, with particular attention to the definitions for each of the characteristics or dimensions. For additional models or characteristics, we refer the reader to [16, 17, 23–25].

Reviewing the definitions in Table 1, we can start to see some key themes in the characteristics considered desirable in any team member and which could be particularly important for machines to be perceived as teammates, not just tools. But in this table alone, only accounting for three published models, there are 20 characteristics that should inform machine teammate design. The design space could get intractably large very quickly, for both design and evaluation considerations.

However, the themes of these characteristics are consistent with the critical dimensions of common ground and autonomy. We hypothesize that many of the constructs discussed in the human-machine team literature are highly associated with one or both of these dimensions. If supported, it would mean that the individual characteristics could be "collapsed" onto the critical dimensions common ground and autonomy. And if someone is designing a teammate for the critical dimensions, the resulting system should support many of the characteristics in Table 1 because it was designed to support common ground and autonomy. Table 1 therefore includes a proposed mapping of these individual constructs onto common ground and/or autonomy.

Table 1. Characteristics of machines as teammates

Citation	Characteristic	Definition	Common Ground	Autonomy
Klein, Woods, Bradshaw, Hoffman and Feltovich [1]	Engage in common-grounding activities	Ability to comprehend messages and signals to coordinate joint activities, pertinent knowledge, beliefs, and shared assumptions	X	
	Model others' intentions/actions	Ability to model the intentions-actions vis-à-vis joint activity's state and evolution	X	

(*continued*)

[1] We note that between papers or domains, "characteristics" are also referred to as dimensions, factors, features, constructs, traits, challenges. We use characteristics herein as a blanket term covering all these.

Table 1. (*continued*)

Citation	Characteristic	Definition	Common Ground	Autonomy
Klein, Woods, Bradshaw, Hoffman and Feltovich [1]	Mutual Predictability	Being predictable and able to predict other's actions	X	
	Directability	Capacity for deliberately assessing and modifying other parties' actions in a joint activity as conditions and priorities change		X
	Revealing status & intentions	Agents make their own targets, states, capacities, intentions, changes, and upcoming actions available/obvious to other agents who are supervising or coordinating with them	X	X
	Interpreting signals	Ability to send, receive, and interpret signals to form models of teammates, including non-verbal cues	X	X
	Goal negotiation	Ability to enter into negotiation when a situation changes and team must adapt; convey current and potential goals		X
	Collaboration	Given and take; processes of understanding, and task execution are necessarily incremental, subject to negotiation, and forever tentative		X
	Attention management	Ability to direct each other's attention to important signals, activities, changes in an intelligent and context-sensitive manner	X	X
	Cost control	Achieving an economy of effort, including time and energy		X

(*continued*)

Table 1. (*continued*)

Citation	Characteristic	Definition	Common Ground	Autonomy
Ososky, Schuster, Jentsch, Fiore, Shumaker, Lebiere, Kurup, Oh and Stentz [26]	Shared Mental Models	Knowledge structures held by a team about relevant capabilities, knowledge, and interactions; enable predicting future system states given a set of inputs	X	
	Shared Situation Awareness	Ability to share task-relevant information after gathering information independently	X	X
	Dynamic Task Allocation	Human and Machine are assigned roles or functions according to abilities; Machine dynamically adjusts its behavior according to Human's action		X
	Coordination	Ability to interact dynamically, interdependently and adaptively; tasks are sequenced, synchronized, integrated and completed within established constraints		X
Lyons, Mahoney, Wynne and Roebke [2]	Perceived agency	Effective agents should be able to observe the environment, process relevant goal-oriented information, and act on the environment	X	X
	Perceived benevolence	Team mates have your best interests in mind, support each other, provide back up when needed	X	

(*continued*)

Table 1. (*continued*)

Citation	Characteristic	Definition	Common Ground	Autonomy
Lyons, Mahoney, Wynne and Roebke [2]	Perceived task interdependency	Tasks are divided into components to be worked on separately by the human and machine to maximize effective use of capabilities		X
	Relationship building	Interactive affordances move from one-sided information-centric transmissions to more naturalistic dialogue-based interactions	X	
	Communication richness	Team mates are capable of rich dialog to convey task & team-based information, including social cues	X	
	Synchrony	Shared, synchronized mental models, including common perception of team/members' capabilities, task, context; facilitates joint adaptation and anticipation of each other's actions	X	

Distilling the characteristics of a machine teammate into two dimensions offers a simplicity that can aid technology design to support HMT. Certainly, the numerous factors that comprise each high-level dimension are important to consider. However, reducing many characteristics to two high-level dimensions may help eliminate possible redundancies among the low-level characteristics, enabling researchers and practitioners to more easily explore and visualize the relationships between these two critical dimensions.

6 Future Research

Our hypothesis that the many design characteristics for HMT reduce down to the two critical dimensions proposed herein, establish and maintain common ground and autonomy, remains to be tested. Future research will pursue both conceptual mappings between characteristics and critical dimensions and empirical usability testing with HMT systems. The former will entail directly asking people to consider the importance of each potential machine teammate characteristic in multiple potential contexts (e.g., everyday smart home appliances, intelligent driving assistants, job-related technologies). The latter, longer effort, will entail designing variations in actual systems for human user experiments. Over this series of evaluations, we will assess the degree to which common ground and autonomy are both necessary and sufficient for a machine to be perceived as a true teammate. As outlined in Table 1, designers interested in developing machine teammates have a variety of characteristics to consider. As we examine the potential to collapse those onto common ground and autonomy, we may identify additional characteristics that do not fit either dimension, or we may identify application domains where more nuance is required. Empirical support that common ground and autonomy act as two critical dimensions would provide much needed clarity and organization for the design community. Such work would also pave the way for research to more deeply explore the relationship between these two critical dimensions of a machine teammate.

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