Interdependence as a Framework forCommon Ground in Joint activity

1 Introduction

Autonomous machines have taken a prominent role in the media debates in recent years, whether the topic is autonomous drones[1], autonomous cars[2] or autonomous surgery[3]. The use of the label "autonomous" invokes the idea of independent actions by these mechanical beings and the debate often centers on how much we should let these machines do[4]. However, despite the moniker "autonomous", all of these systems do not work independently, but instead are *interdependent* with people. Most "autonomous" systems are better described as human-machine systems and as such their activity is better described as joint activity.

The view of robots as teammates has grown as the field of robotics has matured. The future will belong to collaborative or cooperative systems that do not merely *do things for* people, "autonomously," but that can also *work together with* people, enhancing human experience and productivity in everyday life (Bradshaw, Dignum, Jonker, & Sierhuis, 2012). While working together with people increases complexity as compared to standalone systems, it also brings an opportunity for extending individual capabilities and increasing resilience through teaming. Eduardo Salas et al. (Salas, Cooke, & Rosen, 2008) provide insight into why humans work in teams. "However, simply installing a team structure does not automatically ensure it will operate effectively. Teamwork is not an automatic consequence of co-locating people"(Baker, Day, & Salas, 2006, p. 1579). Similarly, putting a human "in-the-loop" does not guarantee effective human-machine teaming. If human-machine teaming is to be viable, then it will be important to understand how a developer designs a system to work effectively as a teammate.

One of the key challenges to automation becoming an effective teammate is establishing and maintaining common ground (Klein, Woods, Bradshaw, Hoffman, & Feltovich, 2004).Common Ground refers to the pertinent mutual knowledge, mutual beliefs and mutual assumptions that support interdependent actions in some joint activity(Clark & Brennan, 1991; Klein et al., 2004). The challenge with common ground is that it requires a grounding process (Brennan, 1998; Klein, Feltovich, Bradshaw, & Woods, 2005) to establish and maintain it. People develop the capabilities to support this process through social engagements throughout their life, but robots require support mechanisms to be designed into them.

We propose a framework based on interdependence as the meansto understanding the common ground needed around joint human-robot activity.The framework is based on three core interdependence relationships; observability, predictability and directability. We propose these three interdependence relationships are foundational to determining what information needs to be shared between humans and robots and how a common basis between humans and robots can be achieved in order to enable smooth human-robot joint action. They provide the basis for a sound design method that enables developers of human-machine systems to address the establishment and maintenance of common ground. We also introduce a design tool, called the Interdependence Analysis (IA) table, as a means to understand system component roles in common ground and how those evolve as team execution strategies change during execution. This approach has been validated in our work with unmanned aerial vehicles (Carff & Johnson, 2009)and more recently during the DARPA Robotics Challenge(Johnson et al., 2015).

[1] http://www.wsj.com/articles/autonomous-weaponized-robots-not-just-science-fiction-1449763884
[2] http://www.wsj.com/articles/baidu-plans-to-mass-produce-autonomous-cars-in-five-years-1464924067
[3] http://www.wsj.com/video/autonomous-robotic-surgery-takes-a-step-forward/B55E5343-CC0B-4742-962E-2FAD9DE4D298.html
[4] http://blogs.wsj.com/speakeasy/2012/08/23/isaac-asimov-warned-us-about-combat-drones/

2 Defining Interdependence

In his seminal book, James D. Thompson (1967) recognized the importance of interdependence in organizational design. Similarly, we feel that understanding interdependence is critical to the design of human-machine systems.Thompson (1967) noted that there was a lack of understanding about interdependence, which is still true today. Much work being done in this area focuses on teams of people (e.g. Cohen & Levesque, 1991; Fiore, 2008; Saavedra, Earley, & Van Dyne, 1993; Salas, Bowers, & Edens, 2001; Salas et al., 2008; Salas & Fiore, 2004) though there has been an effort to bridge these conceptual understandings to human-robot, human-agent and agent-agent systems (e.g. Breazeal et al., 2004; Cuevas, Fiore, Caldwell, & Strater, 2007; Jonker, Van Riemsdijk, & Vermeulen, 2011; Sierhuis et al., 2003; Sycara & Sukthankar, 2006; Sycara, 2002; Tambe, 1997). Understanding the nature of the interdependencies among groups of humans and machines provides insight into the kinds of coordination that will be required. Indeed, we assert that coordination mechanisms in skilled teams arise largely because of such interdependencies (Johnson et al., 2011). For this reason, understanding interdependence is an important requirement in designing machines that will be required to work as part of human-machine systems engaged in teamwork.

We define interdependence in the context of joint activity as follows:

> *"Interdependence" describes the set of complementary relationships that two or more parties rely on to manage required (hard) or opportunistic (soft) dependencies in joint activity.*

Our definition of interdependence builds on the idea that interdependence is about relationships. It includes the purpose of these relationships which is to manage dependencies in joint activity. We emphasize that some dependencies are "hard" (absolutely necessary for carrying out the joint activity) while others are "soft" (defining possible opportunities for improving joint activity).

3 Interdependence System Model

What distinguishes joint activity from individual activity? Consider an example of playing the same sheet of music as a solo versus a duet. Clark (1996) observes that "a person's processes may be very different in individual and joint actions, even when they appear identical." The difference is that the process of a duet requires ways to support the interdependence among the players. From a designer's perspective, this means participants in a joint activity have additional requirements beyond the taskwork requirements. Where do these requirements stem from? They derive from interdependence and the need to understand and influence those engaged in the joint activity. In our framework, these requirements concern observability, predictability, and directability (OPD).

Observability means making pertinent aspects of one's status, as well as one's knowledge of theteam, task, and environment observable to others. Since interdependence is about complementary relations, observability also involves the ability to observe and interpret pertinent signals. Observability plays a role in many teamwork patterns e.g., monitoring progress and providing backup behavior.

Predictability means one's actions should be predictable enough that others can reasonably rely on them when considering their own actions. The complementary relationship is considering others' actions when developing one's own. Predictability is also essential to many teamwork patterns such as synchronizing actions and achieving efficiency in team performance.

Directability means one's ability to direct the behavior of others and complementarily be directed by others. Directability includes explicit commands such as task allocation and role assignment as well as subtler influences, such as providing guidance or suggestions or even providing salient information that is anticipated to alter behavior, such as a warning. Teamwork patterns that involve directability include such things as requesting assistance and querying for input during decision making.

Others in the HRI community have also identified OPD as critical issues.A notable example is Stubbs, Hinds, andWettergreen's(2007) field study of HRI; they do not use the same terminology we do, but the correlation is evident. They state that "had the science team been able to observe the robot executing commands in the desert, they would have had enough contextual information to disambiguate problems"(Stubbs et al., 2007, p. 45). This is akin to observability in our model. They also state, "we noticed that issues arose around why the robot made certain decisions"(Stubbs et al., 2007, p. 47). This is an issue of predicting the robot's behavior. The system was assumed to have no directability since "only the robot could perform certain actions, and the science team couldn't exert authority in those situations"(Stubbs et al., 2007, p. 49). However, it is not hard to imagine how better support for directability would have been beneficial in the system being studied.

By using the OPD framework as a guide, a designer can identify the requirements for teamwork based on which interdependence relationships the designer chooses to support. The framework can help a designer answer questions such as "What information needs to be shared," "Who needs to share with whom," and "When is it relevant." From a designer's perspective, OPD are important because they provide guidance on how to identify design requirements. By determining how these capabilities must be supported in order to be capable of understanding and influencingteam members, designers can create a specification. This design stance necessarily shapes not only the "user interface"for the human but also the implementation ofa robot's autonomous capabilities.

4 InterdependenceAnalysis and Design Tool

We have developed and employed an analysis tool that we call the Interdependence Analysis (IA) table, as shown in Figure 1. It is similar to traditional task analysis techniques (Annett, 2003; Crandall & Klein, 2006; Endsley et al., 2003; Schraagen et al., 2009), but we extend these types of analysis tools to support designing for interdependence by allowing for more types of interdependence than just task dependency, representing other participants in the activity by name or by role, allowing for assessment of capacity to perform and support, allowing for soft constraints, and allowing for consideration of role permutations.

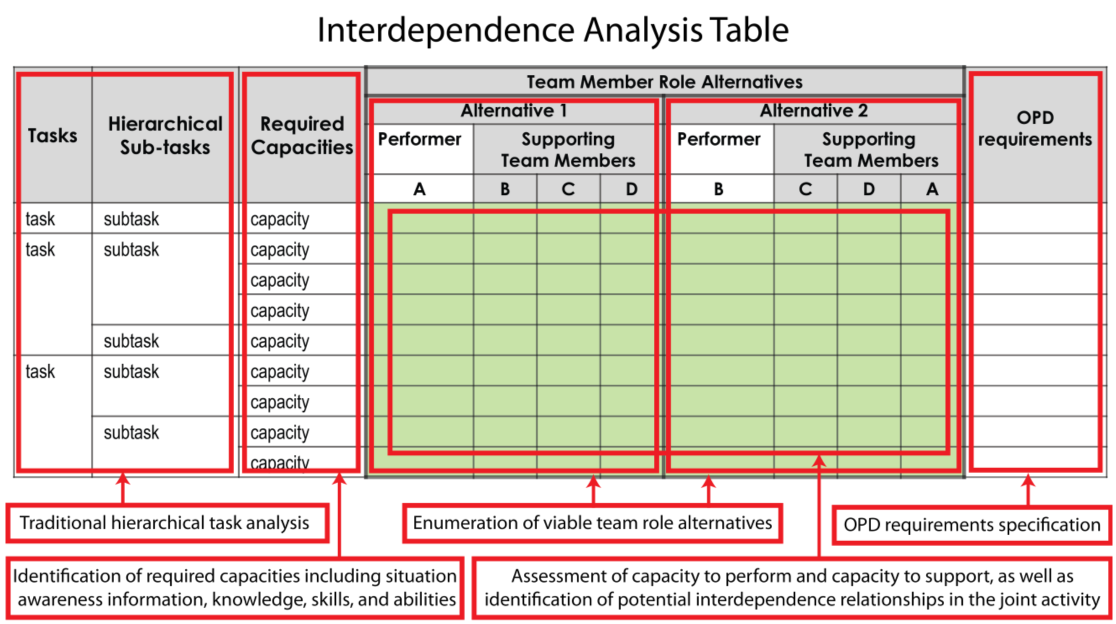

Figure 1 Interdependence Analysis (IA) Table

The IA table begins by identifying the required capacities for the activity and requires traditional task analysis as an input, as well as knowledge of the team members, their capabilities, and the anticipated situation (e.g., environment). Then the team role alternatives are enumerated. They can be thought of as the adjustment options in Adjustable Autonomy or the initiative options in Mixed-Initiative. However, what they really are is an enumeration of the possible ways a team can achieve the task. After the team alternatives are determined, the next step is the assessment. In order to aide future analysis, the assessment process uses a color coding scheme, as shown in Figure 2. The color scheme is dependent on the type of column being assessed.Once the assessment process is finished, the color pattern can be analyzed.To determine the specific OPD requirements, the IA table is used to help provide a detailed specification based on who needs to observe what from whom, who needs to be able to predict what, and how members need to be able to direct each other.

Team Member Role Alternatives	
Performer	Supporting Team Members
I can do it all	My assistance could improve efficiency
I can do it all but my reliability is < 100%	My assistance could improve reliability
I can contribute but need assistance	My assistance is required
I cannot do it	I cannot provide assistance

Figure 2IA Color Scheme. Note the "Performer" has a different meaning than the "Supporting Team Member".

We used the IA table extensively during the DARPA Robotics Challenge and it was effective at helping identify important issues of common ground between our humanoid robot and the operator. An example IA table is shown in Figure 3.

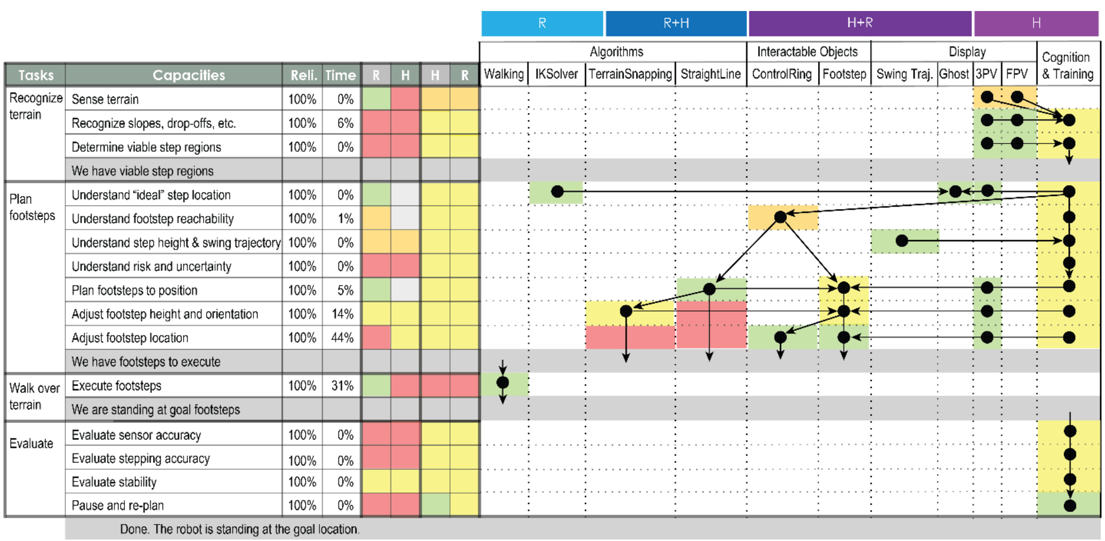

Figure 3 Interdependence Analysis table for the terrain task of the DARPA Robotics Challenge. It shows the potential interdependencies between the operator and the robot as well as viable workflows.

5 Conclusion

Interdependence provides a useful framework for understanding common ground. The three core interdependence relationships of observability, predictability and directability are foundational to determining what information needs to be shared and provides the basis for a design method that enables developers of human-machine systems to address the establishment and maintenance of common ground. Lastly, the IA table has been a useful tool for understanding system component roles in common ground and how those evolve as team execution strategies change during execution.