

Envisioning Human-Robot Coordination in Future Operations

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Abstract—Developers of autonomous capabilities underestimate the need for coordination with human team members when their automata are deployed into complex operational settings. Automata are brittle as literal minded agents and there is a basic asymmetry in coordinative competencies between people and automata. The new capabilities of robotic systems raise new questions about how to support coordination. This paper presents a series of issues that demand innovation to achieve human-robot coordination (HRC). These include supporting people in their roles as problem holder and as robotic handler, overcoming ambiguities in remote perception, avoiding coordination surprises by better tools to see into future robotic activities and contingencies, and responsibility in human-robot teams.

Index Terms—Human-robot-interaction, remote perception, presence, affordances, design methods, human-automation interaction.

I. COORDINATING HUMAN AND ROBOT TEAMS

HOW can we support future human-robot teamwork in differing operational contexts such as search and rescue, military operations in urban settings, and coordinating multiple UAVs/UGVs [1]? This is a problem of envisioning the future of operations undergoing organizational and technological change [2]. These kinds of design envisioning tasks are difficult as different specialists each have only partial views of the potential future impact of alternative design directions [3]:

- It is easy to underestimate the complexities of operational settings.
- It is difficult to examine team play and coordination in evolving situations.
- There is a strong tendency to treat each difficulty in each specific future scenario offered as a specific glitch to be

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addressed one at a time (incremental revision in the face of new cases).

- Each discipline tends to stay in their own point of view.

This paper examines a series of issues that will be critical in supporting future human-robot teams. These issues are particularly relevant to such fields of practice as urban operations and chemical/biological incident response, which present problem holders with changing resource pressures and changing demands on performance. In such cases, the military and emergency first responders are under new pressures, for example, the possibility of first response to injuries from chemical, biological, or radiological incidents.

To anticipate the coordination needs required by introducing robotic systems into an existing workplace, we need to understand the effects of technological change [2]. Generalizing results across many examples of increases in autonomous machine capabilities, we find—

(Robin) Murphy's Law: any deployment of robotic systems will fall short of the target level of autonomy, creating or exacerbating a shortfall in mechanisms for coordination with human problem holders [4], [5].

As robotic system developers strive to achieve a certain level of autonomy, in general, they underestimate the need for coordination with human stakeholders. Deployment into a field and context will leave the robotic system short of the design target level of autonomy, without sufficient provision for human problem holders involvement in handling the situation with or through the robotic system.

This statement generalizes past results on breakdowns in coordination between automata and people [6] [7], [8] with recent experiences from deploying robotic systems in urban search and rescue. The research and experience base shows that, as autonomy and authority of automata increase, the demands for more sophisticated forms of coordination go up as well [9]. This is in stark contrast to the common beliefs that expanding the capabilities of automata reduces human roles in the system and reduces the need for coordination with those people. The difficulty is that, in envisioning future technological capability and future operational systems, it is easy to underestimate the demands for coordination. Plus, development always will be aiming higher than it can currently reach in terms of autonomous capability [4] so that pressures to deploy in the shorter run (from new operational pressures/demands) will add to the shortfall in support for coordination.

II. ENVISIONING AT THE INTERSECTIONS

A. A Robotist, Cognitive Engineer, and Problem Holder Confront Demanding Work Settings

To envision future coordination needs as robotic systems are introduced into demanding work settings, various sponsors have brought together representatives of three perspectives in knowledge elicitation sessions grounded in scenarios of possible future operations: evolving robotic capabilities, cognitive engineering results on coordination successes and coordination breakdowns in human-automation teamwork, and the demands of work settings where robotic capabilities offer promise of new levels of performance. Through participation in three such sessions on urban combat, first response to chemical/biological incidents, and urban search and rescue, this section reifies the kinds of interchanges that occur repeatedly in the form of three characters: a robotist, a cognitive engineer, and a reflective practitioner as problem holder as they envision future operations with robotic systems.

The three apocryphal participants in this exchange serve as personifications of the three cycles of research and development (R&D) in the framework developed in [10]:

The *problem holder* (and reflective practitioner) in the discussions represents timely introduction into practice of new systems to meet pressing needs. Demands for new levels of performance and pressure to be more efficient with resources lead organizations to make significant investments in new rounds of development (and if necessary research) to field the infrastructure for new operational systems (e.g., soldier-robot teams). As a leader in a development process, this character is under a perceptible and omnipresent shadow to demonstrate progress toward fielding new systems in a reasonable time frame. As a reflective practitioner (a veteran lead practitioner), he represents the ideal where the development process is grounded on direct experience with the real difficulties of the operational setting, e.g., urban military operations; search and rescue scenarios.

The *robotist* represents advancing what machines can do autonomously (advancing the technology baseline). In advancing the autonomous capabilities of robotic systems, consideration is given to human interaction issues in terms of (a) building interfaces for remote humans to communicate, guide, instruct or takeover control with robots, and (b) social/organizational consequences of advances in robotic capability. The former is a Robot-Human Interaction perspective (or RHI approach to people and robotic systems) in that advances in robotic systems come first and then drive questions interfaces to people as residual or secondary issues. The latter sees robots becoming more animate and more like artificial persons (or an AP approach to people and robotic systems). and is concerned with the implications of introducing artificial persons into the human sphere [11], [12].

For the technologist, the demands and pressures placed on fields of practice become windows of opportunities for

investment in expanding the autonomous capabilities and in deployment of these capabilities. And the reverse applies as well, promoting the potentially available increases in autonomous power shapes problem holders and stake holders expectations and therefore demands on future operational performance. In envisioning the future, the departure point is that it is self-evident that the autonomous capabilities under consideration have utility so that the critical question is creating the power. Issues about how to wield that power are secondary.

The *cognitive engineer* represents the efforts to abstract lessons about what has been useful (and not useful) in practice to perform cognitive work and coordinative activity successfully, especially as technology and organizations change. Abstracting patterns in cognitive work and coordinated activity across specific fields of practice grounds the development of hypotheses about what would prove useful and about the impact of to-be-realized systems [13]. For the case of human-robot coordination, the cognitive engineer is concerned with using past findings on the reverberations of shifts in levels of autonomy and authority of machine agents to guide the deployment of potential powers of robotic systems (see [7], [14] on the case of aviation automation).

The different perspectives across the three cycles can be defined in terms of the differing status of prototypes. For the technologist, prototypes represent *future technological powers* (what could be available in the technology ‘store’ for problem holders to deploy). For the problem holder, prototypes represent *partially refined final products* – the system that will be fielded as processes of detailing and glitch identification and repair are completed given the schedule pressures. For the cognitive engineer, prototypes represent *tools for discovery* – hypotheses about what would be useful subject to empirical jeopardy. The figure of merit in this case lies in the adaptive response of fields of practice to changes represented or enabled by the introduction of new artifacts—how practitioners and others adapt to exploit new capabilities or workaround new complexities.

B. Stories of Future Operations

The scene opens with briefings on the functions and difficulties in the setting of interest. The fields of practice considered here—urban operations and chemical/biological incident response – represent changing resource pressures and changing demands on performance, despite or because of past success. In one of the cases used here, the military are under new pressures where adversaries are embedded in urban infrastructure and populations.[15] Urban warfare traditionally has leveled the playing field with asymmetric foes and has had high potential for casualties (e.g. consider -- the Tet offensive in Hue City, Vietnam 1968; the US experience in Mogadishu on October 3rd, 1993 during the Somali Civil War; the battles for Grozny, Chechnya in 1995 and 1996; and the 2002 Israeli operation in Jenin, West Bank). Previously, the policy for effective commanders was to avoid cities and urban warfare. In the

case of emergency first responders, new pressures arise for search and rescue operations with the possibility of injuries from chemical, radiological, and biological incidents (e.g., consider the Tokyo Sarin Gas attack, 1996 and the Russian rescue of hostages in a Moscow theatre in 2002).

Grounding the three perspectives on the characteristics and performance demands of these settings enables a discussion of team play and coordination in evolving situations [16]. As the discussion builds the three different points of view intertwine.

1) *‘I want to talk about autonomy ...’*

The mindset of the roboticist is how the needs of the problem holder have implications for what robots can do autonomously. The discussions are viewed through the filter of questions such as—how do I get robots to do that? we can get robots to do this. He tries to understand the desires/needs of the problem holder and reformulate those statements in terms of the maturing capabilities and constraints of robotic technology in mobility, sensors, communication. The discussion points he raises center on the pace and character of the advancing technology baseline.

As the scenario triggers discussions focusing on the human factor and interactions across people and robots, his perspective shifts from robot autonomous capabilities given physical constraints to robot interaction with various people. The interaction requirements are viewed as another set of drivers on autonomous capabilities of the robot (can I get it to do that, where ‘that’ involves communication and updating to/from remote people).

His interest focuses on how to resolve tradeoffs and constraints in robot capabilities versus task demands (tradeoffs created by power limits, bandwidth limits, size, range, etc.). Envisioning future robots for such teams requires balancing these interacting constraints, therefore he focuses the conversation on trying to better understand the performance demands of the problem holder. Practically, the roboticist is figuring out what kinds of working systems could be supplied to the problem within varying time/resource constraints. He considers how to integrate capabilities *and limits* across sub-areas of sensing, mobility, communication (e.g., range limits on wireless communication) into a system that could be fielded into the operational setting.

The backdrop for these discussions is the assumption of future ubiquity and impact of robotic systems, e.g., in x years, robots will be generally accessible, effective, therefore, of common experience, and dramatic in impact on human roles. Given these assumptions, discussions of the relationship between people and robots can lead to broader discussions on the relationship of people to robots as one or another kind of non-human ‘persons’. Robots as agents that can move (and more) on their own in the physical world raise questions about what is an agent, what makes for animacy, and what are the implications of introducing artificial persons into the human sphere (robots as animate and artificial persons, or an AP level of analysis of people and robots).

2) *‘I desperately need help to meet real and pressing demands ...’*

The reflective practitioner emphasizes the new pressures where adversaries are embedded in infrastructure and populations (asymmetric urban operations), and highlights new capabilities such as technical rescues in which the team needs to stabilize damaged structure while performing search and rescue. She considers particular difficulties that need to be overcome: ‘I want to talk about how to get across the street in urban combat, rescue a wounded comrade, enter a room with possible hostiles but also with innocents mixed in.’ Or, ‘I want to talk about how to determine quickly the appropriate care responses to those injured from chemical/biological agents, extend the time human personnel can conduct search and rescue operations in a chemical/biological hot zone, and how to recognize the care needed while the injured are transferred to decontamination stations.

She tries to steer the envisioning process by referring to or playing out stories that illustrate the difficult demands that arise and strategies that have evolved to meet these demands. These stories emphasize how people work in teams and as units, not merely as individuals, to coordinate activities, adapt to surprises, and achieve goals. But it is extremely difficult to consider how the current system will change and function effectively when robotic platforms are introduced into the mix.

As the roboticist lays out advancing capabilities, the reflective practitioner tries to consider how to translate these items (e.g., sensors, mobility) into the operational structure of their organization and the roles of the people who make up the team (their skill sets and processes). As the reflective practitioner/problem holder considers the match of robotic capabilities with demands, she realizes that there are new forms workload as people need to coordinate with these kinds of robotic systems. With limited slack available in the current team organization, she asks, ‘who is going to work with this robot?’ ‘The personnel are all busy already so there is no one to run this?’ The notion that the robotic system will simply replace some person or substitute for a person in some function seems to miss how the current staff do the work together, intertwine and shift roles fluently, coordinate activities, and rely on each other in difficult and demanding situations.

The reflective practitioner describes the team work mentality that pervades the organization – team members rely on each other even trusting each other with their lives. How does a robotic system fit into this atmosphere? Is it a reliable partner? Is its behavior predictable across the range of situations that they might face?

3) *‘I want to talk about adapting to complexity ...’*

The cognitive engineer considers how the changing capabilities and demands will transform the nature of practice, what complexities will need to be worked around, what capabilities will be exploited by leaders, what side effects of change will need to be accommodated. His starting point is understanding the nature of practice, how that links to patterns in the research base, and how new

performance demands and resource pressures potentially reshape the nature of practice [17]. As a result, the cognitive engineer tries to probe the practitioner's experience base and – since this a reflective practitioner – to explore his models of what makes situations difficult in urban or rescue operations. What kinds of surprises and adaptation are needed? How do current teams achieve resilience and robustness? How will practitioners compensate for brittleness and other limits to automata?

He uses the research base on the interplay of people, technology and work as possible storylines. Examples of abstract patterns in cognitive work such as cascading and escalating demands as situations evolve, how to escape or avoid data overload, how to build a coherent assessment from partial data and views coming in over time; how to avoid coordination surprises; how teams adapt when plans are disrupted; how the system will gracefully degrade or reconfigure as assets are lost. The goal is use to past findings on patterns in cognitive work and coordinated activity to find leverage points and critical issues. These patterns are valuable because they help a field of practice avoid repeating or re-learning lessons about cognitive work and coordinated activity abstracted from experiences in other settings.

The cognitive engineer listens very intently to the discussions of the technology changes coming because this information helps him anticipate the kinds of coordination that will characterize the future operational world and how human roles will change with new automata (e.g., how new forms of automata could create workload peaks at high tempo or high criticality periods). To do this he needs to draw on a research base that characterizes the dynamics of people, technology and work.

C. Talking in Synchrony?

Initially, there is a natural tendency for each of these perspectives or cycles to spin inwards exclusively rather than synchronize outwards. The cognitive engineer is sketching scenarios for exploring coordination in human-robot teams, including prototypes as tools for discovery of what would be useful. He is thinking -- how do the issues capture or challenge previously abstracted patterns? how can those patterns in cognitive work be used to explore new forms of coordination emerging in this setting?

The problem holder focuses on learning as much as possible about the growing but concrete capabilities of robots to determine how these might help him escape the traps and dilemmas of urban operations or search and rescue missions (what is reliable and fieldable).

The roboticist is pondering how to reconcile the varying competing constraints to match robot autonomous performance levels with scarce resources and how to integrate component capabilities/limits into a robotic system adapted to the demanding performance required by this application.

As a result, each easily can talk at different levels of the analysis mis-connecting, e.g., discourse on component tasks and lists of capabilities make little contact with

discourse on how operational skills are adapted to differing situational demands or resilience in adapting to changes and surprise.

As the three perspectives begin to synchronize, points of contact emerge. For example:

Problem holder: 'What obstacles can it clear?'

Roboticist: 'It can go over items 15" or less.'

Cognitive engineer: 'How do (would) you tell?'

Practitioner: 'We drive up to the obstacle and if it's higher than the treads we know it cannot be scaled.'

Cognitive engineer: 'The practitioner's heuristic is an example of workarounds and inferences people develop to make up for the impoverished perceptual view through the robotic platform's sensors. In contrast when people are in environment being explored they pick up these affordances immediately.'

This interplay triggers consideration of a broad set of factors that affect movement over broken terrain, situational variables that complicate clearing obstacles, and perception of affordances of environments. An integrative challenge emerges around moving over broken terrain that has multiple reverberations for robot vision and sensing, fusion, enhanced visualization concepts for remote human observers, context sensitive reasoning about risk taking and more.

Another example, in first response human-robot teams, is that energy/time consumption in access and egress to the scene of contamination become dominating constraints for both people and robotic systems (getting in quickly to assess and triage given the risks to the victims and to the rescuers; getting injured out of hot zones quickly to decontamination stations and treatment). Again the interplay defines challenges that cross normal disciplinary boundaries and emphasize new connections.

R&D on HRC often assumes a *remote access* paradigm where the robotic platform is in the environment and the human roles are carried out far removed from the target environment (e.g., space exploration). But the settings explored in the envisioning sessions also mix in *distributed team* situations where a unit composed of robotic systems and people coordinate in the same general environment as in soldier-robot teams for urban operations, first response units to chemical/biological events, or astronaut-robot teams on space station. In these cases, robotic platforms may precede or look ahead for accompanying human actors, but people have the possibility of direct perception-action coupling to the environment of interest.

Overall, broad findings emerge when the three perspectives begin to synchronize, such as:

- Many types of tradeoffs must be respected and balanced.
- Robotic systems take direction and inform distant parties of local conditions.
- From the practitioner's point of view the robotic system is a resource with some, limited autonomy.
- Being a team member includes the ability to pick up and

adapt to the activities of others in the team to achieve coordinated activity.

- The target field of practice is extremely demanding and stresses the resilience of any unit as an adaptive team.
- Inevitably, robotic capabilities will exhibit brittleness as situations develop beyond their boundary conditions.
- The difficulties of balancing the multiple constraints and tradeoffs highlights the adaptability of people, given sufficient training and practice.
- Human capabilities that support high levels of coordination can be used as a competence model to stimulate new ways to use the wide and expanding technological possibilities.

In this process of interacting with the demands of practice and with the reverberations of new technological powers, a common language emerges whose units of discourse are defined in terms of the forms and functions of coordinated activity -- alternative forms of coordination between people and machine agents as they carry out activities in the world -- Human-Robot Coordination (HRC). The next section lays out some of the new issues that have emerged from these envisioning exercises.

III. NEW QUESTIONS FOR INNOVATION IN HUMAN-ROBOT COORDINATION

A. Intent at a Distance

Many technological advances can be viewed as means for perception at a distance or action at distance. In these cases technology extends our perception through sensors and scopes or extends our activities in terms of the sequences, precision, or forces we exert indirectly on the world (e.g., one act triggers a sequence of activities, or one activity is translated into the component physical actions needed to accomplish intent as in modern aircraft controls). New capabilities for robotic systems are a major step forward within this tradition of coupling people to scenes at a distance.

Fig. 1 starts from this tradition to provide a framework for human-robot coordination. The framework juxtaposes at the far left the human as problem holder, i.e., those people and groups responsible for achieving goals, and on the far right the world in which the person/group needs to project perception and action at a distance. Robotic systems provide a new form of perception-action coupling at a distance, especially when these systems are endowed with sufficient capability to move on their own beyond teleoperation only.

As the robotic system's perception-action coupling becomes more sophisticated, this power does not remove the human from the scene but ironically couples them in a way that is paradoxically intimate, though physically removed (or mediated). This relationship is fruitfully conceptualized as intent at a distance as robotic systems provide human stakeholders higher order means to achieve their goals (Fig. 1). The target for human-robot coordination is *projecting human intent into the world* (not

simply inferring or communicating intent across agents). Ultimately, robotic capabilities represent new powers for human problem and stake holders to project intent at a distance.

B. Robot Handler and Problem Holder Roles

But (Robin) Murphy's law, the basic asymmetry in coordinative competencies between people and automata, and other findings from human-automation teamwork reminds us of the limits of automata in coordinated activity (brittleness, literal-minded, etc.). Given the inherent potential for surprise in complex settings and limits of automata, there are two human roles in the ensemble which must be planned for in HRC. The *Robot Handler* role is responsible for managing the robotic capabilities in situ as a valued resource and points to the knowledge, practice, and interfaces needed to manage the robots in a physical environment. This differs from *Problem Holder* which refers to the human roles responsible for achieving mission goals and the associated knowledge and experience. The problem holder role arises from the fundamental constraint that people create, modify and operate automata in human systems for human purposes (see the fourth family of Laws that Govern Cognitive Work in [17]). For example, Casper and Murphy [4] found that the demands of search and rescue operations and the limits of robotic systems today led to an organization where these two roles are represented by different teams. The search and rescue personnel function as problem holders trying to characterize the search situation and achieve rescue goals, while the robot developers act as handlers who better understand robot capabilities and limits, and direct its capabilities [18]. Together they try to use the capabilities and workaround limits to achieve operational goals.

In complex settings difficulties cascade and demands escalate which will challenge robotic systems ability to compensate and demand coordination between people and robots [19]. Inevitably, robot capabilities will exhibit brittleness as situations develop beyond their boundary conditions [20]. Together, these represent challenges to the adaptive power or resilience of the human-robot ensemble (as illustrated by the only partial fit between the robotic systems and the mix of constraints in the world in question in Fig. 1).

Coordinating these roles with the limits of robotic systems creates critical guiding questions for assessing coordination: How will human team members recognize the approach to brittle boundaries and intervene effectively (e.g., bumpless transfer of control)? Inevitably, autonomous resources will be lost or fail. How will the team dynamically reconfigure or gracefully degrade as assets are lost? One function that tests coordination across these human and robotic roles is judgments of traversability or climability in context as such emergent judgments across all of the parts of Fig. 1.

[Figure 1 about here]

The next sections briefly consider issues in HRC moving from perception action coupling through the robot systems to adaptation to responsibility.

C. *Affordances and Remote Perception*

In remote explorations of an environment, a robotic system provides an action/perception stand-in at a distance (Fig. 1). This de-couples the natural dynamic relationship between properties of the scene being explored and the human perceptual system of the remote handler [21], [22]. The decoupling undermines the remote observers' perception of affordances in the scene [23] which is illustrated by recent cases of HRC where remote observers experience various difficulties in understanding the environment being traversed by a robotic system [5], [24]. While a great deal of work has addressed creating an illusion of presence for remote observers, this work has not addressed the fundamental ambiguities that arise in remote perception or how to enable the perception of affordances when access to a scene is mediated. In addition there is the issue of how to integrate partial views from a set of robotic resources into a coherent model of the environment for remote human observers.

Casper and Murphy [4] found examples of the difficulty in using remote vision effectively while studying the use of robots for search and rescue at the site of the World Trade Center (WTC) immediately after September 11, 2001. Rescue workers attempting to use robots to search areas of debris inaccessible to humans had to try to deal with the unexpected perception issues that arose in coordinating the robot's sensing of the world it was in and the remote observer's perception of that world. For this set of issues, the robot can be thought of as a remote, semi-autonomous sensor platform, and the problem is then determining what can we as remote observers understand about the environment being traversed by the robot.

To better understand these issues, consider a specific problem in remote perception – scale ambiguity. This ambiguity arose when robots were used to search through rubble at the WTC -- remote human operators were often unable to perceive whether the robot could pass through openings or over obstacles [5]. Note the contrast to our own perceptual performance. In a directly perceived natural environment, we are able to recognize immediately the scale of the environment relative to our ability to move through that scene (one kind of affordance we directly pick up). In a natural environment we have a very strong sense of our own body size and movement relative to the obstacles or passages we encounter.

This is an example of how people perceive the affordances of the environment based on perception of high level dynamic relationships such as point of view, relative scale, and rate of approach to obstacles [22], [25]. However, when we try to interpret visual information from remote robotic platforms our visual system must overcome the ambiguities that result from the disruption of the correlation between perceptual cues that exists in natural perception. For example, when an observer moves, the

vestibular system provides feedback about acceleration that can in principle be used to interpret rate of motion and thus provide a natural scaling of the distances in the environment. This information also is lost during remote perception. The robotic platform in the field may be moving to create the video images, but the remote observer's vestibular system is indicating the body is stationary. This is actually a cue conflict situation, and so the vestibular system is not merely providing no information about motion, it is contradicting what the remote observer sees.

Cues to depth are limited or in conflict in raw video feeds from robotic platforms. For example, a single camera view to a remote observer creates cue conflicts in binocular stereopsis --one of the most powerful cues to depth and surface shape for human observers. When looking at a video monitor of the remote scene with our two eyes, binocular stereopsis is indicating that all the objects in the remote environment are at the same depth. Of course other cues (e.g., motion parallax, shading, perspective, and texture deformation) are available in the video stream to counteract the flatness indicated by binocular stereopsis, but this cue conflict is another instance of the disruption of the correlations between visual cues found in natural vision.

Another important ambiguity which occurs for the robot handler involves the perceived rate of motion. The relationship between optic flow and rate of motion in the environment depends on our eye height, or camera height for the robotic platform [22], [25], [26]. Thus, some intermediate optic flow rate in the image could result from a slow moving small robot or a relatively fast moving large robot. When viewing video from a remote robotic system our visual system is processing the optic flow without motion feedback information and based on an eye height that may or may not match the camera's height. These discrepancies will introduce ambiguities and misperceptions of perceived velocity by the human operators viewing the remote video from robots.

The limited angular view associated with many remote vision platforms creates a sense of trying to understand the environment through what remote observers often call a 'soda straw'. This is an example of the keyhole effect in viewing large virtual data spaces [27]. Typical consequences of the keyhole effect include missing new events, increased difficulty in navigating novel environments, gaps or incoherent models of the explored space. Keyhole problems arise from the fact that typical virtual environments sever the foveal field of view and focal attention from the orienting perceptual functions that help people fluently know where to look next, despite the potential for new interesting events to intrude on ongoing activities.

Related to this, the mechanisms that allow people to coordinate direction of gaze and direction of movement as they move in a changing scene are removed in remote perception. But the link between the robot's direction of gaze and the mechanisms that support visual exploration of a scene are quite impoverished in today's robotic

systems/human-robot coordination mechanisms. For example, human gaze control is tuned to anticipate future movements and conditions of interest. Contrast how you would direct gaze as you turn to climb a stairs with scattered debris on it and with various items or activities of interest at the top of the stairs versus how robotic platforms position their cameras during the same maneuver. Generally, the robot camera either points at each step one at a time or remains pointed at the ceiling as the robot climbs, whereas people direct and shift gaze in tight coordination with the affordances present in the situation given their purposes and context (e.g., when to look at the activities heading for the top of the stairs and when to look at potential obstacles along the stairs).

Our main point in describing these perceptual ambiguities is to make clear that seeing through a remote camera is not the equivalent performance as having a human observer at a scene. Perception is an active process in which the observer causes the visual image to change by performing actions in the environment [23]. When human handlers interact and coordinate with remote robotic platforms, the perception-action cycle becomes mediated, and the robot handler must respond based on the action capabilities and limitations of the robot rather than his own.

When we fail to appreciate the impoverished nature of the stimulus set in remote perception, we are surprised by findings such as in [24]. Darken and colleagues asked remote observers to track their spatial location and identify objects based on video footage from a remote reconnaissance mission, and found that neither task could be performed adequately. Such results leads to the conclusion that the raw video needs to be enhanced to recover what was lost by decoupling the human perceptual processor from the environment being explored.

D. Functional Presence

The ambiguities in remote perception are part of a broader challenge of creating shared perspective across agents-in-the-scene and remote agents so that they can productively interact and work together. How do we synchronize models of the world across these agents, detect discrepancies and repair them? Understanding the processes involved in creating shared world-views is particularly important in the case of semi-autonomous robotic agents that are operating with direction and intervention from problem holders and handlers.

Shared perspective typically has been framed in terms of the goal of ‘presence.’ Identifying specific ambiguities in remote vision situations shifts the research goal to achieve what we term *functional presence*. Functional presence occurs when a remote observer has sufficient information available to his senses to effectively function as if he were directly perceiving and acting in the remote environment. The emphasis is thus not on creating the “you are there” impression, but instead on providing sufficient perceptual information so that the remote observer can pick up affordances from the environment as if they were there, i.e.,

to enable the natural competencies of perception in exploring and behaving in the scene. Thus, the breakdowns noted in [5] and [24] are natural and expected consequences of the impoverished perceptual environment created by video feeds from remote environments.

To accomplish functional presence research is needed to identify and implement perceptual cues that can augment the remote video stream and allow the human perceiver to compensate for the absence of the complex combination of naturally occurring information (e.g., vestibular feedback) that would exist if he were actually investigating the environment. These cues will be ones that re-establish in the impoverished video stream information about point of view, relative scale and rates of approach, i.e., properties of the environment that defined with reference to the observer/actor.

E. Avoiding Coordination Surprises: Seeing into Future Activities and Contingencies

To achieve new levels of coordination, past research has shown that increases in the level of autonomy and authority of automata require an *increase in the levels and kinds of feedback between agents* about their current, but especially *future*, activities as system state varies. Field studies, incidents and simulation results all reinforce this as a basic finding or ‘law that governs cognitive work.’ When this relationship is ignored coordination surprises occur between agents [8]. The research challenge is to define the levels and forms of feedback needed to achieve coordination across partially autonomous human and computer agents [28]. Critical to the new forms of feedback are representations of automation activity that capture events, are sensitive to future developments, and integrate data into higher order patterns -- not simply current process state or automation configuration.

For example, as robotic systems have the capability to follow plans and to shift to a new plan as the situation changes (e.g., current UAVs), how will human supervisors monitor robot plan selection, plan following, recognize disrupting events, and modify plans [29]?

F. Directing and Delegating

Past research also has shown that increases in the level of autonomy and authority of automata require mechanisms to manage or re-direct automated systems as resources -- *directability*. Giving human agents the ability to observe the automation’s reasoning processes and activities against the evolving state of the world is only one side of the coin in shaping machine agents into team players. Human supervisors also need the ability to substantively re-direct the machine agent’s activities.

From the point of view of coordination, human-robot design is concerned with the kinds of coordination strategies available and how to shift dynamically from one strategy to another as context changes. How will handlers give and robots take direction [30]? A sample of the possible generic strategies include: plan based direction, constraint based direction, direction through commanders

intent. In plan based direction, mission and contingency plans are developed in advance; distant human direction modifies these plans or directs the robot to switch to a different plan [31]. In the absence of specific direction from distant handlers, the robot selects a plan or contingency to follow given its on-board criteria. This is the form of coordination used with some of the Air Force's UAVs and used by NASA with space exploration missions. In constraint based direction, remote robot functions autonomously, while distant human monitors direct the robot by introducing constraints on its freedom of action (autonomy). This form of coordination is being developed and explored for the national air transportation system for aircraft-ATC coordination under enroute free flight rules. Commanders intent is the form of coordination used in military command and control for adapting plans to surprises, both disruptions and opportunities [32]. In this form of coordination commanders communicate the intent behind the plan to subordinates who will be on the scene (the robotic platform in the future). When disruptions to the plan occur, the actors in the scene use the intent information to adapt activities to achieve the goals of the plan. The measure of different strategies for giving/taking direction is the team's resilience in adapting to surprises.

G. Responsibility in Human-Automation Teams-Remote Responsibility

How does responsibility for the consequences of actions influence the design of human-robot coordination? Billings has developed a set of first principles for responsibility in human-automation systems which build from a basic premise ([7], p. 39): *Some human practitioners bear ultimate responsibility for operational goals* (see also [17] particularly the fourth family of laws on responsibility in cognitive work). As a result those with responsibility within the system must have some means to effectively command within that scope of responsibility (as problem holders): *These supervisory human operators must be in command* ([7], p. 39) The question, then, is what does it mean to be 'in command' of robotic agents and what does it mean for robotic agents to be part of a 'command'? Billings answer is that to be in effective command within a scope of responsibility, the supervisory agent ([7], p. 39):

- must be involved;
- must be informed;
- must be able to monitor the automation or other subordinate agents;
- must be able to track the intent of the other agents in the system.

The automated systems' and other subordinate agents' activities therefore must be comprehensible and predictable.

IV. WRITING THE FUTURE STORY OF HUMAN-ROBOT COORDINATION

The interplay across the R&D roles represented by the three characters creates new questions to be pursued and new possibilities for wielding the power of robotic systems while taking seriously the limits of automata.[17] The

advancing capabilities create new opportunities (and new demands) to envision alternative forms of coordination between people and machine agents as they carry out activities in the world. Studying new forms and functions in coordinated activity, given robotic capabilities, then can seed development of specific systems in specific work contexts.

The developments underway in human-robot coordination also become a setting for considering how to aid envisioning as a process of discovery. In this case our three characters are writing out stories of future operations, as they are also actors in the unfolding story. Neither as writers, actors, stakeholders or audience does any one participant have a clear view of the events to come or the ending. The remainder of the story will emerge as real people and organizations balance or mis-balance the intermingled roles, synchronize or mis-synchronize the three perspectives to achieve new forms of coordinated activity to serve human purposes [10].

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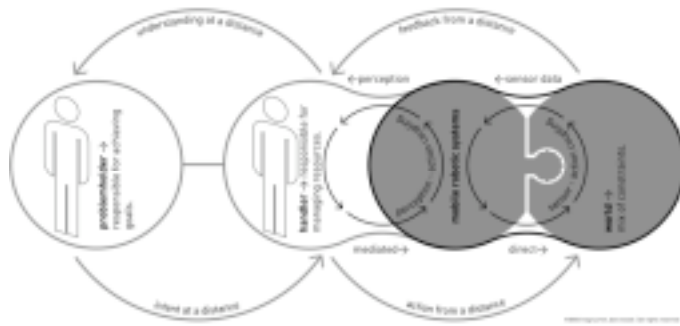


Figure 1. Roles in Human-Robot Coordination. Robots allow a **Problem Holder** to project intent at a distance through a **Robot Handler/Robotic System Couple**. The sensor-action coupling of the robotic system to the world is unstable due to the inherent brittleness of automata and can drift as situations change (indicated in the figure by the loose fit between the robotic system and the world). The robot handler can anticipate context shifts and adapt to re-align this coupling.