COLLABORATIVE TOOLS FOR MIXED TEAMS OF HUMANS AND ROBOTS

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Abstract This paper discusses efforts at the Idaho National Engineering and Environmental Laboratory (INEEL) to develop a control architecture for mixed teams of ground and air vehicles. Our approach has been to consider the air vehicles, ground robots and humans as team members with different levels of authority, different communication, processing, power and mobility capabilities and also different perceptual capabilities. The paper examines the current control–architecture and interface with special attention to the role of a collaborative workspace in enabling mixed-initiative interaction between humans and heterogeneous teams of robotic vehicles.

Key words: Collaborative control, human-robot interaction, dynamic autonomy

1. INTRODUCTION

The potential exists to extend the capabilities of autonomous operations through synergistic interaction between ground and air vehicles. Autonomous, unmanned ground and air vehicles may complement one another in powerful ways. For instance, ground robots can encounter a rich slice of their local environment, yet are often limited by the lack of an accurate 'god's eye' view. To address this limitation, air vehicles can be used to travel large distances, gathering intelligence and reconnaissance data, which helps to orient ground robots within the global environment. In turn, ground robots can support air vehicles by carrying heavy, power hungry sensors, sharing computational processing, relaying communications, providing close up visual and perceptual reconnaissance and even through close proximity interactions such as deploying, refueling and retrieving air vehicles. This paper discusses recent efforts at the INEEL to develop a control architecture that supports mixed-initiative human – robot teaming for a small team of robots. The prototype control architecture has been implemented on a number of ground vehicles and is currently being extended to a number of real and simulated assets through collaboration with the US ARMY Simulation and Training Command and the Tactical Technology Office of the Defense Advanced Research Projects Agency.

This paper describes efforts to create a dynamic umbrella of adjustable autonomy control that can support a spectrum of team interactions throughout a mission as individual capabilities change and needs arise. As workload, data link connectivity, knowledge and action potential change, dynamic autonomy enables each member to adjust its level of autonomy on the fly, leaning on its own, intrinsic intelligence as needed. The vision is that of a continuously adapting control architecture where all team members, including humans, air vehicles and ground vehicles, are empowered to self-monitor, maintain awareness of the environment and task, and actively and cooperatively pursue mission objectives using a common substrate – a collaborative workspace. By sharing information about the task and environment at an appropriate level of abstraction and through a common representation, each team member is enabled to support one another with information, tactical mission support and even more tangible forms of assistance such as offering physical transportation or bringing new supplies.

2. RESEARCH PROBLEM

The nature of 21st Century asymmetric warfare requires systems that operate effectively in highly decentralized environments, making maximum use of local information and resources to provide overwhelming global results. However, the benefits of mixed teams can easily be overshadowed by communication, processing and control challenges inherent to developing and deploying mixed teams of humans, ground robots and air vehicles. For mixed teams of humans and heterogeneous robots to be realized there is a considerable need for further research into the problems of distributed communication, collaborative perception, and shared control.

For the human, mixed teams present particularly difficult HRI questions:

- Do humans lead all aspects of a task? Can a machine give orders?
- What needs to be communicated and at what level of abstraction?
- Can initiative shift throughout the task?
- Can team roles shift to reflect changing capabilities?
- When can machines say no to humans or to other machines?

The operator must not only understand the robotics force in terms of where they are, but s/he must understand what they are doing now and what they will likely do in the near future. Situation awareness is a critical element in decision making, especially in highly dynamic situations that are outside of normal operations. A loss of situation awareness will likely result in slower detection and reaction times as the operator struggles to re-orient him /herself with the current situation. Consequently, our work has focused a great deal of effort on developing appropriate interfaces and possibilities for human monitoring and intervention. Mixed teams will require human interfaces that merge traditional military map-based planning with graphical, iconographic capabilities which permit the operator to interact with abstracted representations of the robots' experience in order to monitor the vehicles, maintain situation awareness and task the autonomous assets.

Most importantly, the individual vehicles must be imbued with the intrinsic intelligence necessary to exploit on-board sensing and serve it up to be fused with data from other vehicles. Establishing a common communication substrate will be a critical issue for teams of diverse vehicles. Especially for heterogeneous air and ground vehicles, this objective requires a means to fuse a wide variety of sensing from disparate modalities and perspectives. Current approaches that assume high-bandwidth, continuous data connectivity between air and ground vehicles are wholly inappropriate for a battlefield where communications will inevitably be lost, jammed or intercepted.

3. MIXED-INITIATIVE TEAMS

Teleoperated systems have often failed to address the limitations of telepresence inherent to current communication technologies. On the other hand, attempts to build and use autonomous systems have failed to acknowledge the inevitable boundaries to what the robot can perceive, understand, and decide apart from human input. Both approaches have failed to build upon the strengths of the robot and the human working as a cohesive unit. Alternatively, mixed-initiative systems can support a spectrum of control levels. Mixed-Initiative robots should:

- Possess intrinsic intelligence, knowledge and agency.
- Have the ability to protect humans, environment and self.
- Dynamically shift levels of initiative to accept different levels and frequencies of intervention.
- Recognize when help is needed (from human or machine)
- Learn from these interactions

Figure 1. One of the current team members – a modified ATRVJR platform from iRobot.

This paper discusses recent efforts at the INEEL to develop a control architecture that supports mixed-initiative human – robot teaming for a team of robots including a number of all-terrain ground robots. At the current time, two ATRVJr's (see figure 1) and two ATRVmini's are being used. Work is underway with the U.S. Army Simulation and Training Command to include simulated vehicles and with DARPA TTO to interface with real world Micro Air Vehicles developed under the MAV program.

3.1 Platform-Centric Intelligence

In order to enable dynamic autonomy, the INEEL has developed sensor-suites and fusion algorithms for sensing, interpreting, responding to the environment. The robotic systems are able to autonomously perform mission-level task decomposition based on commands from other robots or human supervisors. The robots are then able to carry these tasks out by invoking robust, reactive behaviors such as obstacle avoidance, pursuit, escape, get-unstuck, search and explore.

To accomplish these behaviors, each robot must fuse a variety of sensor information including inertial sensors, compass, wheel encoders, laser range finders, computer vision, thermal camera, infrared break beams, tilt sensors, bump sensors, and sonar. The robots use this fused sensor information to navigate safely, placing minimal limits on the user to take the robot's immediate surroundings into account. The robots also continuously assess the validity of its diverse sensor readings and communication capabilities. The robot will refuse to undertake a task if it does not have the ability (i.e., sufficient power or perceptual resources) to safely accomplish it.

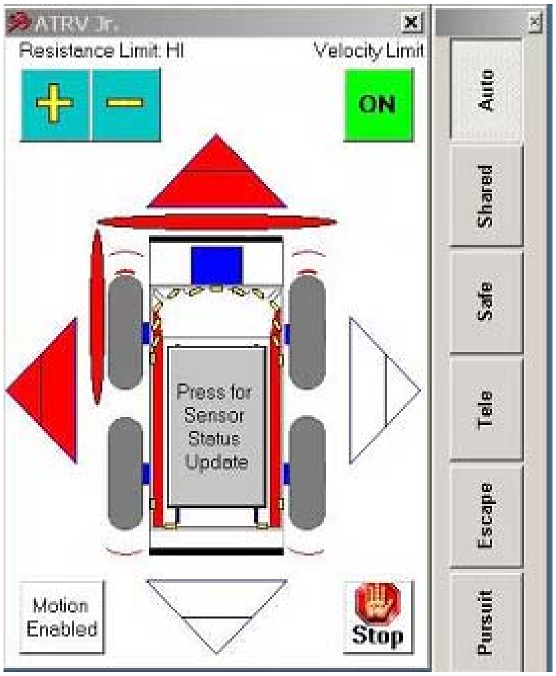

Figure 2. Feedback on an individual robot's immediate surroundings.

Not only must the robot be able to fuse information for itself to utilize, it must also be able to abstract these percepts and communicate them to human supervisors and other robots. Figure 2 shows how the current interface communicates obstacles (red ovals) and resistance to motion (pulses) encountered by an individual robot. The same information which populates this interface module is also received by other robots in the team which can choose to use or ignore it as they see fit.

3.2 Multi-Modal Communications

In order to enable robust team work within critical environments such as Military Operations in Urban Terrain (MOUT), it is not sufficient to assume that high-bandwidth connections such as wireless ethernet exist between all team members. Rather, the dynamic team structure must be supported by an equally dynamic communication infrastructure. Consequently, the INEEL has been working to develop a specialized protocol and multi-modal communication architecture to support dynamic-autonomy. Our approach has been to invest each vehicle with sufficient agency and intelligence so that they can share information at an appropriate level of abstraction. Our robots do not ever need to share raw data, but instead, communicate using extensible, parameterized message strings. These message strings are used by other robots in the team and are simultaneously used to populate the human interface. Although it is presented differently to the human teammates, the basic form of representation is the same across the team. The protocol has been developed to permit abstracted percepts and commands to travel over a low bandwidth communications channel of no more that 9600 baud. This allows the system to use cell phone communications and non line of sight radio links that can travel for up to 60 miles. Robust teamwork must be built on robust communications.

3.3 Dynamic Leadership

Rather than conceive of machines as tools or, on the other hand, as totally autonomous entities that act without human intervention, it is more effective to consider the machine as part of a dynamic human-machine team. Within this team, each member is invested with agency – the ability to actively and authoritatively take initiative to accomplish task objectives. Each member has equal responsibility for performance of the task, but responsibility and authority for particular task elements shifts to the most appropriate member, be it human or machine. For instance, in a remote situation, the robot may be in a much better position than the human to react to the local environment, and consequently, the robot may take the leadership role regarding navigation. As leader, the robot can then "veto" dangerous human commands to avoid running into obstacles or tipping itself over.

However, the ability to shift a robot in and out of the leadership role presents a conundrum. The user comes to rely on the self-protective capabilities of the robot and yet, at times, must override them to accomplish a critical mission. The benefits of allowing the team members to change roles within the team significantly increases team flexibility and reliability in task performance. However, if the interface and human-robot system are not designed in accordance with critical principles of human factors in mind, dynamic role changing may result in mode confusion, loss of operator situation awareness, loss of operator confidence in assuming supervisory control, and degraded and potentially catastrophic performance (Abbott et al., 1996). Systematic human-centered design is necessary to insure that the robot autonomy conforms to the ways in which humans assign and manage tasks.

4. LEVELS OF HUMAN INTERVENTION

Within the last several years, researchers have begun in earnest to examine the possibility for robots to support multiple levels of user intervention. Much of this work has focused on providing the robot with the ability to accept high level verbal, graphical, and gesture-based commands (Perzanowski et al., 2002; Kortenkamp et. al., 1996; Voyles and Khosla 1995). Others have implemented robots that understand the limitations of their autonomous capabilities and can query the user for appropriate assistance (Fong et al., 2002; Murphy and Rogers, 1996). Goodrich et al. (2001) have performed experiments which involve comparing the performance of human-robot pairs using different modes of human intervention. However, very little work has emphasized true peer to peer interactions where the robot is actually able to shift modes of autonomy as well as the user. Scholtz (2002) discusses the need for this kind of peer-peer interaction, and provides categories of human intervention including supervisory, peer to peer and mechanical interaction (e.g. teleoperator).

Our research to date has developed a control architecture that spans these categories, supporting the following modes of remote intervention: *Teleoperation*, *Safe Mode*, *Shared Control*, and *Full Autonomy*. Within teleoperation mode, the user has full, continuous control of the robot at a low level. The robot takes no initiative except to stop once it recognizes that communications have failed. Within safe mode, the user directs the movements of the robot, but the robot takes initiative to protect itself. The robot assesses its own status and surrounding environment to decide whether commands are safe. Within shared control mode, the robot takes the initiative to choose its own path, responds autonomously to the environment, and works to accomplish local objectives. Within the full autonomy mode, the robot performs global path planning to select its own routes, requiring no user input except high-level tasking such as "follow that target" or "search this area." The human user can switch between modes to cope with different components of the task.

For each of these levels of autonomy, perceptual data is fused into a specialized interface (shown in Figure 3) that provides the user with abstracted graphical and textual representations of the environment and task that are appropriate for the current mode. The robot relays a great deal of synthesized, high-level information (including suggestions and requests for help) to the user in a textual form using the feedback textbox within the image window. Also note that the robot provides textual reports on environmental features at the bottom of the map window and reports on communications status at the bottom of the robot status window. The robot status window provides a variety of information about the status of an individual robot including pitch and roll, power, heading, speed and a fusion of this information into a single measurement of "health." The user can shift an individual robot into shared or teleoperation mode and then move the robot by touching the arrows by using a joystick. Also, it is possible to pan and tilt the camera on each individual robot automatically by touching regions of the visual image.

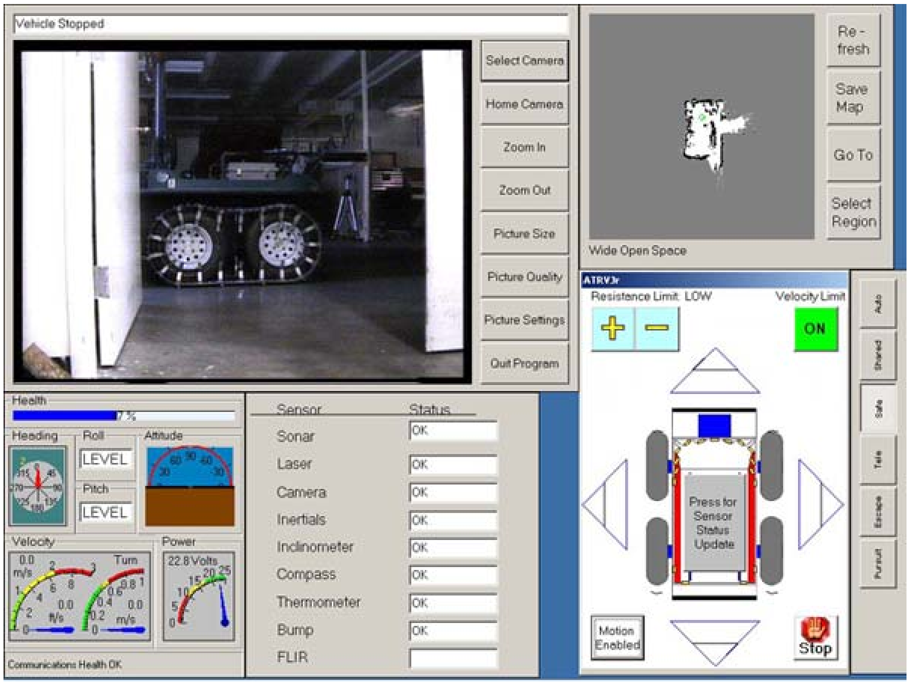

Figure 3. Current Interface for Human Intervention

5. COLLABORATIVE WORKSPACE

The fundamental aspect of a human team that distinguishes it from a simple group is the presence of a shared goal. We must have some mwans to represent this common goal with a common form of representation that is meaningful to all members. Effective teams typically cooperate and anticipate the needs of teammates via a shared mental model of the task and current situation (Yen et al., 2001). If we want humans, air vehicles and ground vehicles to work as a team, we need to develop an appropriate level of discourse, including a shared vocabulary and a shared cognitive workspace, collaboratively constructed and updated on the fly through interaction with the real world.

We have chosen to address this need by building a map that consists of terrain overlaid with semantic abstractions generated through autonomous or user-assisted recognition of environmental features. The current mapping algorithm is based on simultaneous localization and mapping (SLAM) work done at the Naval Research Laboratory. (Yamauchi et al., 1999) At the present time, we have successfully implemented the algorithm on individual robots and integrated it with the control architecture and communication protocol. Since this SLAM algorithm was not designed to localize multiple robots with unknown map locations, the current research effort assumes that GPS will be available, which will allow each robot to add information to a common map based on their known position. Research to identify and incorporate other algorithms for collaborative mapping is ongoing.

For the user, the current map provides point-and click user validation and iconographic insertion of map entities. The user can verify or remove entities, which have been autonomously added and can add new entities, which the robots were unable to find. To test this capability, we outfitted one of the ground robots with a metal detector, which allowed it to autonomously identify the presence of metal objects and add them to the map as red circles. In addition, the human can add a number of other entities such as human victims (shown in figure 4 as the purple circles).

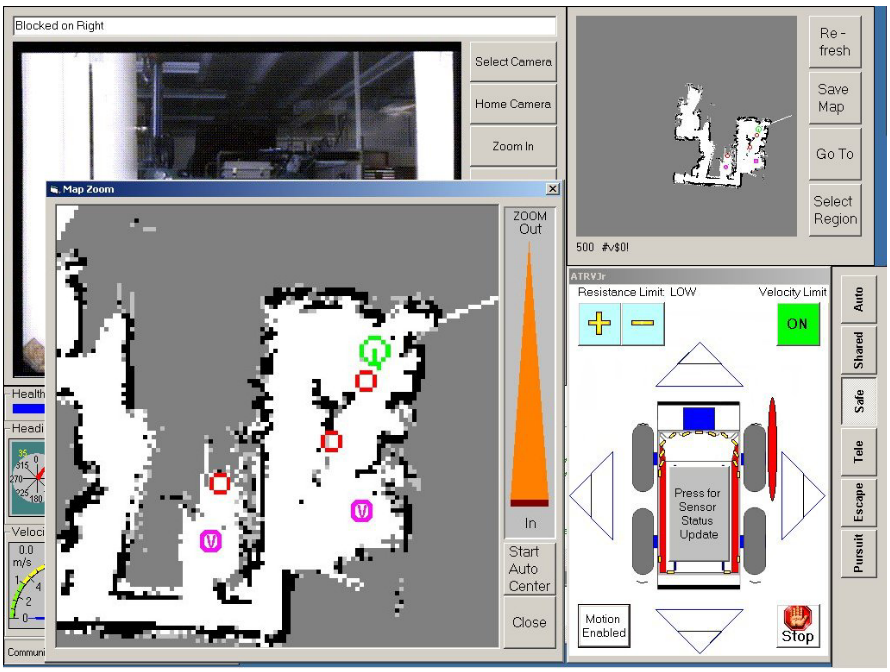

Figure 4. Current Collaborative Workspace

This real-time semantic map, constructed collaboratively by human and machines, serves as the basis for a spectrum of mutual human-robot interactions including tasking, situation awareness, human-assisted perception and collaborative environmental “understanding.” In addition, the collaborative cognitive workspace can be utilized by dynamic planning systems to orchestrate synergistic interactions between air, ground, surface and underwater vehicles. For instance, air vehicles can provide the workspace with a global, “god’s eye” view of terrain, aiding the ground vehicles as they autonomously plan paths. Conversely, the ground vehicles can provide more detailed, precise intelligence, surveillance and reconnaissance (ISR) of areas of interest (AOI).

The collaborative workspace is also a palette on which to interleave multiple levels of human intervention into the functioning of a multi-robotic system. The human can assist in identifying and classifying targets in the environment using an interactive visual display. Collaborative construction of the map enhances each individual team member's understanding of the environment and provides a shared semantic lexicon for communication. Robots can use the workspace to communicate about the task and environment both graphically (e.g. "The highlighted area has been searched!") and verbally ("Landmine found near Victim 2!") using the semantic names which have been assigned within the shared cognitive workspace. Conversely, the human can task the robots in much the same way.

6. CONCLUSION

The work reported on here represents some first steps towards a vision of true team work between humans and robots. We believe that we have developed unique answers to fundamental problems of communication and control, which will permit more robust team interaction between humans and dynamic autonomy robotic forces. The hope is that this work can provide the foundation for investigating these problems further. Already, the workspace is invaluable for user as they investigate new terrain, especially in cluttered, labyrinthine environments. Future experiments with human subjects will analyze the utility of the collaborative workspace more rigorously. At the current time, the INEEL is working to add additional autonomous tasks such as patrol and perimeter surveillance to the capabilities of the control architecture. Also, much work is currently focused on task specific perception such as the ability to more accurately recognize Urban Search and Rescue Victims. As these capabilities grow, the utility of the collaborative workspace grows alongside.

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