Autonomy in Human-Robot Team Control

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Human control of multiple robots has been characterized by the average demand of single robots on human attention or the distribution of demands from multiple robots. When robots are allowed to cooperate autonomously, however, demands on the operator should be reduced by the amount previously required to coordinate their actions. The present experiment compares control of small robot teams in which robots were controlled either independently or coordinated via Machinetta proxies. Coordinated robots found more victims and searched wider areas.

INTRODUCTION

Applications of multirobot systems (MRS) such as interplanetary construction or cooperating uninhabited aerial vehicles will require close coordination and control between human operator(s) and teams of robots in uncertain environments. Multiple robots can substantially increase the complexity of the operator's task because attention must constantly be shifted among robots in order to maintain situation awareness and exert control. In the simplest case an operator controls multiple independent robots interacting with each as needed. Control performance at this task can be characterized by the average demand of a robot on human attention (Crandall et al. 2005) or the distribution of demands from multiple robots (Nickerson & Stevens 2005). Increasing robot autonomy allows robots to be neglected for longer periods of time making it possible for a single operator to control more robots.

The relation between robot autonomy and human control of robot teams has been widely studied typically in comparisons between teleoperation and waypoint control schemes, usually including obstacle avoidance. Crandall et al (2004), for example, compared teleoperation, point-to-point (specifying the next waypoint), and scripted (specifying a series of waypoints) control schemes. The next step in autonomy for controlling robot teams would be to enable robots to cooperate among themselves thereby extending automation to the human control activities previously needed to coordinate actions among team members.

The reported experiment uses Machinetta (Scerri et al. 2004), a distributed multiagent system to supply proxies for each of the robots. These proxies provide communications and domain independent coordination services to the robots. When the system runs in auto mode, the robot proxy is allowed to analyze the range data to determine what nodes the robot team needs to explore and how to reach those nodes from the current position (generating the paths). By exchanging these nodes and route information through Machinetta, a robot proxy can accept and execute a team plan to visit a node by following a path (a series of waypoints). In manual mode the robots cannot communicate or coordinate but can still accept and follow waypoints, behaviors often termed autonomous.

In the experiment, participants were asked to control 3 P2DX robots (Figure 1) simulated in USARsim (Wang et al. 2005) to search for victims in a damaged building. Each robot was equipped with a pan-tilt camera with 45 degrees FOV and a fixed laser scanner with 180 degree FOV and resolution of 1 degree. The participant interacted with the robots through our Multi Robot Control System (MRCS) shown in Figure 2. Status information, camera video, laser scanning range data, and a global map built from that data were available from each robot. Robots were controlled serially with only the currently selected robot capable of accepting commands. To switch robots, the operator clicked on the color coded thumbnail camera view at the top of the screen to bring the new robot into control focus.

Figure 1 Pioneer P2-DX robot in USARsim

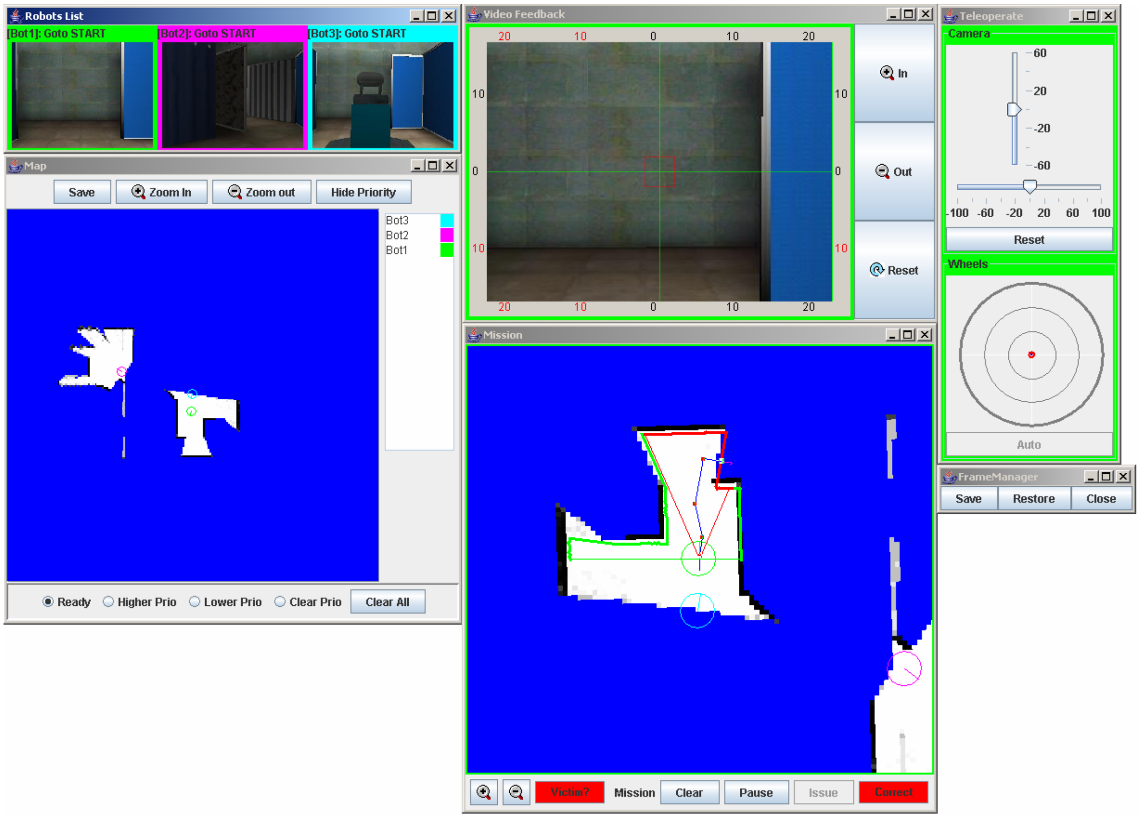

Figure 2 Multi Robot Control System

The operator controlled the robots to explore the building and search for victims by issuing waypoints or teleoperating the robot and panning/tilting the camera. Once a victim was identified, the participant marked its location on the global map.

Challenges to mobility encountered in real robotic search and rescue tasks were simulated in our experiment by obstacles including chairs, bricks, and pipes. Transparent sheets of plastic and mirrors were introduced to cause perceptual confusion and increase task difficulty. The camera's FOV was restricted to 45 degrees to reflect typical limitations. As with real robotic system, there were uncertainties and delays in our MRCS. Range data had simulated errors, the map was based on probabilistic data and some obstacles such as a chair, desk, or narrow wall might not appear on the map due to inaccuracies in laser detection. There were also slight delays in video feedback and response to commands.

The MRCS worked in either auto or manual mode. In auto mode, the robots could cooperate in limited ways to automatically explore the environment. Although Machinetta proxies are capable of complex role-based coordination, cooperation in this scenario was limited to choosing new paths that did not explore already searched areas or interfere with other robots. In *manual* mode, the robots had no automatic exploration capabilities and stopped after completing their queued commands. In either condition the operator could control a robot by specifying waypoints for it to traverse or drive it directly through teleoperation. The operator identified victims by observing camera video from the selected and unselected robots, typically switching control and operating the camera of a robot spotting a possible victim. The experiment followed a repeated measures design in which participants controlled in both manual and auto modes. Modes were counterbalanced and participants explored the same sequence of environments. The robots' location, orientation and the user's actions were recorded and timestamped throughout the experiment. The final map with marked victims was also saved.

Procedure

This experiment compared robot team control performance under *auto* and *manual* modes. Participant demographics were collected at the start of the experiment using an on-screen questionnaire. Standard instructions explaining how to use the interface were followed by a ten minutes practice session in which participants following instructions practiced each of the operations available in the two modes and finished after searching for and finding a victim in auto mode. Order of presentation was counterbalanced with half of the participants assigned to search for victims in Arena-1 in *auto* mode and the other half in *manual*. After 20 minutes the trial was stopped. Participants were given brief instructions reminding them of significant features of the mode they had not used and then began a second 20 minutes trial in Arena-2. At the conclusion of the experiment participants completed an online survey.

16 paid participants recruited from the University of Pittsburgh community took part in the experiment.

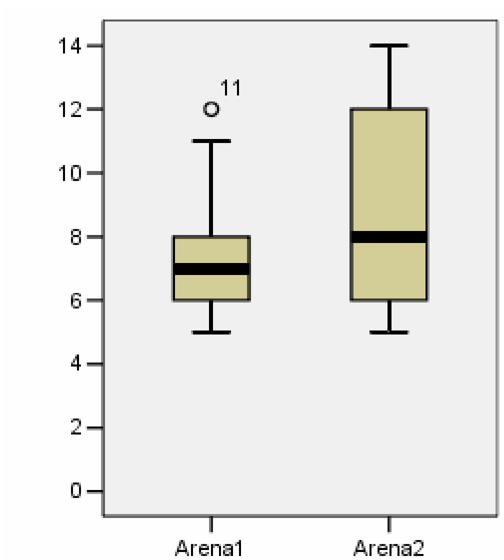

Figure 3 Number of victims

Results

The two oldest participants (> 50 years old) failed to find any victims and were dropped from this analysis. All of the remaining 14 participants found at least 5 of a possible 14 (36%) victims in each of the arenas (Figure 3). The median number of victims found was 7 and 8 for arenas 1 and 2 respectively. Two-tailed t-tests found no difference between the arenas for either number of victims found or the percentage of the arena explored. Figure 5 shows the distribution of victims discovered as a function of area explored. These data show that participants exploring less than 90% of the area consistently discovered 5-8 victims while those covering greater than 90% discovered between half (7) and all (14) of the victims. Within

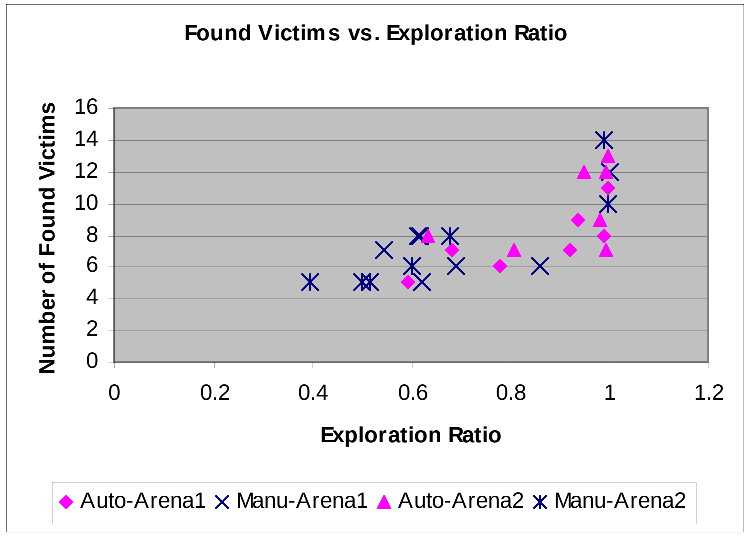

Figure 4 Victims as a function of area explored

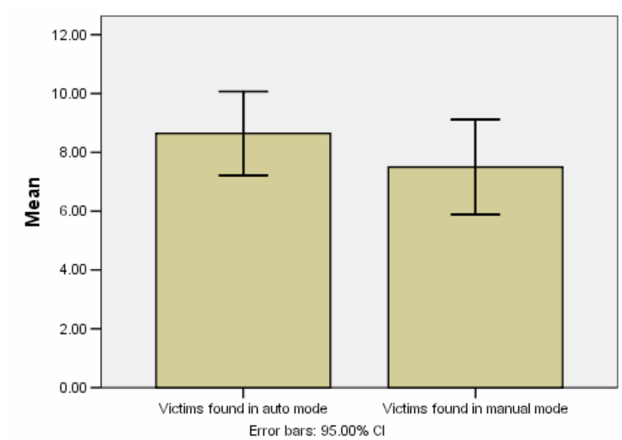

Figure 5 Regions explored by mode

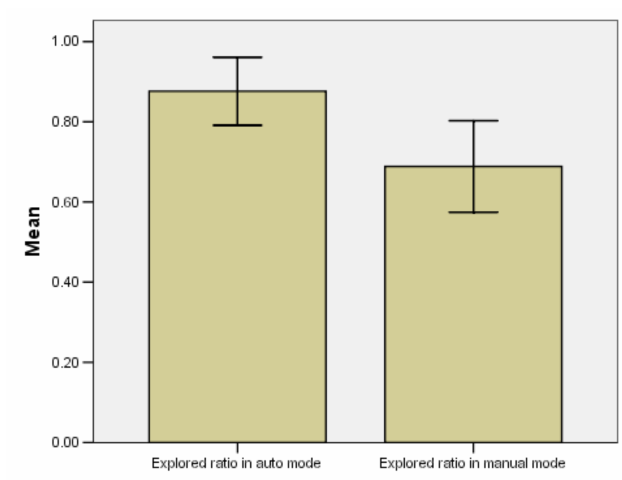

Figure 6 Victims found by mode

participant comparisons found wider regions were explored in *auto* mode, $t(13) = 3.50$, $p < .004$, as well as a marginal advantage for *auto* mode, t(13)=1.85, p= .088, in number of victims found. (Figures 5 and 6).

Distribution of Attention among Robots

Within participant comparisons showed participants switched their control between robots more frequently in auto than in manual mode, t(13)= 2.11, p=0.05 (Figure 7).

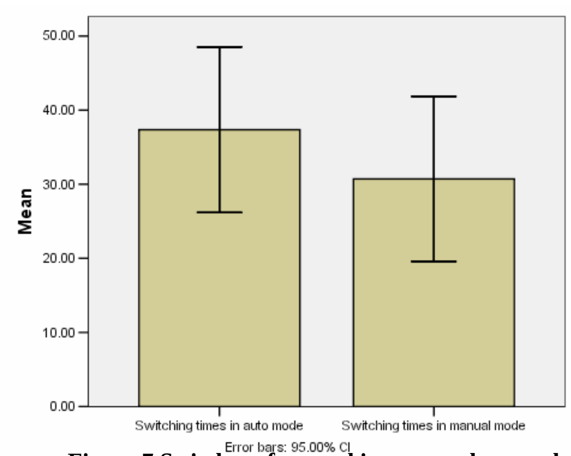

Figure 7 Switches of control in auto and manual modes

Across participants the frequency of shifting control among robots explained a significant proportion of the variance in number of victims found for both *auto*, R^2=.54, F(1,11)=12.98, p=.004, and *manual*, R^2=.37, F(1,11)=6.37, p<.03, modes (Figures 8 and 9).

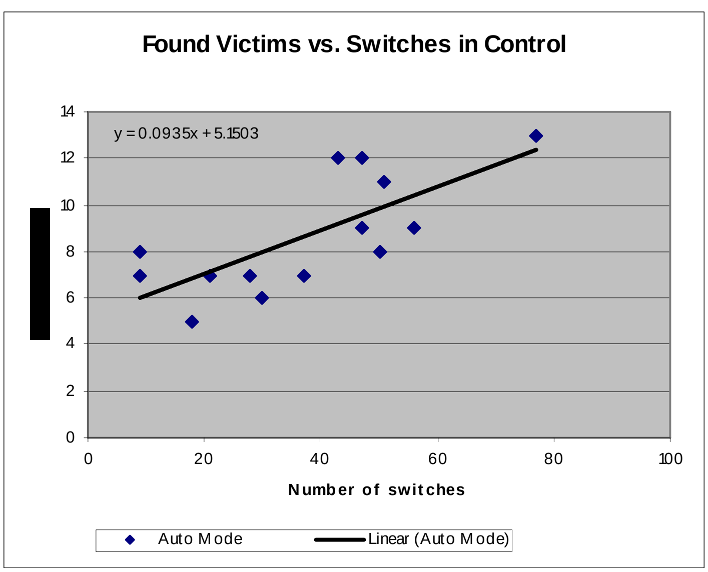

Figure 8 Victims found per switches in control for auto mode

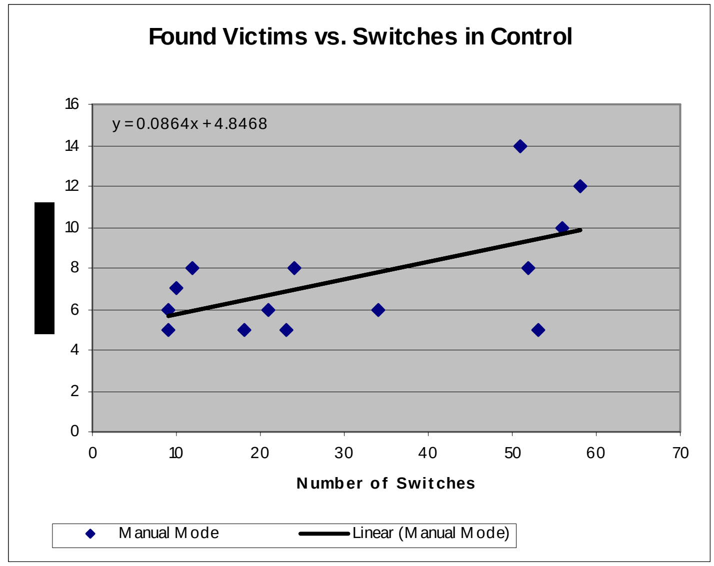

Figure 9 Victims found per switches in control for manual mode

Control Behaviors

Three forms of control: waypoint control, teleoperation control, and camera control were available to the operator. For analysis, times spent at these tasks were expressed as a proportion of available time. Using waypoint control, the participant specifies a series of waypoints while the robot is in pause state. After the waypoints are specified, the robot begins to follow the points and the operator is free to monitor this or any other robot. Therefore, we use only the interval during which the robot is selected and in a pause state that is followed by a command to follow way points as a measure of the time spent in waypoint control. Under teleoperation, the participant manually drives the robot while monitoring its state. Time spent in teleoperation was measured as the duration of a series of active positional control actions that were not interrupted by pauses of greater than 30 sec. or any other form of control action. For camera control, we used the time for a series of camera pan/tilt/reset commands not interrupted by pauses of greater than 30 sec.

While we did not find differences in overall waypoint control times between auto mode and manual mode, auto mode operators had shorter, t(13)=1.51, p < .01, control times during any single control episode (Figure 11), the period during which an operator switches to a robot, controls it and then switches to another robot.

Figure 11 shows the relationship between victims found and total waypoint control times. In manual mode this distribution follows an inverted 'U' with too much or too little waypoint control leading to poor search performance. In auto mode by contrast the distribution is skewed toward long control times with most observations and highest numbers of victims found occurring at the shortest control times.

Overall teleoperation control times, t(13)=2.179, $p < .05$ were reduced in the auto control mode as well, while teleoperation times within episodes only approached significance, t(13)=1.87, p= .08. No differences in camera control times were found between *auto* and *manual* control modes. It is notable that operators made very little use of teleoperation, .6% of mission time, and only infrequently chose to control their cameras.

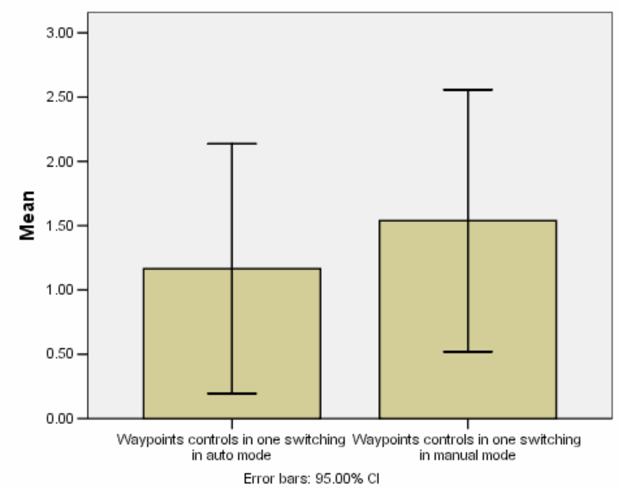

Figure 10 Waypoint control times by mode

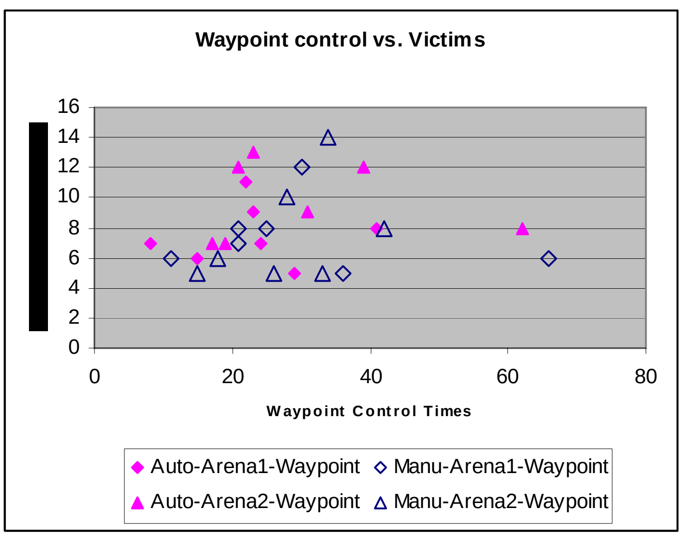

Figure 11 Victims found as a function of waypoint control times

DISCUSSION

While this experiment is the first of a series investigating control of cooperative teams of robots cooperation was of a limited sort primarily involving the deconfliction of plans so that robots did not re-explore the same regions. The experiment shows that even limited autonomy in cooperation can help in the control of multiple robots. The results showed that team autonomy helped the operators explore more areas and find more victims. In both the conditions participants divided their attention approximately equally among the robots but in the auto mode they switched among robots more rapidly thereby getting more detailed information about different areas of the arena being explored.

The frequency of this sampling among robots was strongly correlated with the number of victims found. This effect, however, cannot be attributed to a change from a control to a monitoring task because the time devoted to control was approximately equal in the two conditions. We believe instead that searching for victims in a building can be divided into a series of subtasks involving things such as moving a robot from one point to another, and/or turning a robot from one direction to another with or without panning or tilting the camera. To effectively finish the searching task, we must interact with these subtasks within their neglect time (Crandall et al. 2005) that is proportional to the speed of movement. When we control multiple robots and every robot is moving, there are many subtasks whose neglect time is usually short. Missing a subtask means we failed to observe a region that might contain a victim. So switching robot control more often gives us more opportunity to find and finish subtasks and therefore helps us find more victims. This focus on subtasks extends to our results for movement control which suggest there may be some optimal balance between monitoring and control. If this is the case it may be possible to improve an operator's performance through training or online monitoring and advice.

References

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