The Effect of Situation Awareness Acquisition in Determining the Ratio of Operators to Semi-Autonomous Driving Vehicles

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ABSTRACT

We used a technical readiness level assessment to obtain intervention time and the time to acquire situation awareness for different classifications of interventions. We analyzed this data to determine if it is feasible for one operator to control multiple robots of this type in similar environments. We conclude that in both terrains analyzed (an arid terrain and a wooded terrain) it would be feasible for one operator to control two robots. While it is also possible for an operator to work on another task and control a robot as well, there is an issue of providing situation awareness about the robot. There are also constraints on the tasks that could be effectively accomplished.

Keywords: human-robot interaction, situation awareness, neglect tolerance, off-road driving, autonomy

1. INTRODUCTION

Robotics systems are coming out of the research laboratories and into practice. The military is using current systems for applications such as searching dangerous areas and for explosive ordnance disposal. They are designing new semiautonomous systems for use as a middle weight force. To use semiautonomous systems wisely, we need to consider the capabilities and limitations of such systems and develop new procedures and workflows accordingly. We need to understand that the capabilities will increase and the limitations decrease over time; therefore, the concept of operations (CONOPS) should be developed with evolution in mind. A prime issue to be considered is the division of labor between humans and the robotic systems. As completely autonomous robotic systems currently do not exist in domains requiring more than simple repetitive behaviors, it will be necessary for humans to interact with the robots to accomplish certain tasks. A number of related questions exist such as:

- How many robots can any one individual control?
- What other tasks may a human be able to do and still control a robot?
- How does situation awareness affect the number of robots that one operator can control and the performance of another non-robotic task?

We use the term *Human-robot interaction (HRI) efficiency* to refer to this set of questions. In this paper, we discuss a number of factors that should be considered in developing these CONOPS and present an example based on experimental evidence.

2. BACKGROUND

2.1 Interaction and Intervention

We define two types of human-robot “interaction”. We use the term *interaction*, for planned collaborations [1]. For example, if an operator is required to input information about a mission to the robot scout, this event would be called a human-robot interaction. We use the term *intervention* for unplanned instances of collaboration. If the scout robot is supposed to be able to navigate between waypoints on its own, but in a particular mission has a problem and is unable to maneuver around an obstacle. The robot calls for help from the operator to identify the obstacle and plan a course of action. This may simply be setting new way points for the operator or it may involve a period of remote teleoperation. The interaction requirements can be well defined given any particular implementation of a robotic system. This will be discussed in a later section. However, we must probe further to determine how to predict intervention possibilities.

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2.2 Taxonomies of human-robot interaction

Conway [2] defines tele-autonomous control to denote the "the interactions of humans with remote, intelligent, partly-autonomous systems of many forms (not just robots or vehicles)." Conway notes that a number of modes of tele-autonomous control exist. Some specific examples of control modes between a human controller and a remote device include:

1) Direct continuous teleoperator control. We refer to this as teleoperation.

2) Shared continuous teleoperator control of a remote device. The remote device has autonomous low level behaviors. The human controls higher level behaviors.

3) Discrete command control by the human operator of the remote device. The human can issue task specific commands to the remote device. Autonomous low level behaviors will be very generic.

4) Supervisory control. The human only intervenes when required; either by noticing that the behavior of the system is deviating from the plan or when the system is unable to carry out the plan and requests help.

Parasuraman, Sheridan, and Wickens [3] define a ten point scale of autonomy ranging from the system decides everything to the system offers no help (manual). In between, are levels such as the computer suggests several alternatives, the computer asks for approval, the computer informs the human only if asked.

Adjustable autonomy [4] refers to the ability of an intelligent system to change the level of autonomy during operation. This ability allows the combined human-robot system to take advantage of the capabilities of both humans and robots. Either the human or the robot may change the level of autonomy.

In our work, we looked at a robotic system in supervisory control. The humans only intervened when requested by the robot. At that point, the human could either issue a command or assume manual control of the system.

2.3 Interface Efficiency

Crandall [5] defines interface efficiency as the measure of the effectiveness of the interface. We apply the more traditional usability measures of interaction effectiveness and efficiency [ISO 92411-11]. In these definitions, efficiency is the measure of the time needed to complete a given task. Effectiveness is the percentage of a task that the user is able to complete using the given user interface. Along with user satisfaction, these measures are used in assessing the usability of a user interface. The three measures are weighted relative to the requirements of an application. If an application is time critical, then more weight is applied to the efficiency measure. For applications that are life critical, more weight is given to the effectiveness measure. Applications for home use and entertainment place a higher weight on user satisfaction measures.

For HRI purposes, if a user is unable to complete a task using the interface, a different task must be substituted or some sort of work around devised. Even if an acceptable substitute can be found, the interaction time will go up significantly. If the user cannot find a substitute and the task is never completed, the robot's performance will drop to zero.

We need to consider a number of components when investigating the factors that affect HRI efficiency. The first two are: the mode of autonomy and the user interface. Crandall defines *neglect tolerance* as the "measure of the efficiency of a robot's autonomy mode." Neglect tolerance measures how the robot's performance decreases as the human ignores it. Crandall notes that a robot operating in direct continuous teleoperator control cannot be neglected. As soon as the operator stops control, the robot stops performing. However, we may choose to move the robot into a certain position to give situation awareness about other humans or robots in the mission. In this case, the operator is not actively controlling the robot but the robot is providing utility. A completely autonomous robot operates under supervisory control. If the robot never required any intervention, then the neglect tolerance of this robot would be infinite. However, the robot may not be doing anything useful. Neglect tolerance is a useful metric, but it cannot be specifically equated to the necessity for user intervention.

Crandall does not elaborate on *world complexity* but notes that robot performance decreases as the complexity of the world increases and it is necessary to determine how the interaction scales to higher or lower complexities than the situation for which it was specifically designed.

2.3 Situation Awareness

In remote operations, it is vital that the operator have situation awareness. When the vehicle is completely teleoperated, the operator is always in involved. Any lack of situation awareness can be attributed to ineffective presentations in the user interface or to a lack of sensory input. When the operator is less involved, there will be some amount of time needed to acquire current situation awareness.

The literature contains a number of references to the out-of-the-loop performance problem which is a negative effect of automation. Two major issues are:

- The operator's loss of skill to perform the task manually
- The operator's loss of the state of the automated system.

For our HRI work, we are particularly interested in the loss of situation awareness.

Endsley defines [6] three levels of situation awareness. Level 1 is the perception of the relevant status information. Level 2 is the comprehension of this information and level 3 is prediction, the ability to use this understanding to consider what alternatives may occur. A loss of situation awareness implies that an operator taking over in the case of the failure of an automated system will need additional time to determine the current status of the system.

Endsley [7] conducted an experiment using four levels of automation, ranging from completely manual to completely automated. The experiment was setup so that in each case, except the manual case, the user had to intervene. In all cases, the time to complete the task was slower than the time to do it manually. The subjects in the experiment were asked questions corresponding to level 1 and level 2 situation awareness. There was no significant different in the level 1 situation awareness for the subjects dealing with the automated systems and subjects using the manual system. However, there was a statistically significant difference for level 2 questions, with the manual subjects obtaining higher levels of SA than the subjects working with the automated systems.

The next section describes an evaluation effort to assess the technical readiness level of an automated off-road driving system. As part of that effort, measure of workload, interventions, and time to acquire situation awareness were conducted.

3. TECHNICAL READINESS LEVEL ASSESSMENT

Consider that during a mission the operator is either interacting (in some form) with the robot or not. Olsen [8] defines robot attention demand as the time spent interaction with the robot divided by the entire mission time (the time spent interacting with the robot plus the neglect time). This robot attention demand is the time that an operator could devote to another task, such as controlling another robot.

Our objective is to look at these measures more closely to determine what characteristics of the operator, mission, robot, and user interface affect the interaction time and the robot neglect time. This will help us to understand the circumstances under which operators could safely control multiple robots or work on other tasks.

3.1 Technical Readiness Assessment Experiment

We participated in a study assessing the technical readiness level of a semi-autonomous ground vehicle. In a previous paper [9,10] we reported on the differences between two different terrains used in the study with respect to time to acquire situation awareness. The vehicles used were given way points to navigate to by the operator. After that initial interaction, the vehicles were to perform the navigation autonomously but were allowed to request help when they could not make any progress. To control for differences between operators, operators were only allowed to respond to requests for help from the robot. The robots could request help for nine categories of problems. These are shown in Table 1 along with an explanation of each type. Operators announced the reason that they were intervening so that we could track the type of problems the robotic systems encountered.

Table 1: The categories of help requests

NeedOperator	OCU map display says it needs help Cannot back up Max backup attempts exceeded Other as displayed in the GUI window
Motion	The vehicle has not moved on the OCU map for more than 30 sec The vehicle loops back onto its path The vehicle stays in the same general area (20m) for more than 60 seconds
Speed	Vehicle speed stays below 0.2 m/s for more than 20 sec Speed is larger than assigned or less than -5m/s (negative)
Terrain	Vehicle pitch or roll is more than 20 degrees Traction is slipping and the vehicle is stuck Too rough
Communications	COMMS are lost with either of the two boards Loss of GPS fix
Obstacle	Bumper hit- starting to backtrack Bumper is stuck Bumper hit – cannot backup Stopping because the SIC says so Navigation confused Water is too deep
Path	The vehicle is more than 50 m off assigned path The vehicle is pointed in the wrong direction at start of mission The vehicle is about to cross into a restricted area
Plan failure	No good plan for a while Planner died
Mechanical	Engine too hot Ladar went down

The two types of terrain considered in our study were arid and wooded terrain. Each terrain was further divided into a moderate and difficult section. Furthermore, the actual trials were of four different lengths: 500 meters, 1000 meters, 2000 meters, 5000 meters and 7000 meters. We have not included the data from the 7000 meter runs in our analysis here. Table 2 shows the number of trials conducted in each section, the number of trials in which interventions occurred, and the number of trials that had multiple interventions.

Table 2: Trials and intervention data

	Arid Terrain		Wooded Terrain	
	Moderate Course	Difficult Course	Moderate Course	Difficult Course
# trials	91	86	91	90
# trials with interventions	2	33	39	51
# trials with multiple interventions	1	8	29	13
Total # interventions	3	45	106	67
	48		173	

We analyzed a subset of the interventions to determine the time needed for the intervention and the time needed for the operators to acquire the needed situation awareness. We analyzed only the trials actually completed; not the trials ending in a stop or emergency stop. There were a number of runs in which some military personnel were used as operators.

We omitted these runs so that we could compare the strategies of the two operators. Some of the interventions that occurred require no situation awareness on the part of the operator. The request requires only a command to be issued or external help to be obtained. For example, if communications are lost or the engine overheats, the operator merely shuts down the trial.

Table 4 shows the interventions that we analyzed for situation awareness in both the Arid and Wooded domain. In the Arid trials, a high percentage of the total interventions were analyzed. However, in the Wooded trials, the interventions that were analyzed for situation awareness only amounted to slightly over half of the total.

Table 4. Time needed for interventions and situation awareness

	Arid			Wooded		
Type of intervention	#	Total IE time (seconds)	SA time (seconds)	#	Total IE time (seconds)	SA time (seconds)
Terrain	24	154	25.1	6	181.5	17
Motion	9	190	28.4	4	102	4
Plan failure	1	29	0	3	229	22
Need operator	10	162	31.8	77	136.4	18
Total	44	161	26.7	90	143.1	17.4

Note: IE = intervention; SA= situation awareness

It should be noted that although the operators did not have direct line of site to the remote vehicles they were controlling, they were in a vehicle that was following the semiautonomous vehicle closely. This was necessary to maintain communications. Also, the operators were not doing another task. The operators were not allowed to see the video from the remote vehicle unless they had actually taken over control, but they were continually monitoring the path of the vehicle on the operator control unit along with vehicle status messages. Therefore the results from this study should be considered a best case scenario.

We had originally hypothesized that the wooded terrain would be the more difficult and that it would take the operator more time for the interventions and more time to acquire situation awareness. Although, there was a considerable increase in interventions in the wooded environment over the arid terrain, the average time needed for acquisition of situation awareness was reduced for the interventions (in the wooded environment) as was the total time needed for the intervention.

Workload measures were also obtained during this assessment [11], both for the periods of intervention and for periods without intervention. For the study in the arid terrain, the workload during periods of intervention was 5.8 out of a possible 10. The workload assessed for periods without intervention was 1.6, significant at the $p < .0001$ level. In the Wooded terrain, the mean workload during periods of intervention was 7.75 and the mean workload for periods of no intervention was 2.4, again significant at the $p < .0001$ level. Schipani[11] found that the independent variables, terrain and mission, had a significant effect on the operator's perception of their degree of workload in both cases. Longer missions caused higher workload. However, in the case of the wooded terrain, the highest perceived workload occurred in the moderate terrain. Although the terrain had been assessed earlier and the courses had been designed, dynamic conditions (snow) caused the moderate course to pose traction problems.

The level of autonomy observed in this study averaged 93.5% (wooded) to 98.5% (arid). Table 5 shows the total time for all the trials, the percentage of that time that the vehicle was automatic and the time that the operator was in control of the vehicle.

Table 5. Teleoperation time versus Autonomous time

	Arid	Wooded
Total Time for trials	34:18 (hh:mm)	39:33 (hh:mm)
Autonomous time	31:52 (93%)	33:04 (83%)
Teleoperation time	2:25 (7%)	6:32 (17%)

In this analysis of HRI in the two environments we found:

- The number of interventions in the more difficult wooded environment was four times as great as in the arid terrain.
- The percentage of time needed for teleoperation was doubled in the wooded environment.
- The difficult course in the arid terrain had approximately the same number of trials with interventions as the moderate course in the wooded environment.
- There were interventions on over 50% of the trails in the difficult course in the wooded environment.
- The time for each intervention in the arid terrain was more than the intervention time in the wooded area.
- The time needed to acquire situation awareness was more for interventions in the arid terrain trials.
- With the exception of the moderate course in the arid terrain, 25% to 75% of the trials with interventions had more than 1 intervention.

4. APPLICATION TO MEASURES OF OPERATOR RESOURCES

In this section we use the data from the technical readiness assessment to compute the time that an operator would have to perform other tasks besides coming to the aid of the robot. We consider two cases: one where an operator of a robot has another non-robot task to work on when the robot is in autonomous mode; and the second case where the operator is controlling two semiautonomous robots.

4.1 Case One: An operator controls one robot and works on a task

For this rough calculation, we ignore the lengths of the various trials and simply compute an average run time. For the first case, we consider the arid terrain. Average trials here took approximately 11.6 minutes. We assume that the intervention is a NeedOperator category. These interventions averaged 2.7 minutes of operator time. If the intervention occurs at either the beginning or near the end of an average run, we have a maximum of 8.9 minutes that can be devoted to another task. If the intervention occurs exactly in the middle of the trial, we have about 4.5 minutes for working on another task. Then the operator would devote 2.7 minutes to the intervention and return to the second task for another 4.5 minutes. This would be the case only if the operator is able to transition instantaneously from one task to another. In reality, the operator has to either monitor the status of the robot which would detract from the second task or has to respond to some sort of alert from the robot when help is needed. In this case, the operator has to notice the alert, be able to pause the second task, and then acquire the situation awareness to determine what to do to help the robot. Our best case measures in the arid terrain show that acquisition of situation awareness takes on the order of ½ minute. During the time that it takes the operator to notice the robot needs help, pause the second task, and gain situation awareness to decide what to do, the robot has been of no utility. Moreover, the robot is most likely stationary at this point. If we are performing a time critical task, this is expensive. If we are performing a task in a hostile environment, there may be safety concerns associated with the robot staying in one place for a prolonged period of time.

We make some assumptions. First, we assume that the operator needs to perform some functions at the beginning and end of each trial. This might be uploading a new path and plan to the robot at the beginning or downloading data at the end of the trial. The transition between tasks takes some time. For this example, we select 30 seconds to mentally switch between one task and another. We also assume that noticing that the robot needs help will take 20 seconds. Putting the second task into pause mode will take 40 seconds. Figure 1 shows the time that would be available for the second task.

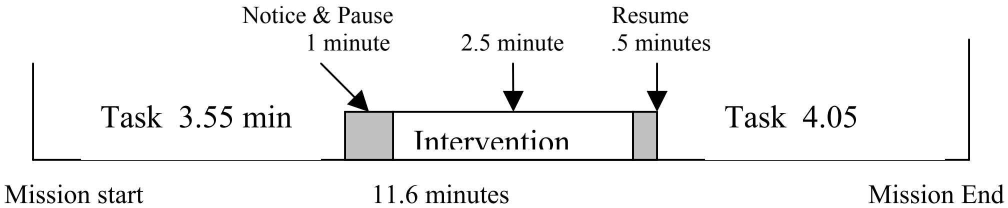

Fig. 1. Graphic of intervention in a mission

4.2 Case Two: An operator controls two robots

Now we assume that our operator is going to control two semiautonomous robots, both with the same performance characteristics as those in the assessment. We use the wooded environment this time to construct figure 2. In the wooded environment, the trials averaged 13.1 minutes and the NeedOperator interventions averaged 2.25 minutes.

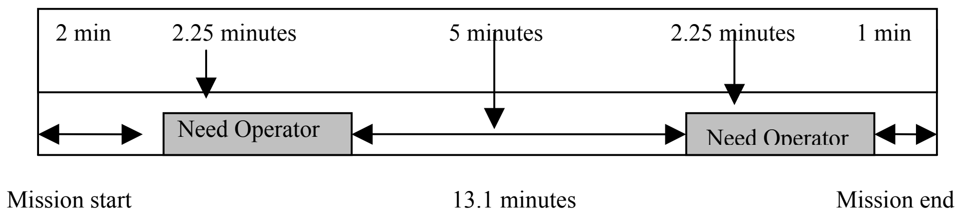

Fig. 2. Two interventions in one mission

In the wooded environment, there was an intervention in 51/90 trials or approximately 55% of the time. Running two robots with the same capabilities, it is very probable that a number of trials will have interventions with both robots, and a few trials where three interventions will occur. If two interventions were requested at exactly the same time, the first robot serviced would have no utility for 2.25 minutes. The second robot would not be operational for at least 4.5 minutes, the time needed to intervene with the first robot, followed by the intervention time for the second robot. This assumes they both have called for help with the "NeedOperator" request.

5. DISCUSSION

In case two the situation awareness acquisition time has already been included in the intervention time. This, however, represents the best case. For a remote operator managing two robots in different locations or with different capabilities, the time needed to acquire situation awareness is likely to increase. Moreover, the operator may not be in the same location as the robots and will not have the advantage of physical clues such as the roughness of the terrain, to help in problem solving.

We had hypothesized that the operators in the wooded environment would encounter more problems and have longer intervention times. Although, they had considerable more interventions, the times needed for acquiring situation awareness and for accomplishing the intervention were less than in the arid terrain. In retrospect, the majority of the interventions were need operator, generated due to the robot's inability to find a path in a heavily wooded environment. After the initial requests for help, the operators quickly learned that it was easy to handle the request by locating an opening and pointing the robot in that direction. This turned out to be easier and quicker to handle than determining a path with better traction in the arid environment.

Calculations to determine how many semi-autonomous vehicles one operator can manage need to take into consideration the robot neglect time, the time to acquire situation awareness for a given type of problem and environment, and the average intervention time for this type of situation. The type of mission dictates the constraints on how long robots can be out of operation. The intervention time will be affected by the efficiency and effectiveness of the user interface. This, however, is a relatively simple issue. Human-robot interfaces that have been designed by usability engineers will optimize user interactions.

When the operator is supervising and controlling several robots as needed, the operator may have time in between interventions to monitor the vehicles. If we provide interfaces to display only relevant information for situation awareness for both vehicles, as opposed to too little or too much information, the time to acquire accurate situation awareness should be reduced and the situation awareness should be maximized. In the case where the operator is performing another task, this monitoring will only occur at the expense of the second task. If the second task given to the operator has a high workload demand, this will certainly have a negative impact on the time needed to acquire situation awareness.

6. CONCLUSIONS AND FUTURE WORK

Based on analysis of the data from the arid and wooded terrain, it is reasonable to assume that one operator could control two robots operating with this level of autonomy in either environments. It would be advisable to design the display on the operator control unit to optimize the situation awareness provided for the two vehicles [12] . If it is necessary to have the operator perform another task, then the task selected must be interruptible, should have a low workload, and should not take much time to resume. In this case, it is even more critical to have an interface design to quickly provide the operator with situation awareness as the operator may have little bandwidth to monitor the autonomous system.

We still have data on another terrain to analyze. In this terrain, different types of missions were run as well. This will give us a chance to determine the situation awareness requirements for the different missions and how this affects the situation awareness acquisition time and the overall intervention time. We are also interested in looking in more depth at what characteristics of the terrain make interventions in one environment more time consuming than in another. We need to also consider the impact on the operator of supervising robots operating with different capabilities and in different spaces, for example indoors/outdoors and ground/air.

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