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A CONFIGURABLE TELEROBOTICS SYSTEM FOR HUMAN FACTORS EDUCATION AND RESEARCH

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Abstract

The emergence and explosive growth of the Internet has transformed not only the technological landscape, but also the educational one. Through the World Wide Web, it is possible to make engineering education available to everyone, anytime, anywhere. This article describes a configurable laboratory system that supports the study of human-robot interaction in a physical context. The laboratory system serves two primary purposes. First, it supports the transition of human factors engineering education from a group-oriented experience to an individual-oriented one. Second, it serves as a reference point for research to span traditional modelling (cognitive, task, and environment modelling) and teamwork concerns in an effort to address human-robotic issues. The system is based on the popular LEGO®MINDSTORMS^{TM}sets and enables tele-operations through the World Wide Web. We call it the LEGO®MINDSTORMS^{TM}–based Configurable Telerobotics System (LMCTS). This system was used in two graduate-level human factors and one graduate research and experimentation course. We report initial data collected in the research course and provide recommendations on the scalability of the LMCTS.

Key Words

Telerobotics, human factors, engineering education, human-robotic interaction

1. Introduction

A 1997 study conducted by the Department of Education [1] showed that the number of universities offering distance education was expected to increase by 25% within three years. In a visionary paper, Tien [2] describes an "individual-centered" education where technology can be harnessed so that engineering education can be experienced by anyone, anywhere. This article describes a configurable laboratory system that supports the study of human-robot interaction in a physical context. The laboratory system serves two primary purposes. First, it supports the transition of human factors engineering education from a group-oriented experience to an individual-oriented one. Second, it serves as a reference point for research to span traditional modelling (cognitive, task, and environment modelling) and teamwork concerns in an effort to address human-robotic issues. The system is based on the popular LEGO®MINDSTORMS^{TM}sets, and we call it the LEGO®MINDSTORMS^{TM}–based Configurable Telerobotics System (LMCTS).

We are interested in investigating the impact of individuals and teams on human-robotic interaction (HRI) of supervisory control systems from not only an educational perspective but also a research one. Therefore, LMCTS was used to study how operators control telerobotic systems (machines that extend an operator's sensing and manipulation capability to a remote location [3]), as well as how humans collaborate to control teams of semi-autonomous telerobots. The three courses using LMCTS (see Table 1) included interaction with distance learning sections, had varying learning objectives, and emphasized teaching and research.

The use of MINDSTORMS^{TM}sets in higher education is not uncommon. In fact, they have been modified to teach college courses in mechanical engineering [4], software programming [5], artificial intelligence [6], and instruction theory [7]. What distinguishes LMCTS from the other uses of MINDSTORMS^{TM}is that it serves as a configurable laboratory platform for teaching as well as research.

This article is organized in five sections. The introductory section provides an overview of the work. It is followed by a description of the LMCTS apparatus in terms of LEGO®MINDSTORMS^{TM}components, video and audio broadcast equipment, and communications and control software. Section 3 presents the uses of LMCTS in each of the courses listed in Table 1. An evaluation of LMCTS as part of a pedagogical and research methodology makes up the Section 4. Conclusions are drawn in the final section.

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Table 1
Courses Using LMCTS for Laboratory Instruction

Course	Level	Interaction	Laboratory Objective	Purpose
Quantitative methods in cognitive modelling	Graduate	On-campus	Modelling user cognitive and physical activities in supervisory control	Teaching and research
Understanding and aiding human decision making	Graduate	On-campus and distance learning	Understanding team decision making to inform interface design	Teaching and research
Experimental study	Graduate	On-campus	LMCTS apparatus design, design of experiments, and analysis of results	Research

2. Apparatus

The LMCTS baseline components consists of:

- Two LEGO®MINDSTORMS^{TM}sets, each containing a Robotic Command Explorer, more commonly known as a RCX
- Two Pentium III 866 MHz processor PC with 128 MB RAM for RCX control. Each PC was loaded with an application programming interface (API) to enable RCX programming as well as Microsoft NetMeeting software to allow remote RCX control and communications between human controllers
- One Webcast PC equipped with a Pentium III 866 MHz processor with 512 MB RAM running iVista^{TM}software to broadcast video and audio over the Internet

In the following sections on the use of LMCTS in coursework, different configurations will be described using, at a minimum, the LMCTS baseline components. The RCX 1.0, which is a Hitachi H8 microcontroller with 32Kbyte of external RAM, is the centrepiece of the LMCTS. It can be used to simultaneously control three actuators, three sensors, and an infrared serial communications port. User programs can be downloaded to the RCX as byte code and are stored in a 6Kbyte region of memory. The range of the infrared transceiver is 2.5 m, individual motors attached to actuator ports operate at 350 rpm, touch sensors are capable of providing raw resistance values, and light sensors attached to the sensor ports can read reflectance ranging from 0.6 to 760 Lux.

The default software shipped with LEGO® MINDSTORMS^{TM}sets provide a visual programming environment [8] so that users can download executable programs from the PC to the RCX and observe the RCX execute programs autonomously. However, because the laboratory exercises served different purposes in each of the courses, programming languages were selected according to the goals of the course. For the modelling course, the API used to program the RCX was based on a variant of C called Not Quite C (NQC) [9]. NQC offers real-time control and data-logging capabilities along with an adequate graphical user interface (GUI). For the decision-making course, a Visual Basic API was used to program the RCX [10] to facilitate GUI prototyping.

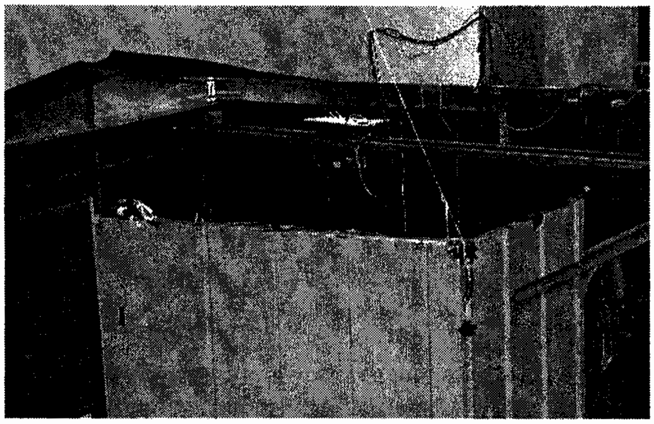


Figure 1. LMCTS test area.

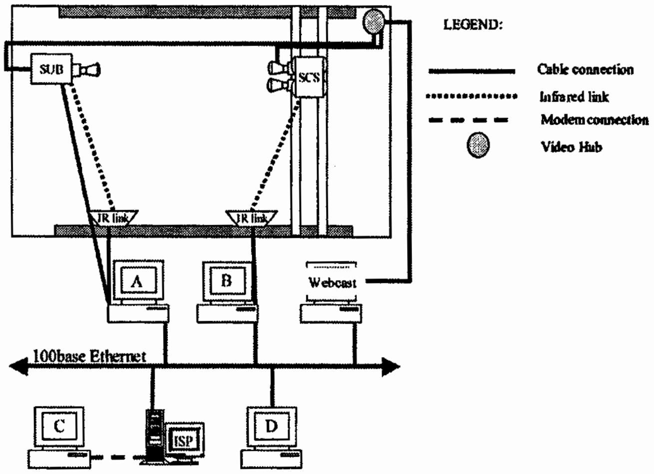


Figure 2. Standard LMCTS configuration.

The selection of video and audio communications equipment as well as RCX remote control software for the LMCTS was driven by the equipment constraints of the distance learning pupil. Consistent with Tien's vision [2], we sought to meet the capabilities of the student by adopting off-the-shelf technologies that are standard in the home computing market. NetMeeting software, which is a part of the Microsoft Windows®(2000/XP) operating system,

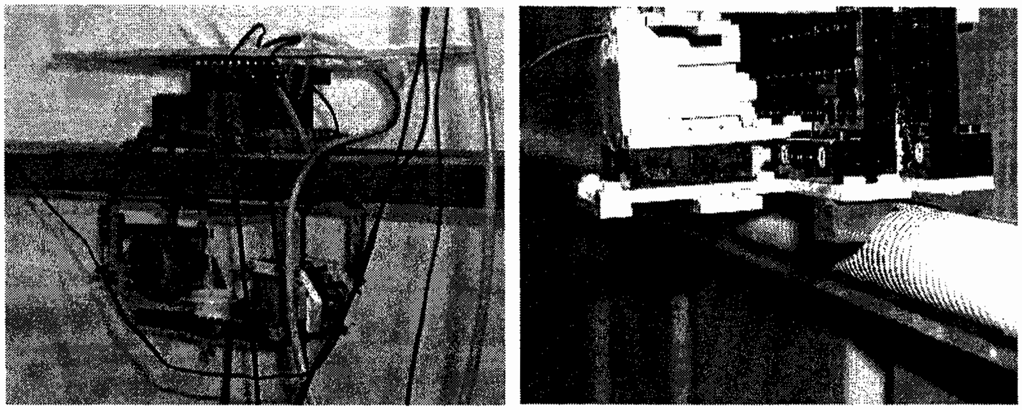


Figure 3. SCS assembly (left) and carriage assembly (right).

facilitates conferencing among distance and on-campus students as well as shared access to the RCX control program. The iVista^{TM}software broadcasts video and audio signals to anyone with a Java-enabled Internet connection point.

The LMCTS test area is shown in Fig. 1. Fig. 2 shows the standard configuration for LMCTS components. In each laboratory exercise, a student (or student group) controlled a surface control ship (SCS) through PC *B* (see Fig. 2). The SCS can also be controlled remotely from an Internet-accessible location at PC *D*. The SCS assembly (see Fig. 3) rested on a railing assembly 1.5 m above the ground and operates much like a Cartesian robot to enable forward, backward, or lateral manoeuvrability. Moreover, the SCS could retrieve or release an object by lowering a spooled cord from its position. A second student (or student group) controlled a remotely piloted sub (SUB) using PC *A*. Similar to the SCS, the SUB could also be controlled remotely from an Internet-accessible location at PC *C* (see Fig. 2). Cameras were mounted on both the SCS and the SUB and through iVista^{TM}video was broadcast at the rate of 10–20 frames per second.

3. LMCTS in Coursework

The three courses shown in Table 1 were taught or supervised by the first author during a span of two years. Although the courses were all part of a human factors engineering program, each focused on different applications of scientific principles and methods of design and development of human-machine systems.

3.1 Quantitative Methods in Cognitive Modelling

LMCTS was first utilized in a graduate course modelling user cognitive activities in a supervisory control context. Specifically, the course focused on the application of artificial neural networks and genetic algorithms to model human operator performance in a series of five exercises in the LMCTS environment. The exercises were designed to increase in difficulty and complexity, and culminated in a capstone exercise. The continuum of supervisory control presented in the exercises enables students to understand the difficulty of automating systems where human control is required [11]. In each task, subjects were allowed to configure the telerobot (i.e., build the LEGO®assembly) as well as the command interface to accomplish the objectives. Table 2 lists each LMCTS-based laboratory exercise, the pedagogical lesson of the exercise, and the human modelling technique used to represent operator (student) behaviour while engaged in the exercise.

The first exercise was designed to introduce students to tele-operations. From PC *B* (Fig. 2), each student was tasked to manoeuvre the SCS around one obstacle and finish with a specified scene in view. Students observed and recorded the performance of classmates and were given the assignment to construct a production system model of user behaviour in the exercise.

The second exercise was designed to teach students to conduct rudimentary search in a remote environment. From PC *B*, each student was tasked to navigate the SCS in searching for a prespecified object in a timely manner. As in the first exercise, students observed and recorded the performance of fellow classmates. The assigned model for the search exercise was a neural network model based on adaptive resonance theory [12] or backpropagation learning [13] to represent user search behaviour as pattern recognition.

In the third exercise, the students were introduced to an undersea task context. The scenario required a group-controlled SCS to retrieve a disabled remotely piloted submarine (SUB) from the ocean floor. The SUB, which was a second RCX, provided simulated distress conditions by emitting a beacon every minute. The model assigned for the exercise was a genetics-based classifier [14, 15] that utilizes prior user data to infer rules for SCS manipulation.

In the last two exercises, dual group tasks were devised so that collaboration and communication were required. In these exercises, the second team controlled a remotely piloted submarine (SUB) using PC *A* (Fig. 2). In the fourth exercise, a rendezvous was required between the groups. In the Capstone, the SUB was dispatched from the SCS to find and a retrieve an object in the dark. As these final exercises involve a substantial level of complexity, no

Table 2
Cognitive Modelling Course Laboratory Exercises

Exercise	**Pedagogical Lesson**	**Modelling Technique**
Manoeuvre SCS	Navigation	Production system
Use SCS for search for object	Search	Pattern recognition
Manipulate SCS to retrieve RPV	Tele-operations	Classifier system
RPV/SCS rendezvous	Tele-operations	Hybrid model
Capstone	Collaborative tele-operations	Descriptive model

prescribed modelling technique was assigned. Nevertheless, students were expected to use their course experience to generate hybrid and descriptive models of user behaviour.

3.2 Understanding and Aiding Human Decision Making

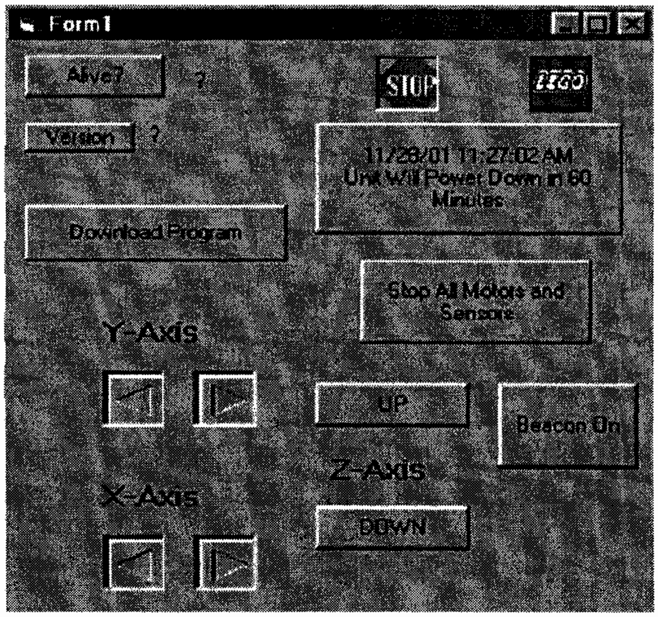
Using lessons learned from the cognitive modelling course, LMCTS was modified and utilized in a graduate course in understanding and aiding human decision making. The purpose of the course was to introduce the student to the science of behavioural decision making. Whereas the cognitive modelling course taught modelling through repetitive laboratory exercises, this course emphasized on gaining an understanding of decision making from assigned readings. Students were then assigned a course project to use knowledge gained from the readings to design a decision-aiding mechanism. Three students were enrolled in the distance section of the course: one from Minnesota, one from Connecticut, and the third from Ohio. The composition of the class enabled the students to gain insight into the problems and challenges of team telerobotic interaction [16].

For the project, LMCTS was configured so that distance students could control the RCX from an off-campus location in the same manner as on-campus students. Similar to the final exercises in the modelling course, one student manoeuvred the SCS through PC *B* (Fig. 2) and another operated the SUB through PC *C*. The task was designed so that only distance students operated the SUB.

As involvement of distance learning students was essential in the decision-aiding design project, careful planning was required to ensure all students had meaningful learning experiences. We created student groups so that each consisted of one distance learning student. Moreover, each group was required to design, create, and demonstrate their decision-aiding mechanism in a fixed scenario that required rescue of a simulated submarine using the LMCTS. The following scenario was given:

> A research submarine with five crew members on board has been involved in a collision with a tanker. It has sunk to a depth of 500 feet. The crew is desperately in need of fresh air supply as they attempt to repair the submarine. Your rescue ship is responsible for attaching a mechanical umbilical cord to the damaged submarine to sustain the on-board life support system. You have 15 minutes to locate the submarine, move your ship to the submarine, lower the umbilical cord to the submarine, and connect the cord to the submarine.

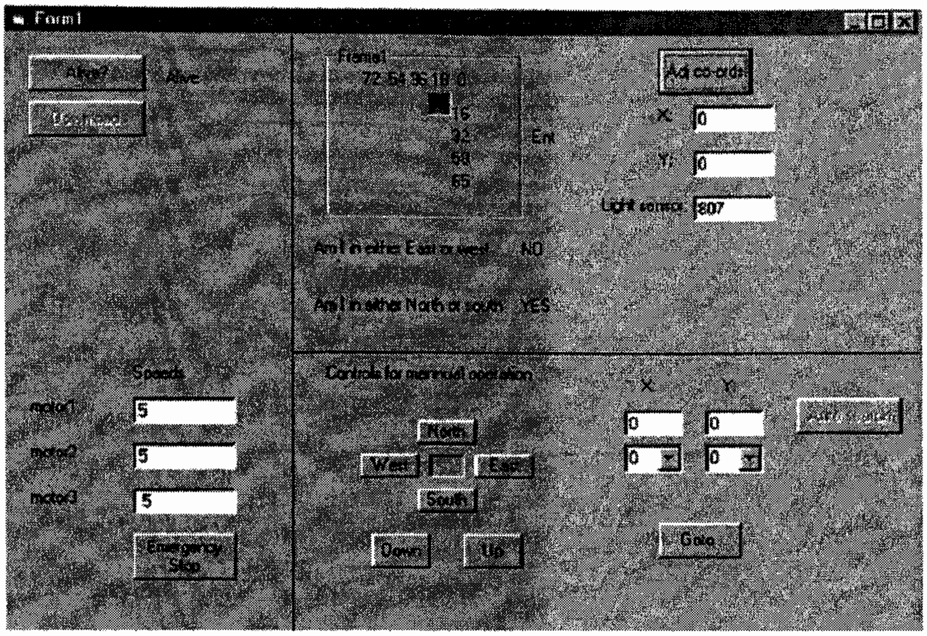
To simulate conditions at a depth of 500 feet, each group ran the task in the dark with only the aid of LEGO®lamps to manipulate the SCS and SUB. Students groups were assessed based on their ability to implement and execute a decision-aiding mechanism for the given scenario. Each group was provided with a rudimentary interface (Fig. 4) from which to build the decision-aiding mechanism. The interface enabled students to accomplish basic manipulation of the SCS, such as movement (forward, backward, and laterally) and load movement (up or down).



11/28/01 11:27:02 AM
Unit Will Power Down in 60 Minutes

Figure 4. Basic SCS controller interface.

Each student group used a different theoretical basis for the development of their interface. Moreover, each group used varying methods to determine the effectiveness of their decision-aiding mechanism. An interface designed by one of the groups is shown in Fig. 5. The student-designed interface reveals the group's understanding of the information needs of the decision maker to successfully complete the scenario. The left side of the panel indicated the current state of the rescue ship (alive or inactive and motor power settings). The upper right region of the panel showed the present location of the rescue ship. The lower right region provided the controls required to manipulate the rescue ship.



X: 0

Y: 0

Light sensor: 807

Am I in either East or west NO

Am I in either North or south YES

Speeds

motor1 5

motor2 5

motor3 5

X 0 0

Y 0 0

Figure 5. Sample student decision-aiding interface.

Verbal and written feedback from members of the class identified two characteristics of LMCTS that caused difficulty in accomplishing the task. First, distance students experienced webcast delays that resulted in poor resolution of the video image. The delays resulted in frames-per-second (fps) rates as low as 0.2. Second, the NetMeeting connection to control the submarine interface also experienced delays and caused synchronized activity between the SCS and the submarine to be very difficult.

3.3 Experimental Study

The second author of this article, who was enrolled in the decision-making course, was intrigued by the course and decided to pursue further research on team interaction in the LMCTS environment. Specifically, he conducted an experimental study to investigate the impact of time delay and video quality on team interaction.

The lessons of the decision-making course motivated two specific research questions:

1. In a complex, dynamic decision-making environment, what is the impact of time delay and video quality on team performance?
2. Given that two rolės exist, primary and supporting, what is the impact of delay and quality on the team if one or both roles had degraded conditions?

3.3.1 Subjects

Thirty-six students from Wright State University participated in the experiment and were paid \$5.00 per hour for approximately two hours of time. Students were randomly assigned to 18 two-person teams.

3.3.2 Experiment Apparatus

To facilitate the research, a more realistic environment was created in the LMCTS test area. The landscape (Fig. 6) for the scenario was constructed by a group of graduate student volunteers. Within the landscape, two landmarks were established: a helicopter landing pad and a pond (Fig. 7).

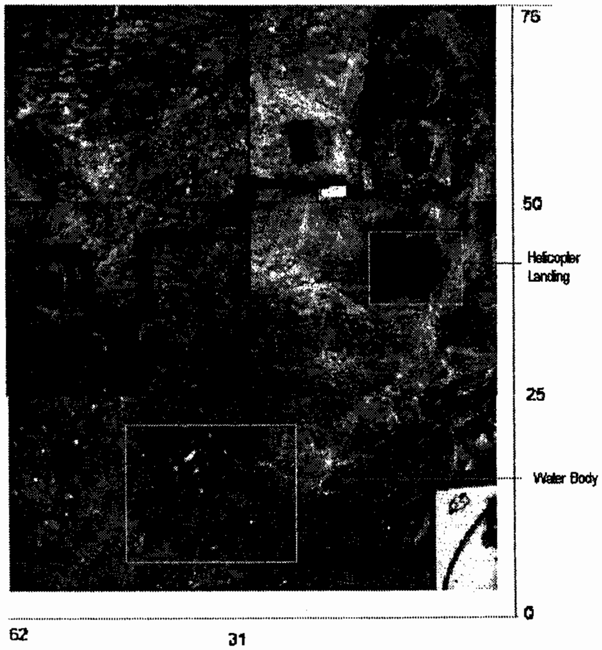


Figure 6. Landscape created for research scenario (top view, scale in inches).

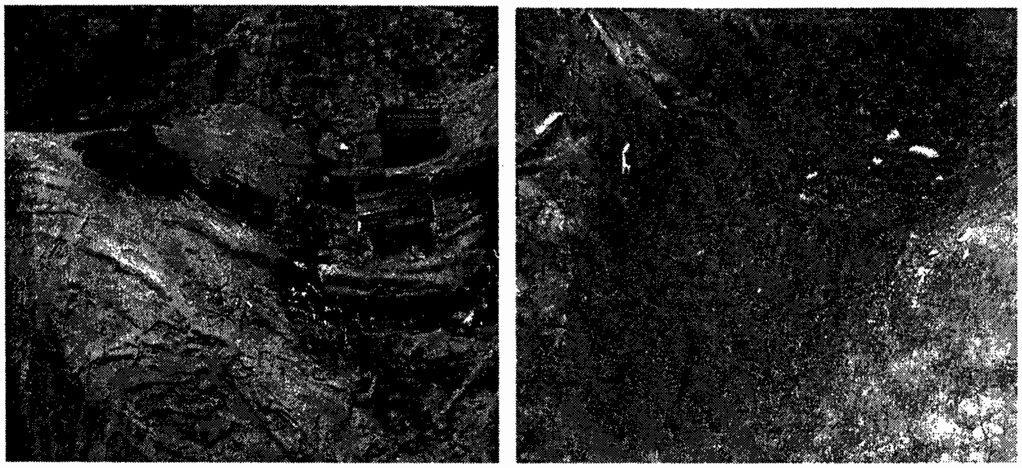


Figure 7. Helicopter landing pad (left) and body of water (right) in the LMCTS test area.

3.3.3 Procedure

Prior to the actual study, all participants received a brief overview of the experiment. Participants were then trained under supervision to perform each procedure in the experimental task through controlling the SCS or SUB and receiving feedback via the Internet video feed. By completing the training, each operator demonstrated the capability to control his/her assigned position. The training took approximately 45 minutes to complete.

For the experiment, students were tested in teams of two. One member of the team served as a pilot and controlled the SCS, and the other acted as the observer (and controlled the SUB in a rescue mission). The pilot could manoeuvre the SCS forward, backward, and laterally, and had a camera view of the terrain below (see Fig. 6). The pilot also had a rescue mechanism (i.e., a magnet) that he/she could raise or lower to retrieve a soldier (i.e., a metallic figure). The observer controlled the SUB (Fig. 8) and was located at ground level in the bottom right hand corner of Fig. 6.

The experimental task was a simulated rescue scenario to retrieve a military soldier behind enemy lines. Each team was given a maximum time of 20 minutes in which to locate the soldier, retrieve the soldier, drop the soldier off at a designated location, and return to base. The pilot was given the following instructions:

> You are a rescue ship pilot and you have received a distress call from a downed soldier in enemy territory. Your mission is to rescue the soldier. The last whereabouts of the soldier are unknown, but you have contact with a ground observer who can see the vicinity of where the soldier landed. Execute the following steps:
>
> (1) Locate the downed soldier;
> (2) Manoeuvre the SCS to a position above the soldier and lower the rescue mechanism to retrieve the soldier;
> (3) Drop off the soldier at the designated location; and
> (4) Return to base.
>
> Maintain complete radio silence and communicate with the observer strictly through textual chat.

The observer was given the following instructions:

> You are a ground observer overlooking enemy territory. You have been informed of a distress call from a downed soldier in enemy territory. Your mission is to locate and guide the pilot to retrieve him and drop him off at the designated area. Maintain complete radio silence and communicate with the pilot strictly through textual chat.

All subjects who assumed the role of the pilot controlled the SCS and started the scenario from a common position. The observer controlled the SUB (Fig. 8) and was located at ground level in the bottom right-hand corner of Fig. 6. The task was structured so that the pilot was responsible for accomplishing all the objectives and, under ideal conditions, could complete the task without the aid of the observer.

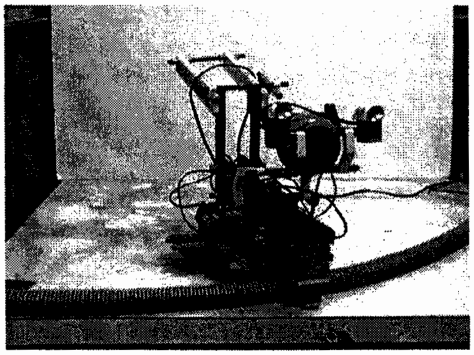


Figure 8. SUB in the downed pilot scenario.

3.3.4 Experiment Design

The planned experiment consisted of a 2 x 2 x 2 x 2 fractional factorial design with three replications. The first factor was the pilot video quality, which varied between good (0.5 image compression ratio) and poor (0.1 image compression ratio). The second factor was the pilot time delay, which varied between short (0.1 second delay) and long (1.0 second delay). The third factor was the observer video quality, which was varied in the same way as the pilot's video quality. The fourth factor was the observer time delay, which, again, was varied identically as the pilot's delay conditions. In essence, high compression rate resulted in poor video quality but fast image updates. The time delay was set in the graphical user interface so that control feedback of the RCX could be manually manipulated.

The levels examined for the experiment are shown in Table 3. We found in initial systems tests that task accomplishment was unlikely when both the pilot and the observer were operating under poor conditions (poor video or long time delay). Therefore, we designed the experiment so that one role had idea conditions (good video quality and short time delay) while the other did not. The dependent measures consisted of time to complete each of the four pilot steps and the total number of steps completed.

3.3.5 Results

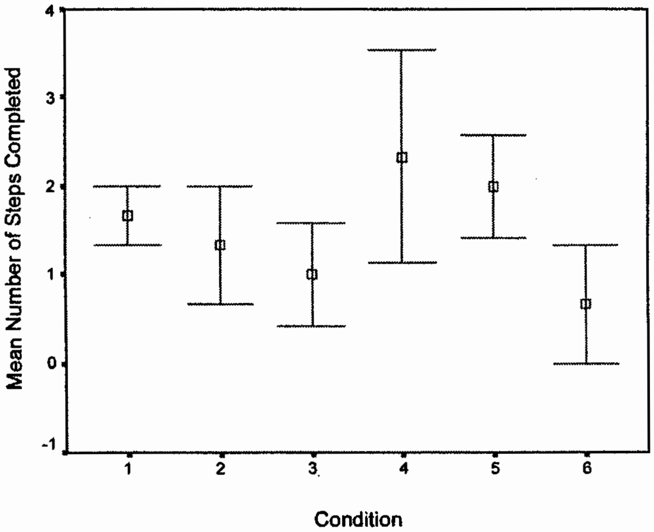


Figure 9. Comparison of mean number of steps completed for each condition. Error bars indicate standard error.

Only one team completed all four steps necessary to successfully accomplish the rescue. Fig. 9 shows the average number of steps completed by subjects in each condition. Although teams executed more tasks in Conditions 4 and 5, the results were not significant (main effect for pilot video, $F(1,13) = 1.69$, $p<0.22$; main effect for pilot delay, $F(1,13) = 0.27$, $p<0.61$; main effect for observer video, $F(1,13) = 0.42$, $p<0.53$; main effect for observer delay, $F(1,13) = 1.08$, $p<0.32$).

If we consider the data in Fig. 9 as trends, we see that teams in Conditions 4 and 5 were the most successful. The results suggest that the pilot was the dominant member of the team, who could complete the task alone given ideal conditions (good video and short delay) as in the case of Conditions 4 and 5. On the other hand, teams with poor pilot conditions (Conditions 1, 2, and 3) needed to communicate effectively in order to succeed.

From the perspective of communications, we analyzed both the number of words exchanged between team members and the content of the exchange. It is clear from an analysis of the average number of words exchanged between team members during the task (see Fig. 10) that success of a team does not depend on the number of words spoken.

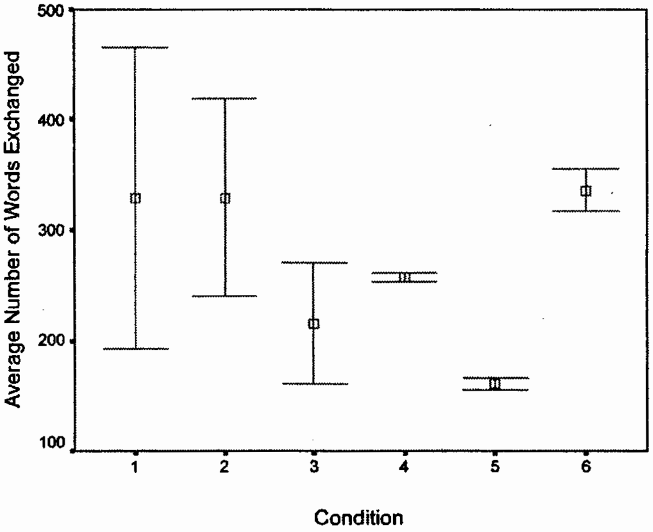


Figure 10. Comparison of mean number of words exchanged for each condition. Error bars indicate standard error.

Harvey and Koubek [17] suggest that for successful team/group collaboration, the following attributes play an important role:

1. *Common ground* of communication
2. Ability to apply knowledge from previous experiences to formulate strategies

As the team members come to the task with different experiences, it is critical that the team come to a common understanding very quickly. The understanding has to be well defined in aspects of jargon, "referential communication" [18], and the work setting. The term *common ground* summarizes this intra-team understanding by emphasizing the need for commonalities between the operators for successful task completion. In terms of the experiment, the majority of the teams lacked a common ground. For example, Group 6 had the highest average of communication exchanged (words spoken) with an average of 336 words (Fig. 10) compared to the experiment average of 271 words per team; however, they were not able to

Table 3
Experimental Conditions

	Pilot Conditions		Observer Conditions	
Condition ID	Video Quality	Time Delay	Video Quality	Time Delay
1	Good	Long	Good	Short
2	Poor	Long	Good	Short
3	Poor	Short	Good	Short
4	Good	Short	Poor	Short
5	Good	Short	Good	Long
6	Good	Short	Poor	Long

Note. Compression ratio was set at 0.5 for good video quality and 1.0 for poor video quality. Time delay was set at 0.1 seconds for short and 1.0 seconds for long.

succeed due to incoherent communication and differences in jargon. The following excerpt is from one team in Group 4 and shows the importance of having common ground, in which the team is clearly setting up direction-related referential communication early in the task:

9:38:19 pm	*aerial pilot:*	*forward or backward?*
9:38:39 pm	*aerial pilot:*	*right or left?*
9:38:46 pm	*ground observer:*	*when you come to my position that was moving right*
9:38:53 pm	*ground observer:*	*now move backward*
9:38:57 pm	*aerial pilot:*	*i do not know where you are*
9:39:16 pm	*ground observer:*	*when you came here from 0,0 you moved right*
9:39:23 pm	*ground observer:*	*now go backward*

The above excerpt can be contrasted with the following excerpt taken from a team in Group 1 that did not establish common ground early in the task:

3:05:05 pm	*ground observer:*	*move man*
3:05:16 pm	*aerial pilot:*	*i am doing*
3:05:48 pm	*aerial pilot:*	*now where?*
3:06:08 pm	*ground observer:*	*move more in the horizontal direction towards your left*
3:06:27 pm	*aerial pilot:*	*its end there*
3:06:45 pm	*ground observer:*	*hey i asked your left and its end on the right*
3:07:00 pm	*aerial pilot:*	*i am moving towards left...*
3:07:15 pm	*ground observer:*	*then there is so much space on the left...*
3:07:17 pm	*ground observer:*	*i can see it*
3:07:24 pm	*aerial pilot:*	*ok*
3:07:39 pm	*ground observer:*	*move it*

To accomplish the experimentation task under adverse pilot conditions, the affected teams needed to establish common ground early in the communications process. However, based on review of communications logs, this was never done in teams from Conditions 1–3. This result is consistent with those of prior literature [17, 18]. Moreover, this initial study gives impetus for follow-on studies with the LMCTS.

4. LMCTS Assessment

The utility of LMCTS in teaching can be assessed with regards to broad goals. First, given the explosion of distance education programs and courses, it is essential to meet students on their technological terms [2]. Therefore, LMCTS is an ideal candidate to allow students to be creative in their programming and, to some extent, LMCTS hardware design and implementation while restricting the course tool set to those components that are commercial, off-the-shelf packages.

Second, LMCTS offers HRI researchers an opportunity to investigate individual and team interactions in a configurable laboratory setting. Using lessons learned from courses on cognitive modelling and human decision making, we were able to construct an experimentation apparatus to investigator key team research questions. However, LMCTS does have its disadvantages. A summary of LMCTS advantages and disadvantages is given in Table 4.

Please see Table 4 at the end of the paper.

5. Conclusion

The current state of higher education has caused some to decry the way students are being taught [2, 19]. With current technological advances, faculties around the country have been called upon to change their role from lecturer to guide. Consistent with Tien's vision of individual-centred education, the development and use of LMCTS has represented this transition of roles. LMCTS was first used as a test bed in a quantitative methods course to model user cognitive activities. Based on student comments from the course, LMCTS was improved for use in a course to understand and aid human decision making. While student assessment in the modelling course was based on incremental learning assumptions—there were five graded exercises—students were evaluated in the decision-making course from an active learning perspective. That is, students were given an open-ended task to design an interface-aiding mechanism and were expected to design, code, and evaluate their own system.

The research questions raised in the decision-making course caused one particular student to pursue an experimental study course. In the experimental study, the professor became a guide to direct the student towards independent research. Using LMCTS as a platform to investigate HRI research issues has also yielded some promising directions for future work.

Acknowledgements

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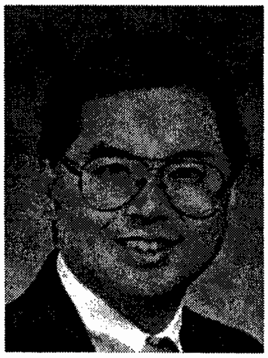
Biographies



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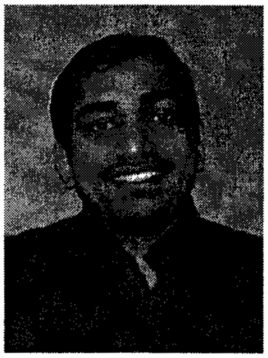

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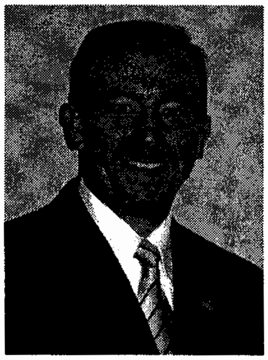

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Table 4
Overview of LMCTS Advantages and Disadvantages

	LMCTS Advantages	LMCTS Disadvantages
Location of Students		
In-class	• Students engaged in an engineering activity to construct hardware and software components to execute a complex scenario	• Multiple hardware configurations require time to setup and must be carefully managed to avoid inter-group conflicts
Distance	• Individual-centred laboratory experience through participation in a complex, collaborative task without cost of specialized software	• Connectivity via distance slow and not stable
Type of Project		
Groupwork	• Encourages assignment of roles to accommodate student competencies and enables project participation regardless of student location	• Requires synchronous participation to ensure LMCTS components are properly implemented to run scenarios
Independent study	• Provide hands-on research experience to extend classroom learning	• MINDSTORMS^{TM}equipment not designed for research and does not allow fine and consistent control
Use in Human Factors Course(s)		
Individual course	• Course feedback used to continuously improve laboratory experience	• Time cost of learning control and calibration of RCX. Requires hands-on practice
Course sequences	• Laboratory apparatus does not need to be learned each term and allows reconfiguration to meet course objectives	• Labs only designed to teach human-machine interaction in the context of human supervisory control