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An Ecological Interface Design Approach to Human Supervision of a Robot Team

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Summary. When supervising a team of robots, the operator's task is not only the manipulation of each robot but also achievement of the top goal that is assigned to the entire team of humans and robots. A main goal of this study is development of a design concept based on the ecological interface design for human supervision of a robot team, providing information about states of functions that are necessary to understand the overall progress in the work and the situation. This paper describes an experimental study conducted to reveal basic efficacy using an experimental test-bed simulation. The results suggest that the proposed approach has the ability to enable effective human supervision.

Keywords: Human–robot interface, Ecological interface design, Functional displays, System-centred view, Multiple robot management.

19.1 Introduction

Regardless of use of multiple robots, the operator's task involves not only manipulation of each robot but also achievement of the top goal that has been assigned to the entire team of humans and robots. There are several factors which pose a challenging problem in supervision and management of multiple robots. Although cognitive resources of humans are limited, operators are demanded to understand highly complex states and make appropriate decisions in dynamic environment. Furthermore, operators have to deal with large amounts of complex information which may risk overwhelming them in the supervision tasks. As a consequence, there has been increased interest in developing human–robot interfaces (HRIs) for human supervision of multiple robots [3].

The main goal of our project is the development of an interface design concept based on *ecological interface design* (EID) for human supervision of a robot team. EID is a design approach based on the externalization of the operator's mental model of the system onto the interface to reduce the

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cognitive workload during state comprehension [9, 10]. EID provides information about states of functions that are necessary to achieve the top goal of a human–machine system. Information on function is identified using the abstraction–decomposition space (ADS). An ADS is a framework for representing the functional structures of work in a human–machine system that describes hierarchical relationships between the top goal and physical components with multiple viewpoints, such as abstraction and aggregation [7]. Since the operator's comprehension of the functional states based on the ADS is an essential view for the work, supporting the view is crucial for them to make operational plans and execute the plans appropriately under high-workload conditions [5]. However several attempts have been made to apply the design concept to HRI [4, 8], empirical evidence of the effectiveness of this approach, while necessary, is not sufficient.

This paper describes an experimental study conducted to reveal the basic efficacy of EID in human–robot interactions, where the material was first presented at [2]. The next section explains an application and implementation approach to a test-bed simulation platform of the proposed design concept, and a procedure of the experiment using the prototype system. We then discuss the results to examine the usefulness of ADS for representing whole tasks allocated to humans and robots, the feasibility of designing indications for the functions in the ADS, and the efficacy of function-based interface design to improve human–robot collaboration.

19.2 Methods

19.2.1 The RoboFlag Simulation Platform

This study uses the RoboFlag simulation, which is an experimental test-bed modeled on real robotic hardware [1]. The chief goal of an operator' job is to take flags using home robots and to return to the home zone faster than the opponents. The basic tasks for achieving this goal are two: *Offence* and *Defence*. One operator directs a team of robots to enter an opponent's territory, capture the flag, and return to their home zone without losing the flag. Defensive action takes the following form: a rival robot will be inactivated if it is hit by a friendly robot while in friendly territory.

Figure 19.1 shows the display used for an operator to monitor and control his or her own team of robots. A circle around a robot indicates the detection range within which the robot can detect opponents and obstacles. The simulation provides two types of operations that operators can select according to their situation: manual controls and automatic controls. In manual control mode, an operator indicates a waypoint to a robot by clicking the point on a display. Two types of automatic controls were implemented in this study. When *Rush and Back* (R&B) mode is assigned, the robot tries to reach the

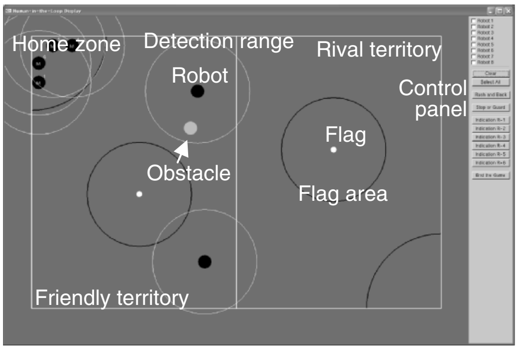

Fig. 19.1. Display for the RoboFlag simulation

flag and returns home after it captures the flag. The course selected is straightforward, in that the robot heads directly to the destination. In *Stop or Guard* (S/G) mode, the robot stays in the home position until it detects an opponent. If an opponent robot comes into detection range, the robot tries to inactivate the opponent.

The robots are semi-autonomous, that is to say, they have the ability to change their own courses to avoid rival robots or obstacles. Offensive and defensive tasks of the rival robots were fully automated by using the two types of automatic controls implemented in this study.

Because time constraints are severe in this RoboFlag game, human operators need gain an understanding of the situation as rapidly as possible. Furthermore, it is necessary for operators to comprehend the state of entire area as well as the local area.

19.2.2 Implementation of Functional Indications

The following are descriptions of two function-based interface designs, in which one was designed to represent the state of a lower-level function under an *Offence* function, and the other under a *Defence* function. Previous studies using the RoboFlag simulation showed that human–robot interactions depend on various contributory factors [6]. Because of the high complexity of the interactions, a part of the whole ADS was selected as the target functions indicated on the interface in this study.

To specify each state of the function, expressions that graphically showed the state in the physical relations between each robot and the object was used. This has aimed to enable operators intuitive to understand the state of the functions.

Figure 19.2 depicts a part of the ADS whose top is the *Offence* function. One of the means of achieving the function *Avoid opponents* is *Set way-point such as not to encounter opponents.* To select an appropriate course to reach the flag, the situation along the course, especially the positions of opponents,

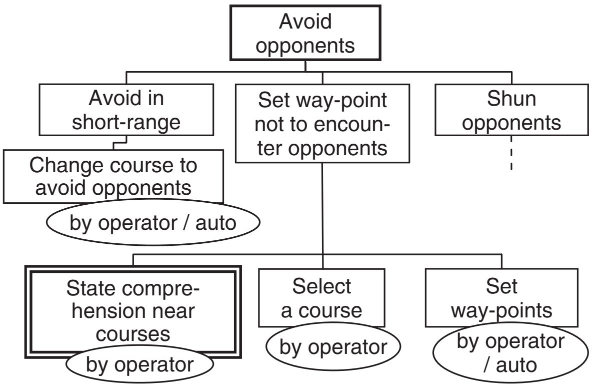

Fig. 19.2. An ADS for the function *Avoid opponents*

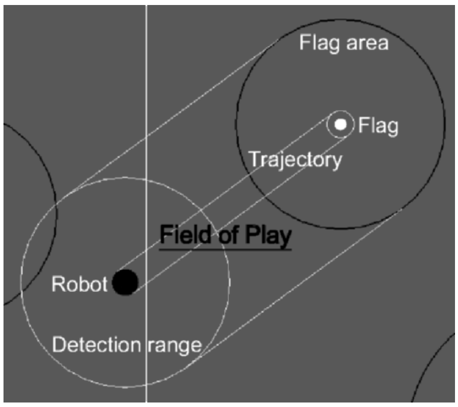

Fig. 19.3a. An interface design indicating the state of the function *State comprehension near courses*

should be understood by the decision-maker. The proposed indication was applied to the function *State comprehension near courses*, which is one of the key sub-functions included in the *Offence* function, and is allocated to the human operator. The indication is depicted in Fig. 19.3a. A robot is shown as a black circle and the flag as a white circle. The two straight lines connecting the robot and the flag show the trajectories along which the robot is going to move. The two lines on the outside, which connect the detection range and the flag area, show the range in which detection becomes possible when the robot moves along the route. In other words, opponents in this area can tackle their own robots moving along the course. The display clearly indicates the *Field of play* of the target task. One of the operator's options is to send a robot as a scout to the field if there is an area where the situation is unknown.

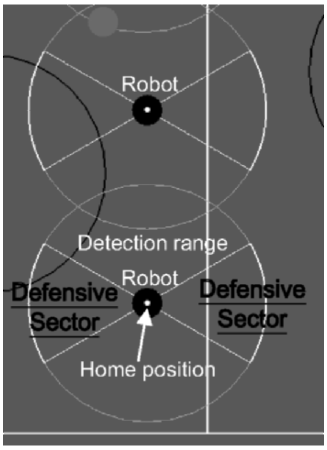

Fig. 19.3b. An interface design indicating the state of the function *Cooperation between defensive robots*

Cooperation between defensive robots is a type of defensive function realized by a team of robots, and an indispensable sub-function for achieving the *Defence* function. The picture illustrated in Fig. 19.3b is the functional indication designed for enabling an operator to be clearly aware of the state of the function. A circle around a robot indicates the detection range as described in the previous section. A fan-shaped sector, a *Defensive sector* is where a robot in S/G mode has a high ability to intercept opponent robots coming through. Outside the Defensive sector, the possibility of catching opponents is lower than within the sector. An operator can use spaces between the sectors as an indication of the defensive ability of the defensive robot team in the position.

19.2.3 Procedure

Twenty-two paid participants took part in the experiment. The participants were randomly divided into two groups of eleven. One group (the *original* group) used the original human-robot interface for the RoboFlag simulation, and the other group (the *modified* group) used the modified interface display designed according to the proposed concept.

The participants learned their tasks, rules of the game and the details of the assigned HRI, and mastered skills for controlling the team of robots through playing the game. They were asked to try it out until they found their own strategies to play the game. After they had decided on their strategies, they played the game five times as part of the main experiment. At the end of each game, they were asked to write the details of their strategies and usage of information represented on the display. The quantified data acquired in the main experiments were then statistically analyzed.

19.3 Results and Discussion

19.3.1 Statistical Data Analysis

The number of flags captured was counted for every game. The averages and standard deviations of participants' captures in the *original* and *modified* conditions are M = 0.75, SD = 0.62, and M = 1.20, SD = 0.85. A repeated-measures ANOVA test indicates that the difference between two conditions is significant ($F(1, 20) = 6.164$, $p < 0.05$). This result may suggest that the modified display is effective in supporting operators in their offensive task, regardless of their ability or the strategy used for the task.

The results of the statistical analysis show that there are no significant differences between the *original* and *modified* conditions for the number of flags captured by opponent robots, win percentages, the numbers of times that participants' and opponents' robots were tagged, total elapsed times, and time before the first capture by participants' and opponents' robots. However, at least, the results show no sign of any ill effects caused by using the modified interface.

19.3.2 Strategies Developed and Use of Functional Indications

This section illustrates the strategies developed by the eleven participants of the *modified* group and how they used the information on functions represented on the display.

For offensive operations, five participants mainly used the R&B automatic operation to capture the flag. Four of them, i.e. 80% of the five operators, tried to comprehend the state of the robots and situation around the course using the *Field of play* indication. For defensive operations, ten participants allocated two to four robots on a course that opponent robots followed to capture the flag. Eight of ten, i.e. 80% of them, used the *Defensive sector* indication to decide appropriate spaces between the guarding robots at the training phase and/or the main experiments. Their usage and target functions exactly match with those expected in designing phase.

The six participants who chose manual controls for offensive actions fixed all the waypoints and timings of the orders in advance. The *Field of play* indication was not necessary for them during the main experiments. In spite of this, they mentioned that the indication was useful for developing their own strategies during the trial-and-error processes in the training. One participant who used the manual-controlled strategy for offence decided not to take any defensive action. A swift attack was his only strategy. The *Defensive sector* display is not necessary for this strategy.

19.3.3 Discussion

The analysis on the operators' uses of the functional indications suggests that definition of functions specified in the ADS meets the participants' understanding of functions, and that the ADS includes all the functions to which participants directed their attention in the operations. It also demonstrates that the functional indications, which are designed for the functions, were useful for participants to comprehend states of the functions.

The results also indicate that the need for a functional display closely depends on the strategies actually used during operations. This result suggests that individual difference in strategies should be taken into account when designing suitable interface displays for supervising multiple robots.

As for this experiment, the functional indications added to the original display did not cause obvious harm to the participants even when the information was not necessary in their operations. It can be said that the ADS and the interface display based on the ADS were appropriately built, which do not cause any interference in participants' supervision.

These findings may lead to the conclusion that the proposed design concept can offer a proper framework for developing HRIs which provide effective human supervision of multiple robots.

19.4 Conclusion

This paper describes an experimental study conducted to reveal basic efficacy of a human–robot interface design concept, in which the *ecological interface display* approach is used as the basic framework for implementing the information about a human–robot team work into an interface display. The results may suggest that the whole work can be modeled using ADS, and it is feasible to design useful functional indications based on the ADS. This study provides empirical evidence for the efficacy of the proposed approach to enable effective human supervision of multiple robots.

The results also show the need to consider two factors to design effective HRI displays: the one is participants' strategies developed for tasks, and the other is how they use the functional indications.

To elaborate the practical and effective design concept for HRIs, several techniques are necessary. Typical examples are methods for designing functional models for target tasks using an ADS as a framework, methods for selecting functions for which support of comprehension is necessary for operators, and methods for designing effective indications for easy understanding of states of the functions.

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