An Empirical Study on Ecological Interface Design for Multiple Robot Operations: Feasibility, Efficacy, and Issues

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1. Introduction

Multiple robots systems are one of effective solutions to implement robust, flexible, and adaptable systems that can be used in various conditions (Lee et al., 2000). The systems are increasingly being used in environments that are inaccessible or dangerous to humans (Stoeter et al., 2002 ; Chaimowicz et al, 2005). Operations in these environments are numerous, and include reconnaissance, exploration, and surveillance. As an example, one of promising areas of the application is a network robots system, which is a distributed architecture for remote control of multiple robots systems (Wirz et al., 2006). Another example is swarms of insect robots (Lee et al., 2000). Large amount of small and simple robots are used to achieve tasks in a form of agent-based automation. Regardless of their purpose of use, there are several factors which pose a challenging problem in supervision and management 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. Clearly, support of the operator’s skill-based behaviours is important. Equally, it is important to support human operators in their understanding of the overall state of a work-in-progress and the situation around it using a system-centred view. Although cognitive resources of humans are limited, operators are demanded to understand highly complex states and make appropriate decisions in dynamic environment. Furthermore, human-machine interfaces (HMIs) can display large amounts of complex information which risk overwhelming the operator at exactly the worst time, i.e., in an emergency situation (Sheridan, 2000). As a consequence, there has been increased interest in developing human-robot interfaces (HRIs) for human supervision of multiple robots (Goodrich et al., 2005).

The main goal of our research 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 paradigm based on visualization of constraints in work environment onto the interface to reduce the cognitive workload during state comprehension (Vicente, 1999; Vicente & Rasmussen, 1992; Vicente, 2002). 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) (Rasmussen, 1986). An ADS is a framework for representing the functional structures of

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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. 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 operators to control a human-machine system, comprehend system states, make operational plans, and execute the plans appropriately under abnormal or unanticipated conditions (Miller & Vicente, 2001). EID is a design paradigm in which the ADS of a target system is represented in such a way as to allow operators to comprehend the states of the functions intuitively. The function-based HMI is designed to enable operators to develop a system-centred view even under high-workload conditions. This can be thought of as an externalization onto the HMI of the operator's mental model of the system (Rasmussen & Pejtersen, 1995). However several attempts have been made to apply the design paradigm to HRI, empirical evidence of the effectiveness of this approach, while necessary, is not sufficient.

In this study, the EID paradigm was used as the basic framework for implementing the information about a human-robot team work into an interface display. This chapter describes two experiments conducted to reveal the basic efficacy of EID in human-robot interactions, and the development of a design method using a multi-level representation of functions to improve human-robot collaboration.

The first experiment, Experiment 1, was conducted to reveal the feasibility of the proposed concept using an experimental test-bed simulation, as the first step of the project (Furukawa, 2006). The results indicated that the whole work can be modelled using ADS, and it is feasible to design useful functional indications based on the ADS. The results also show the need to consider participants' strategies developed for tasks to evaluate the effectiveness of HRI display. However, because the operation tasks were not complex, only a few strategies were used by the participants in the experiment.

The aim of the second experiment, Experiment 2, was to evaluate the basic efficacy of the human-robot interface design concept under the condition that the wide variety of strategies was used for operations (Furukawa, 2008). The conditions of the test-bed simulation had been changed to prompt the participants to develop various strategies. The results demonstrate that the designed interface design has basic efficacy to provide adequate and useful functional information for supporting human operators for supervision of a robot team.

2. Related Works

This section shows several proposed methods that used the EID paradigm for robot operations, and discuss the promising usages in designing of HRI for multi-robots systems.

Sawaragi and his colleagues applied the EID concept to HRI to support naturalistic collaboration between a human and a robot at the skill level via a 3D display (Sawaragi et al., 2000). Nielsen et al. proposed an ecological interface paradigm for teleoperation of robots, which combines video, map, and robot-position information into a 3-D mixed reality display (Nielsen et al., 2007). In both studies, the target level of operation is limited to skill-based control on a robot. The proposed methods can be used for direct operation of an individual robot in a multi-robots system. Jin and Rothrock propose a function-based interface display which indicates the state of communication between human operators and multiple Robots, in which the target function is limited to one (Jin & Rothrock, 2005). The indication can be used as a display design for representation of a function of a multi-robots system. On the other hand, the proposed paradigm of the HRI design described in this chapter is a function-based display that indicates the *whole work* assigned to humans and *multiple robots*.

In a study conducted by Xu, an ADS is adopted as an analytical tool to identify problems and suggest opportunities for enhancing a complex system with agent-based automation. ADS models of human-machine systems indicate incomplete knowledge of human operators, lack of information displayed in interfaces, lack of procedures of operators, and so on. This analytical method can be used to evaluate appropriateness of HRI for multiple-robots systems.

3. Display Design based on Ecological Interface Design Paradigm

3.1 The RoboFlag Simulation Platform

This study uses the RoboFlag simulation, which is an experimental test-bed modelled on real robotic hardware (Campbell et al., 2003). 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. 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: while in the rival's territory, a rival robot can inactivate an intruding robot by bumping into it. Similarly, a rival robot will be inactivated if it is hit by a friendly robot while in friendly territory.

Fig. 1 shows the display used for an operator to monitor and control his or her own team of robots (Campbell et al., 2003). A circle around a robot indicates the detection range within which the robot can detect opponents and obstacles.

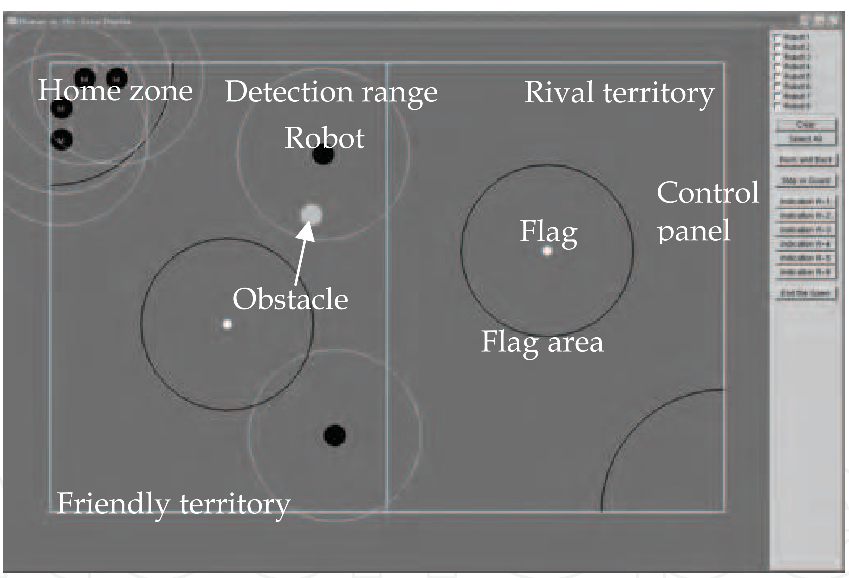


Figure 1. The original display for the RoboFlag simulation

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 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 make fine adjustment to their own course to avoid rival robots or obstacles near the original course.
The basic tasks for achieving the chief goal are two: *Offence* and *Defence*. The former comprises two sub-tasks, which are *Capturing the flag* and *Taking it to one's own home zone*. *To keep the robot active* is also necessary for the sub-tasks. The sub-tasks of the latter are to prevent opponent robots from coming close to the flag and returning home with it.
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.

3.2 Design of Ecological Interface for Human-Robot Systems

The definition of human-robot systems in this chapter is illustrated in Fig. 2. The system consists of four agents: *Top Goals*, *Work Environment*, *Robots* and a *Human Operator*. Top goals are settled by the designer of the system. The robots, sometimes also environment, are designed to match these goals, and operators are trained to achieve these goals. Arrows with "Information" indicates flows of information to comprehend other agents, and "Control" indicates flows of signals to control other agents. "Negotiation" indicates settlement of interference in goals or means between robots and an operator. This framework is a general form, which just shows possibility of existence of each flow. There may be a situation that some of them are not included in real systems.
Top goals are functions that are defined on a human-machine system with quantified or qualified criteria. The goals are classified to two groups: positive goals and negative goals. The formers are reasons for existing of the system, and correspond to its beneficial influences to the outside world, e.g., exploration of moon surface. The latter correspond to a task to prevent bad influences to the outside world, e.g., collision avoidance.

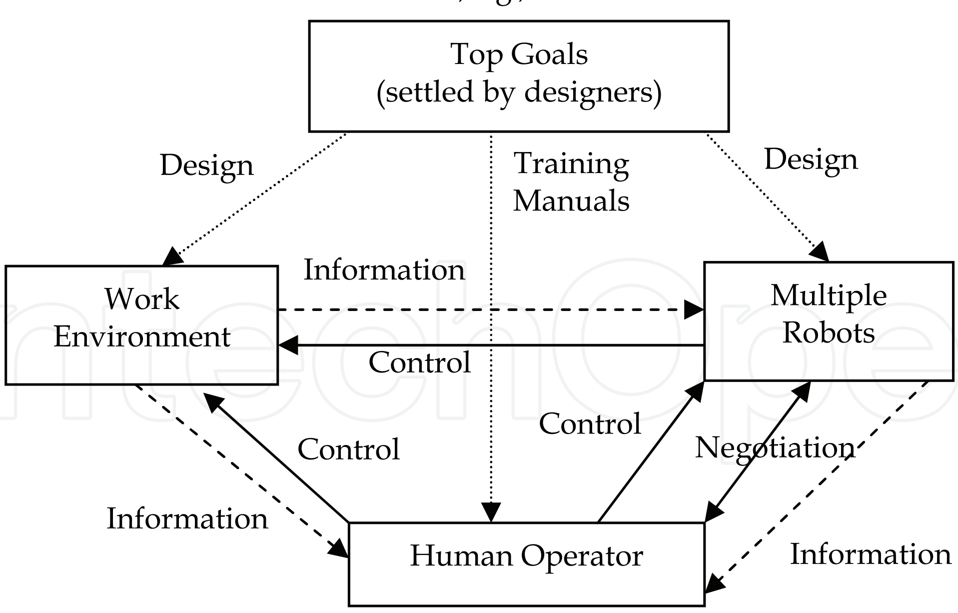


Figure 2. An overview of of multiple robots systems

Many researches have reported the effectiveness of means-ends models which functions are defined as primitive elements of controlled artefact (Vicente & Rasmussen, 1992; Burns & Hajdukiewicz, 2004). The ADS is the basic concept of the means-ends models, which is also known as the abstraction hierarchy. A design concept based on the ADS is EID (Vicente &

Rasmussen, 1992), in which the ADS of a target system, i.e., the means-end relations of the work, is represented to allow operators to comprehend the ADS intuitively. The HMI is also designed to support skill-, rule- and knowledge-based behaviours (Rasmussen, 1986).
In this study, an ADS was introduced as a basic framework for state representation of the multiple robots system, and the HRI was designed according to the EID paradigm to support operators to comprehend the states of functions dedicated to the controlled artefact.

3.3 Implementation of Functional Indications for Multi-Robot Operations

This section shows the human-robot interface for the RoboFlag simulation used in this experimental study and the design process of the functional indications based on the proposed design concept.
The following are descriptions of four function-based interface designs, in which one was designed to represent the state of a lower-level sub-function under an Offence function, and the second under a Defence function. The third and forth were designed for common sub-functions under the two functions. Previous studies using the RoboFlag simulation showed that human-robot interactions depend on various contributory factors (Parasuraman et al., 2005). These four functions were selected because results from the previous studies indicated that it was difficult to comprehend the states of the four functions during plays.
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 and relationships between the functions.

3.3.1 A Functional Indication for Offensive Function

Fig. 3 shows the outline of the ADS whose top is the Offence function. Two functions, *Capture flag* and *Take flag home*, depicted below the function are the means of achieving the top function. To capture the flag, the robot needs to reach the flag (*Reach flag*). At the same time, the robot should be in active mode (*Stay active*); and avoid opponents: *Avoid opponents* is one of the necessary functions to achieve the goal.

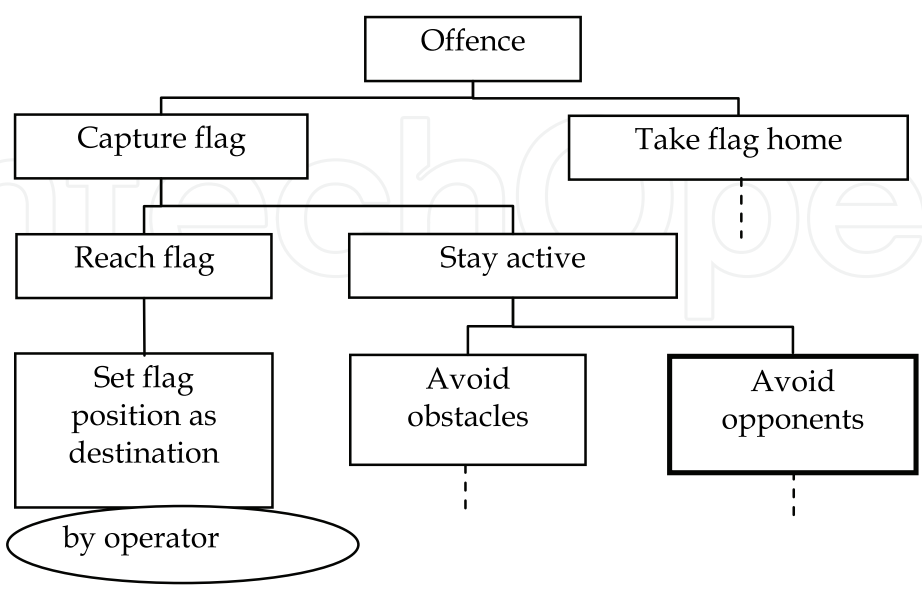


Figure 3. A hierarchical functional model for the function *Offence* identified using the abstraction-decomposition space

Fig. 4 depicts the ADS below the function *Avoid opponents*. 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, 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.

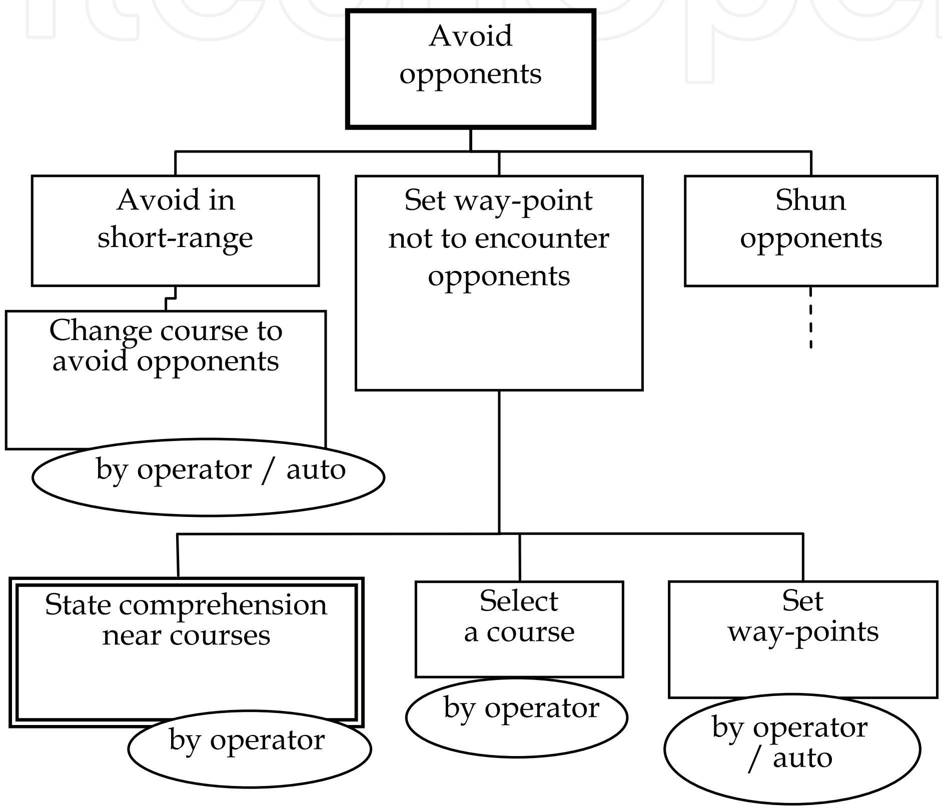


Figure 4. A hierarchical functional model for the function *Avoid opponents* identified using the abstraction-decomposition space

The indication is depicted in Fig. 5. 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.

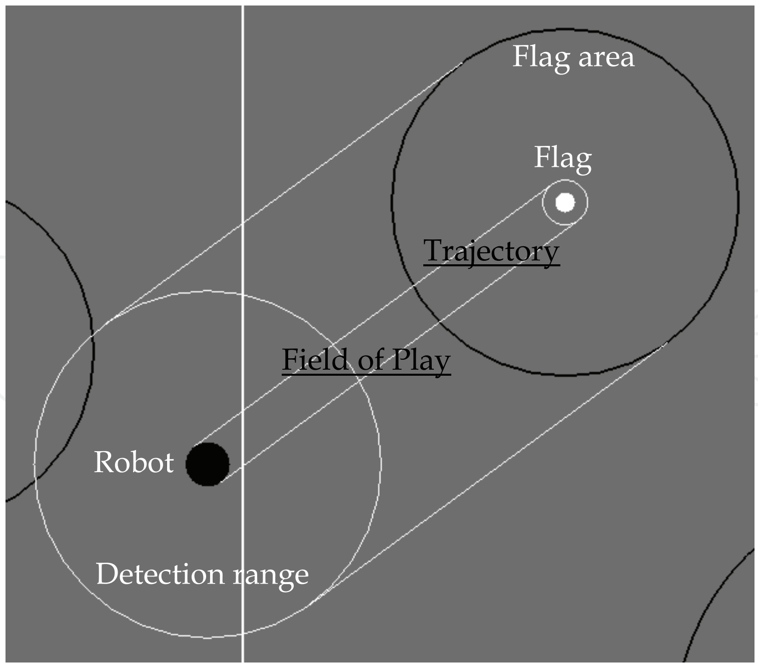


Figure 5. An interface design *Field of play* indicating the state of the function *State comprehension near courses*

3.3.2 A Functional Indication for Defensive Function

The *Intercept opponents* function is an indispensable sub-function for achieving the Defence function. Fig. 6 shows the ADS. *Cooperation between defensive robots* is a type of defensive function realized by a team of robots, and *Block opponents* is a defensive function possessed by individual robots.

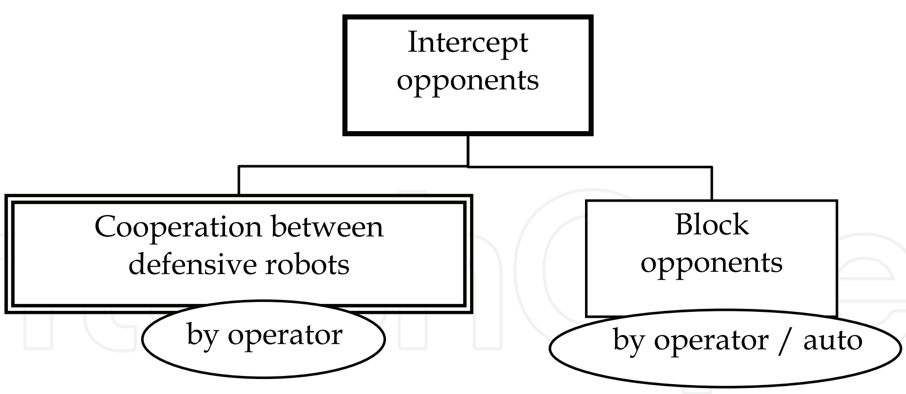


Figure 6. A hierarchical functional model for the function *Intercept opponents* identified using the abstraction-decomposition space

The proposed indication was applied to the function *Cooperation between defensive robots,* which allocated to a human operator. The picture illustrated in Fig. 7 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.

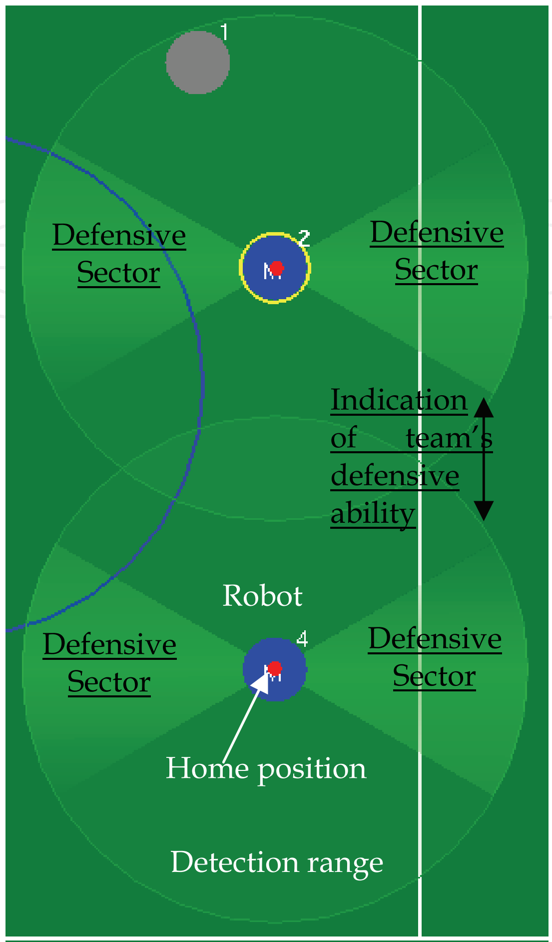
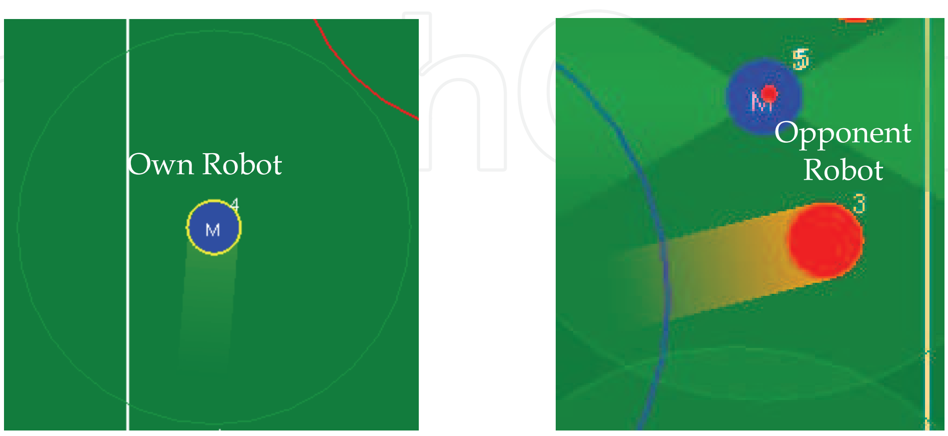


Figure 7. An interface design *Defensive sector* indicating the state of the function *Cooperation between defensive robots*

3.3.3 Functional Indications for Avoidance and Deterrence



(a) Ally movement (b) Opponent movement

Figure 8. An interface design *Ally movement* and *Opponent movement* indicating the state of the function *Shun opponents* and *Block opponents*

The third and fourth indications were designed for two functions of *Shun opponents* and *Block opponents*. The two functions are represented by indications of movements of own and opponent robots. *Ally movement* and *Opponent movement* are bar-like indications drawn on the robot, where they point to the direction of movement of the robot and the length of the bar is set in proportion to speed of the robot. The indications are shown in Fig. 8. The necessity of the two indications was recognized through the Experiment 1. Therefore, the indications were only used in Experiment 2.

4. Experiment 1

This section describes the first experiment conducted to reveal the basic efficacy of EID in human-robot interactions, where the material was first presented at (Furukawa, 2006). After explanation of a procedure of the experiment using the prototype system, we 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.

4.1 Procedure

Twenty-two paid participants (undergraduate and graduate students) took part in the experiment. All participants reported that they had normal or fully corrected vision and hearing. The participants were randomly divided into two groups of eleven. One group (the original group; O1 – O11) used the original human-robot interface for the RoboFlag simulation, and the other group (the modified group; M1 – M11) used the modified interface display designed according to the proposed concept.

Offensive and defensive tasks of the rival robots were fully automated by using the two types of automatic controls implemented in this study.

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 several times. 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 of five games were then statistically analysed.

4.2 Results

4.2.1 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 ($F(1, 20) = 6.164$, $p = 0.022$**). 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.

Averages and standard deviations of win percentages under the original and modified conditions are M = 45.4%, SD = 34.7%, and M = 63.6%, SD = 26.6%. However, a t-test shows that the difference between two conditions is not significant ($t = 1.379$, df =18.712, $p = 0.184$).

In addition, 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, 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.

4.2.2 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. The participants played RoboFlag several times using the original display after they had completed the main experiments with the modified version. In an interview immediately afterwards, they were asked to explain the strategies they used during the main experiments, their usages of the indications of functions during the experiments, and the importance of the information in completing their missions. The typical strategies for offensive and defensive tasks are described in Tables 1 and 2 respectively with the usages of the functional indications and the participants who used the strategies.

For offensive operations, five participants mainly used the R&B automatic operation to capture the flag. Four of them 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 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.

Strategies	Use of functional indication (Field of play)	
	Used	Did not use
used R&B	M1, M2, M7, M10	M11
manual operation	none	M3, M4, M5, M6, M8, M9

Table 1. Participants categorized by their strategies for offensive tasks and usage of the *Field of play*

Strategies	Use of functional indication (Defensive sector)	
	Used	Did not use
no operations	none	M3
defensive operations	M1, M2, M4, M5, M7, M9, M10, M11	M6, M8

Table 2. Participants, categorized by the strategies for defensive tasks and usage of the *Defensive sector*

The participants who chose manual controls for offensive actions fixed all the waypoints and timings of the orders in advance. The 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.

4.3 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. Because only a few strategies were used by the participants, further experiments should be conducted under a condition that the wide variety of strategies was used for operations.

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.

5. Experiment 2

This section describes the second experiment conducted to discuss three research questions about the basic efficacy of the human-robot interface design concept under the condition that the wide variety of strategies was used for operations (Furukawa, 2008). The first question is "Do the indications provide adequate information about status of functions that operators want to comprehend?" The second is "Are the indications useful for state comprehension of the functions?" and the third "Are the indications effective in appropriate comprehension of states of the functions?" The conditions of the test-bed simulation had been changed to prompt the participants to develop various strategies. The results provided positive evidences for the first and second questions, and valuable suggestions for the next stage of this project.

5.1 Procedure

New settings were applied for the robots in this study. The number of defensive robots was changed from three to four for improvement of the defensive ability. The offensive robots had three different courses to enter the player's territory, and three types of the timings. A pair of settings was randomly selected from the alternatives. Because of the randomness, the participants had to operate their robots adaptively.

Twenty-one paid participants took part in the experiment. The participants were randomly divided into three groups of seven. One group (MO group) used the modified human-robot interface for the RoboFlag simulation at the first stage and the original HRI at the second stage of the experiment. The second group (OM group) used the original interface at the first stage and the modified HRI at the second stage. The third group (OO group) used the original HRI at the first and second stages.

At the first stage, the participants learned their tasks, rules of the game, and the details of the assigned HRI. They also 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. The time limit of the training phase was set eighty minutes. After they had decided on their strategies, they played the game ten times as part of the main experiment. At the second stage, they tried to master the assigned HRI. The time limit was fifteen minutes. 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.

5.2 Results

5.2.1 Strategies Developed and Use of Functional Indications

This section illustrates the strategies developed by the participants of the MO and OM groups and how they used the information on functions represented on the modified display. The both groups of participants had experiences in playing RoboFlag with the modified display. In an interview immediately after the main experiments, they were asked to explain the strategies they used during the main experiments, their usages of the indications of functions during the experiments, and the importance of the information in completing their missions. In this study, we considered that a functional indication was used by a participant only when the participant mentioned actual usefulness or necessity of the indication.

1) Disposition of Defensive Robots: Table 3 described the typical strategies used for disposition of defensive robots and the usages of the Defensive area. The first number in a cell is the total number of participants who used the strategy or the indication. The two numbers in parentheses are the subtotal numbers for MO and OM groups, respectively.

All fourteen participants (MO and OM) assigned one or few robots defensive tasks. Three of them tried to set defensive robots adaptively during plays, and all used the Defensive area for the disposition. The other eleven had decided positions to set them up in their training phases. Understandably, the numbers of users are low.

Strategies	No. of participants		Percentage (b/a)
	Used the strategy (a)	Used Defensive area (b)	
fixed	11 (6, 5)	1 (1, 0)	9% (17%, 0%)
adaptively set	3 (1, 2)	3 (1, 2)	100% (100%, 100%)

Table 3. The typical strategies used for disposition of defensive robots with usages of the designed functional indication

2) Defensive Actions: The strategies used for defensive actions and the usages of the indications are shown in Table 4. Whether they selected the S/G automated control or manual control, all participants used one or two of the functional indications, which are Defensive area, Opponent movement, and Ally movement.

Strategies	No. of participants			
	Used the strategy	Used Defensive area	Used Opponent movement	Used Ally movement
automated (S/G)	13 (7, 6)	5 (4, 1)	9 (4, 5)	2 (0, 2)
manual	1 (0, 1)	0 (0, 0)	1 (0, 1)	0 (0, 0)

Table 4. The typical strategies used for defensive actions with usages of the designed functional indication

3) Selection of Offensive Routes: As shown in Table 5, four typical strategies were developed by participants for selecting routes to reach the flag and to go back home. During the training phase, some participants found a route in which own robots could travel without going inside of opponent's defensive areas. They used the fixed route in every trial. This strategy is called *fixed detour* in this study. *Adaptive routing* is a way that participants tried to find an opening in opponents' defence line during play and send robots through it. Because the setting depended on situation, every route might be different every time. In *feint strategy*, participants move own robots near opponent robots to let them follow the own robots. As a result, participants can use the opening of opponent's defensive line as a safe route. The fourth strategy is *swift attack*, where participants send robots into opponent's flag area as soon as the game stated. This strategy can be used only for routing from own home to opponent's flag.

Strategies	No. of participants		
	Used the strategy	Used Trajectory	Used Field of play
Task: route to reach the flag			
fixed detour	2 (1, 1)	0 (0, 0)	0 (0, 0)
adaptive routing	4 (4, 0)	2 (2, 0)	0 (0, 0)
feint	6 (2, 4)	2 (1, 1)	1 (1, 0)
swift	2 (0, 2)	0 (0, 0)	0 (0, 0)
Task: route to back home			
fixed detour	2 (1, 1)	0 (0, 0)	0 (0, 0)
adaptive routing	4 (2, 2)	2 (1, 1)	1 (0, 1)
feint	8 (4, 4)	2 (2, 0)	1 (1, 0)
swift	0 (0, 0)	0 (0, 0)	0 (0, 0)

Table 5. The typical strategies used for selection of offensive routes with usages of the designed functional indication

None of the participants who selected the fixed detour or swift strategies used either of two functional indications relative to routing, which are Trajectory and Field of play. It is understandable because state comprehension was not necessary in the operation with the strategies. On the other hand, state comprehension of the offensive robots was important

when they were using the other two strategies. Some of them, who used the functional indications, pointed out the usefulness to comprehend the states. The other who did not use the indications explained that they were trained well enough to comprehend situations without the information.
4) Offensive Actions: All participants selected manual control for offensive actions (Table 6). Only two participants in MO group used Opponent movement, and other five did not. On the other hand, six participants in OM group made use of the functional indication. The causes of the difference in the number between the two groups were not confirmed through the interviews.

Strategy	No. of participants	
	Used Opponent movement	Used Ally movement
manual	8 (2, 6)	5 (3, 2)

Table 6. The typical strategies used for offensive actions with usages of the designed functional indication

5.2.2 Subjective Evaluation of Adequacy of the Functional Information

In the interview, the participants were asked to answer additional information which was not displayed in the modified display but they wished to use in the operations. All participants answered that they did not feel inadequacy of functional information. And three pointed out that some information about own robot's intent might be useful to predict the robot's move. For example, indication that shows a robot is going to change the direction because there is an opponent robot right before it.

5.2.3 Quantitative Analysis of Effects on Performance

Several performance parameters were measured for every game, which are the number of flags captured by participants' and opponents' robots, 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. In addition, win percentages were calculated for every condition.
Statistical analysis on the parameters could not show any significant differences between each pair of two conditions described below:

Analysis I: The first main experiment with the modified display (MO group), and the first main experiment with the original display (OM group).

Analysis II: The second main experiment with the modified display (OM group), and the second main experiment with the original display (OO group), where the original display was used for the first stage equally.

Analysis III: The second main experiment with the original display where the modified display was used for the first stage (MO group), and the second main experiment with the original display where the original display was used for the first stage (OO group).

However, at least, the results show no sign of any ill effects caused by using the modified interface.

5.3 Discussion

The variety of strategies was larger than the previous experiment where only a few strategies were developed. From this point of view, the experimental condition designed in this study was appropriate for the study on the functional indications based on the proposed design concept. Although the number of participants is limited, the experiment offered sufficient data for this initial stage of the project.

5.3.1 Adequacy of the Functional Information

The results in Section 5.2.2 indicate that the participants did not feel any need for indications for functions which were not considered during the design phase. In other words, the designed functional indications covered all the functions of which the participants needed informational assistance. This suggests that the proposed design method has basic efficacy to design appropriate HRI that provides sufficient information to operators for conducting their work.

As the participants pointed out, we have claimed the importance of providing information about intention of automated systems (Furukawa et al, 2004). In next stage of this study, we are planning to apply the idea to designs of HRI.

5.3.2 Usefulness of Designed Functional Indications

The use of functional indications can be recognized as results of participants' subjective evaluation on usefulness of the indications for their operations. Through trials in the training phase, he or she selected proper functional indications to use for conducting tasks with his or her own strategies. The reason for selection was that the participant recognized the indications were useful and worth to use. The results show that every functional indication was actually used in selected conditions. This may suggest that the designed indications in this study were useful to comprehend situations of the functions, and that the proposed design concept is practical to design HRIs adaptable to operations with variety of strategies.

5.3.3 Effectiveness of the Designed Functional Indications

The results of the statistical analysis indicate that the measured performances are distributed widely throughout the participants, suggesting that more factors should be considered in data analysis on their performances.

For some strategies, state comprehension is not a necessary task in conducting operations. It means that the necessity of a functional indication for a participant depends on a strategy developed by the participant. Furthermore, the necessity of a functional indication depends on participant's ability to comprehend situation. The necessity is low for who has high ability to understand dynamic states of own and opponent robots. The numbers of data in this study were not sufficient to conduct statistical analysis using additional factors. It is expected that additional experiments can quantitatively reveal the efficacy.

6. Conclusion

This chapter describes two experiments conducted to reveal basic ability of a human-robot interface design concept, in which the ecological interface display concept is used as the

basic framework for implementing the information about a human-robot team work into an interface display.
The results from the first experiment may suggest that the whole work can be modelled using ADS, and it is feasible to design useful functional indications based on the ADS. 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.
In the second experiment, the adequacy, usefulness and effective of the functional indications were evaluated under the condition that the wide variety of strategies was used for offensive and defensive operations. The results demonstrate that the designed interface display has basic efficacy to provide adequate and useful functional information for supporting human operators for supervision of a robot team. It is expected that additional experiments with a large number of participants can quantitatively reveal the ability where strategies developed and use of functional indications are taken into account.
This empirical study provides empirical evidence for the efficacy of the proposed approach to enable effective human supervision of multiple robots.
To elaborate the practical and effective design concept for HRIs, several techniques must be necessary to develop. Typical examples are a method for designing functional models for target tasks using an ADS as a framework, a method for selecting functions for which support of comprehension is necessary for operators, and a method for designing effective indications for easy understanding of states of the functions.

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