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User Interfaces for Human Robot Interactions with a Swarm of Robots in Support to Firefighters

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Abstract— **There are many different forms of human-robot interactions, allowing a team of humans and robots to take advantage of skills of each team member. A developing area of research is focused upon the potential of robot swarms working in emergency settings. In particular we consider a swarm of robots that are capable of supporting and enhancing fire fighting operations co-operatively.**

This paper outlines some of the key characteristics of this emergency setting, robot swarms within it and the work conducted to develop effective human-robot interaction.

I. Introduction

THE work described in this paper arises from developing and applying the concept of using autonomous robots in urban search and rescue operations. The particular search and rescue focus for this is the operations of an emergency fire service working at a large scale incident. Such incidents are safety critical and highly complex involving the management of fire fighting teams, their operations and equipment. A key factor supporting effective operations at an incident is the level of situational knowledge available about the fire itself. For example, the more that is known about the fire's extent, its chemical characteristics, its source and also potential victims at an incident, the more effectively the fire service can operate to minimize loss of, and risk to, human life.

The technological approach adopted in the Guardians project [1] is to employ robot mounted sensors to provide a heightened level of feedback. The specific robotic approach taken is that of employing a swarm of robots that shall co-operatively communicate and compute environmental maps to enhance incident management and operations. The robotics swarm is built upon the pioneering work by Reynolds, who simulated a flock of birds in flight. Sahin [2] describes the swarm robotics as a (i) a large number, of (ii) homogeneous, (iii) autonomous, (iv) relatively incapable or inefficient robots with (v) local sensing and communication capabilities. In the case of this project the robot swarm consists of a number of robots with differing communication and sensing capabilities.

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The specific search and rescue activity focused upon is that of fire-fighting in a large warehouse. This setting is one provided by the project partners South Yorkshire Fire Service. The swarm is intended to support South Yorkshire Fire Service with real-life tasks of navigation and search in an industrial warehouse filled with smoke. This partner's involvement is particularly valuable as they are able to provide realistic and practical expertise relating to the most appropriate use of advanced robot technology.

The interest here is that although the robots in a swarm are primarily autonomous, they are designed and configured to address an overarching requirement of assisting fire fighters' operations. For example:

- Employing the robot swarm as early as possible as a mean of gaining essential information about an incident prior engaging with it. This enhances situational knowledge while minimizing risk to life.
- Employing robots and the robot swarm as an aid to fire-fighters once they engage with the fire. This also can enhance local knowledge of an incident without additional risk to life.

In this paper, we focus on a situation where human fire fighters are involved and the main task for the robot swarm is to provide support in navigation and safeguard the humans. From the point of view of human interaction there are two types of users:

- Users working in the context of a control/communication station, remotely overseeing and managing operations in real-time (aka. “Remote interaction”, in Goodrich & Schultz’s survey [3]). These base station users are able to monitor and control the overall activities of both the swarm of robots and humans on the field, and to provide decision making support to the operations commanders.
- Users working directly in the environment, engaged in specific exploration and rescue tasks in the field (aka. “Proximate interaction”, in [3]).

For both of these user types, initial research focus was to ensure that the robots and related infrastructures properly comply with and support existing human practices and rules.

The safety of the human fire fighters is the highest priority in such operations. The situation is complicated by the fact that the typical operating environment is one in which the robots performance and communication reliability cannot be ensured. This issue is a major factor influencing the system requirements and the overall design approach.

I. Fire Fighting Context, Setting and Operations

A. Emergency setting

The emergency setting environment for the project is a large single story industrial warehouse. Such warehouses usually consist of large open spaces with a variety of differing goods and materials stored throughout. Such warehouses can be as large as (400 x 200) m2, and are often divided into sections separated by fire resistant walls. However, during a fire incident, smoke and fumes may cover entire sections in the warehouse. As a consequence visibility becomes an issue for firemen. This is a common concern for firefighters, their normal training includes working fully blind-folded. A significant risk in such incidents is that firefighters can become easily lost. There have been notorious tragic examples where fire fighters lost life during search and rescue. In the warehouse fire of 1991 in Gillender Street London (UK), two firefighters died this way, and in the 1999 warehouse fire in Worcester (USA), six firefighters lost their lives in similar conditions. In a more recent tragedy in November 2007, four fire fighters were killed in a vegetable warehouse blaze in Warwickshire (UK).

Thus, the warehouse fire setting is one where poor visibility means the search and rescue is both time consuming and high risk. Moreover, a warehouse in fire may contain high quantities of toxic gases or inflammable materials. Adding to the complexity and risk of such an incident is that key information about the fire may be limited: ambient conditions, warehouse layout, the potential for flashovers (i.e. a simultaneous ignition of all the combustible material in the area) are often unknown and likely to change.

B. Fire fighters operations

There is usually little information provided when the fire brigade is alerted to an incident. The first task of the arriving appliances is to assess the incident and the primary risks. The fire fighters safety is considered as a high priority at all times. Firefighters are initially grouped into teams and briefed with their specific tasks and roles. Commonly, for large industrial premises some sort of map is available, however this will only show structures such as walls and doorways. Other details such as interior materials will not be known.

The span of control for any officer is arranged to be between three and five lines of communication, in order to avoid an overload (and consequently neglect of) information.

In large incident involving industrial warehouses, the incident commander deals with the overall supervision of the incident, where the Operations Commander deals with the sector commanders and crews who are directly involved. In addition, an Entry Control Officer (ECO) for each entry point is appointed with the following duties: (i) to update the Entry Control Board with the information of the firefighters who have committed into the scene of incident or have left it; (ii) to check the breathing apparatus's 'Time of Whistle' for committed crews into the incident; (iii) to liaison with other ECOs; (iv) to liaison with the sector commander.

Firefighters are usually committed into the incident in teams of two. They are normally protectively clothed including a minimum of heavy jacket and trousers, gloves and head protection and helmet, in addition to equipment including breathing apparatus. In the United Kingdom procedures are to deploy a guideline along a wall. The guideline is a special line which is used to indicate a route between the Entry Control Point and the scene of operations. Subsequent teams are able to follow the guideline. Once within a fire incident firefighters progress is slow due to unknown obstacles, such as debris, and very poor visibility.

One of the firefighters, usually the squad leader, moves forward while feeling for obstacles/survivors and testing the integrity of the floor. The other firefighter holds on to the leader and maintain the communication with the squad leader (verbally) and ECO through the radio channel. On the way out, the squad team debriefs the ECO who reports back to the sector commander. Further the sector commander feeds back the collected information to the operations commander.

II. Proposed interfaces for Human Swarm Interactions (HSI)

A. Challenges, design and development process

The potential for robot support for the search and rescue is high. However there are some significant challenges for fire fighters involved in search and rescue to work effectively with robots.

- The search environment of an incident is highly oppressive and fire crew operations can be impaired through: poor visibility due to smoke; poor tactile awareness due to safety-clothing; and limited hearing due to fire fighters headgear and ambient noise. This presents ergonomic and communicative design problems for any direct human robot interactions.
- Fire fighters operate with established protocols to ensure mutual safety, it is important that robot behaviours complement these protocols, enhancing some search and rescue tasks and not disrupting others.
- Fire fighters engaged in "search and rescue" are working under considerable mental and physical stress. This means human robot interaction tasks could easily become too complex in the setting described.
- These factors also influence our approach in designing human robot interfaces. Recommended good design practice of user centred design is potentially limited by such factors.
- The dedicated access to domain experts is limited as fire fighters are normally required to be available for emergency response while at work;
- Understanding the context of use is particularly hard, it is both high risk and highly skilled;
- For the same reasons, the context of use is demanding, varied and unpredictable, thus limiting any realistic experimentation and evaluation process;
- Complementing these points, early development processes are also complicated by the end users not necessarily understanding the capability and competences of robot technology.

In order to address these points the approach that has been followed is for the development team to closely engage with fire fighters and employ interviews, questionnaires and available documentation to develop an understanding of their technical requirements [4]. For user centred concerns low fidelity prototypes have been employed as a mean of engaging with the domain experts. These have served mainly as the focus for participatory design input as opposed to more formal assessment. In addition, as part of the project team's orientation to the domain project’s partner have engaged in one day of fire fighting training.

B. Proximate Human Swarm Interactions

The conceptual design for proximate HSI was to ensure that the robot behaviour and human robot interaction represented a minimal additional mental and/or communication load [5] [6] for fire fighters. Based on this, the conceptual model of the fire fighter being treated as an exceptional swarm member was developed. The exceptional features being the predominance of the fire fighter in terms of autonomy, skill and authority. In terms of interaction, this meant that the robots will in effect be in surrounding of the fire fighters and move with them. The swarm of robots determines a direction that fire fighter has to follow taking into account the fire fighter position, the position of possible obstacles that have to be avoided and the destination position.

In cases where the robots identify hazards or specific safe routes they provide information for the fire fighter to employ and act on at their discretion. This conceptual model of HRI for swarms presents some questions about how to inform the fire fighters about potential hazards and potential safe routes to follow during the activity of fire fighting.

Fig. 1. Prototype of Light Array Visor (LAV1)

In formulating the problem the firefighters were consulted and shown likely or possible configurations using a simple display desktop based prototype. The prototype simply illustrated possibilities and also animated the intended robot operations through a number of animated storyboards (in presentation programs like e.g. MS Powerpoint). Through this consultation a peripheral visual display was chosen as the most appropriate means of helping direct fire fighters.

A simple operating hardware prototype was then developed to enable experimentation with alternative means of helping direct fire fighters (Fig. 1).

Based on a swarm recommended direction, the fire fighter’s pose and direction is calculated and presented to him using the light array. Two key alternative approaches to visually depicting directions to the fire fighters have been considered.

- An analogical view where the light array is used to depict a direction directly. The angle of the illuminated light is computed to be the angle to the views head for the safe direction. The benefit of this is approach is that it is unlikely to require any effort to interpret. If in doubt the fire fighter can simply follow the light. Specific questions for which this approach needs to be refined concern the number of lights used represent the direction and the effective resolution in terms of number lights, light intensity and angular accuracy.
- A logical view where the light array is used to portray encoded commands to the fire fighter. At face value this has the potential to further burden the fire fighter as he'll have to interpret the encoded commands. Specifically this approach is likely to be more mentally demanding. The questions to be answered about such an approach concern identifying the appropriate command language and its portrayal.

In order to assess the use of the alternative designs in a realistic setting a trial of a more realistic prototype was developed and conducted with fire fighters [7]. A range of easily configurable versions of the two alternatives described above were prototyped to operate with the Light Array Visor (LAV1), for assessment with fire fighters at their fire station. At this stage in the project an operational robot swarm was not fully developed hence the prototype was used to simulate robot swarm guidance to the fire fighter. The same prototype could also be operated by the experimenter for live direction control, hence providing a wizard-of-oz style set-up

The evaluation studies [7] showed that subjects expressed a strong preference for a simplistic and unambiguous direction indicator. Hence, they showed a preference for low resolution analogical use of the light array, to the extent that array would be being used as though in a logical style. This is substantiated by one subject suggesting a clearer direction indicator be limited to basic angles such as -90, -45, 0, 45 and 90, and also suggesting that flashing and coloured lights would help to indicate when a change in direction is recommended.

A second version of the Light Array Visor was developed to include the inputs and feedback provided by the end user in to the design. A real operational fire fighting helmet was used for the second prototype to fit their gear to allow for more realistic trials (Fig. 2). The logical style of LAV1 interfaces was more suited to the fire fighters and therefore LAV2 is consisted of RGB leds positioned in a more logical layout in comparison to the previous linear layout of the first prototype.

Fig. 2. Light Array Visor [LAV2] using real fire fighting helmet.

In addition to the development and modification of the LAV1, additional technologies supporting the design as whole had been assessed. This meant that trials with the fire fighters were not only opportunities to explore the LAV2 but also trials and test supporting technology. Specifically, in this second trial an internal measurement unit (IMU) sensor was also integrated with LAV2 in order to detect the human's orientation while following swarm commands. By integrating the IMU the wizard-of-oz approach could be enhanced with the local directions shown by the LAV2 being computed from the operator providing a global direction. Hence, the operator in this second trial did not have to compensate if the fire fighter turned unintentionally.

C. Remote Human Swarm Interactions

In order to centralize robot's measurements and data, and to supervise the joint activities of the swarm of robots and the fire fighters, a remote monitoring and control station is being developed.

1) Approach and mechanisms: touch screen, ecological display inspiration, HMI Plugins

As a baseline principle, we decided to promote touch screen interaction methods. In particular the majority of operator time will be monitoring robots activities and this will mean there is a relatively low frequency of user inputs. It was felt that sporadic interaction was well suited to the nature of touch screen interaction.

The HMI display inspiration comes from Ecological Interface Design (aka. EID) [8] [9], which is an approach to interface design that fits well applications involving multiple users with multiple perspectives, in complex systems (has been applied in process control for power plants [10], aviation [11], medicine, etc). It has been further proposed as a paradigm for mobile robotics teleoperation (as "Ecological Display") in [12],[13].

In Guardians, we applied Ecological Display notions through e.g. limiting the amount of potential user focus points in the GUI (and in particular the amount of gauges), and making as obvious as possible the status and characteristics of the robots in their environment, with a main area of the GUI representing in a synthetic way the contextually relevant robot information.

HMI Plugins (HMIP) is an attempt to modularize HMI elements, separating HMI element enabling / disabling conditions from their individual action modes. We apply this paradigm in the Guardians' base station's GUI, through the definition of a variety of rather simple individual visualization modes, and how these different modes are interleaved when particular actions are performed. For instance, the selection of a robot from a bird's-eye 2D view of the overall scene may result in opening a health status window or panel beside this 2D view. The novelty is not on events (e.g. "clicking") chaining, which has already been used for a long time in GUI design and development, but rather in making modular and flexible the connection between the different visualization modes. In this GUI context, HMIPs are defined in terms of:

- The HMI modality itself, i.e. the GUI sub-component providing certain visualization and/or interaction means.
- The HMIP transition events: a certain number of actions in this HMI modality are identified as potentially triggering an HMIP transition, i.e. an event which interpretation will result in effects for other HMIPs.
- HMIP entry points: a given HMIP may itself contain several visualization options or approaches. One may want to clearly identify them.

Once all available HMIPs have their transition events and their entry points defined, they can be linked altogether into an overall HMI layout instance. For that purpose, an HMIP configuration file is used to express the relationships among HMIPs, i.e. connecting the transition events to the entry points.

In addition we make it possible to apply transition effects, i.e. a particular effect which will be performed while the transition occurs. These effects essentially deal with the way the connected HMIPs are made, e.g.: visible or hidden, minimized or maximized, move to the top or the bottom of windows stack, swapping windows position, etc. We apply the HMIP paradigm for the GUI of the Guardians base station, in order (i) to offer powerful windows dynamic arrangement for the user, depending on the context and on the actions, and (ii) to easily design and experiment alternative GUI layouts, from available GUI elements.

For the purpose of the implementation of the base station HMI, an existing GUI framework has been chosen: the JUCE framework [14]. The main assets of this framework are its OS-independent rendering (Linux, Windows, Mac OS), its high quality C++ implementation and compliance, and its appealing visual rendering compared to other popular solutions such as WxWidgets, Fox, or Qt. As a drawback, the collection of graphical widget is less extensive (although rather large), and is maintained by a single person (but open source).

2) Early prototyping results

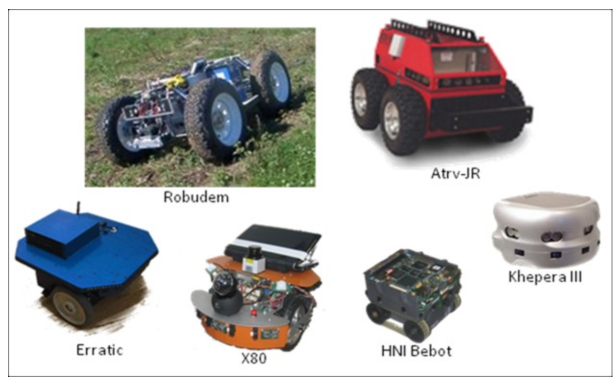

Fig. 3. Overview of robotic platforms for which trial monitoring and control demos with the base station have been performed.

As a demonstration setup for the Guardians project, the base station physically consists of (1) a Linux PC running essentially the Base Station core, a Mission Data Recorder and Dispatcher (MDRD) and the interfaces to the different Guardians agents (i.e. the Guardians robots and fire fighters), and (2) a Windows one running essentially the HMI client for an end user. In the current setup, the focus is on the operations and on telemetry and direct video images visualization. This base station setup has been used in trial demos for the monitoring and control of a number of different indoor and outdoor robots, including those illustrated on Fig. 3, through either a Player communication interface [15], or dedicated solution over TCP/IP.

The operator GUI is depicted on Fig 4. below. Several areas can be identified:

Fig. 4. Operator GUI prototype layout

(1) The main visualization zone, filling the largest screen space. It provides with an overall, immediate understanding of the global situation. Robots are represented in their (known) environment.

(2) View navigation: these controls allow to zoom in/out and to rotate in the 2D plan of the environment.

(3) Operator actions area: in this area are gathered a number of buttons allowing swarm level control of the robots.

(4) Overall map view: this overall view helps understanding where in the overall space is situated the currently observed area. The highlighted area represents the field of view appearing in the area (1).

(5) Mission log: here are notified the essential actions occurring in the Guardians system (issued from the base station or not).

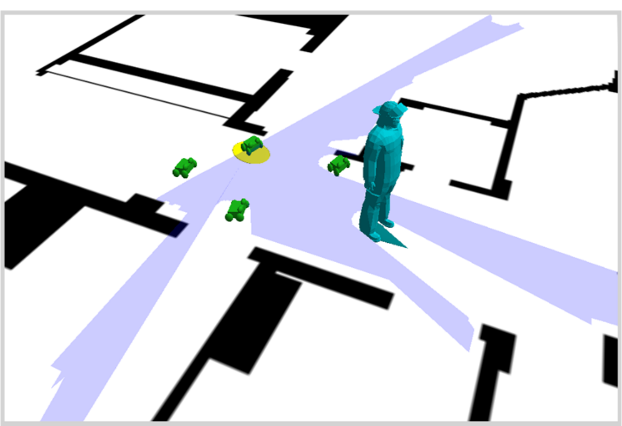

Fig. 5. OpenGL based environment perspective representation and navigation with 3D robots and fire fighter.

Further prototype visualization modes have been designed, including a 3D model representation display (Fig. 5) for bird's eye view, and relying on OpenGL (supported by JUCE).

D. *End users preliminary evaluation feedback*

Taking into account the complex nature of incident management and the advanced technology under consideration in this project, end user involvement is key to effective HMI design. User feedback not only helps manage users' expectations about the nature of the solutions under consideration but it also provides important formative feedback. It is widely recognized that effective HMI design is reliant upon a good fit with user needs and this is only best achieved through direct user engagement with prototypes and design decisions. To support user engagement both the base station HMI and direct human-swarm interaction approaches have been evaluated through open engagement with fire fighters.

1) *Proximate HSI evaluation*

In order to assess the use of the LAV2 in realistic setting further trials of was conducted with fire fighters. To include the feedback provided by fire fighters and to add to the realism of the trial context, a few specific changes were made to the way that second trial was conducted. A group of two fire fighters were asked to take part in the second trial. This was mainly considered since fire fighters work in group of two or more in real incidents and trainings. In addition, to add to the stress, two different colored peripheral lights were used instead of one. Each light flashed at a random interval and fire fighters were asked to count the number of the time each of them flashed.

In this trial the lead fire fighter was provided by the LAV2 prototype and the second fire fighter was asked to follow the leader according to the reported commands. Both of them were blind folded. In a similar way to their real trainings, the two fire fighters were connected through a rope (Fig. 6).

Fig. 6. Fire fighters search and rescue operation using LAV2 at trials

The result of the conducted studies with LAV2 clearly showed that fire fighters were under more stress in comparison to the conducted studies using LAV1, they also mentioned the stress load and the attention they had to pay to the flashing lights to be able to count them, while trying to navigate and report at the same time.

As it was observed, the fire fighter managed to correctly follow the commands, although there were drifts, and in such cases the data provided by IMU for Leader's orientation was used to update the navigational commands displayed on LAV2.

An interesting result was that in the follow-on interviews there was a clear shift in fire fighters attention from how the interface (and LAV) should operate to what information it can provide using the robot swarm and what other functionality the swarm may support. This result can be interpreted as a constructive progress in allowing the end-users to become more involved in the exploratory design process.

A similar point was raised in post discussions that it would be useful to the fire fighters to use the provided information to be able to come off the wall when searching an area. Also, it was mentioned it would be very useful if the swarm/LAV could provide them simple right direction when at the wall.

2) Remote HSI evaluation

The prototype design of the base station HMI has been presented to a board of four Syfire fire fighters, in order to collect feedback and evaluate further needs or expectations, based on the presented material.

Interviewees considered that such a tool would drastically improve the level of situational awareness that fire fighters can nowadays have during operations. However it shall be mentioned that it was sometimes not possible to distinguish whether the enthusiasm was because of the overall Guardian system's concepts or actually related the HMI itself. We summarize in the following some of the feedback we received during this meeting.

The mission log was considered an essential component of the display: different users may need to be aware of the course of events, the status of performed actions, and possibly other (outside) relevant information to point out. Moreover logged information shall be time tagged, as time is essential in successful fire fighting operations.

The 3D representation was considered an appealing asset for training purpose, as it would allow trainers and trainees to better visualize and apprehend reference situations, thus improving the common understanding of a given situation. In the same way, such representations would be extremely useful in briefing a fire fighting brigade or team on the mission to be performed, prior to mission execution. Offline use was stressed first, although online use was considered positively too.

Among suggested improvements, the capability to display areas delimitations, with name in accordance to the name provided by the mission commander, would be very useful. In particular, when properly covered and checked, a given area is "greened": greened / non-greened zone shall ideally appear on the map. Using specific colors codes is considered a must.

Programmable alarms, according to particular states of the system, was also suggested, e.g. relying on the chemicals, temperature, remaining time, fire fighter and robots health status, etc. Alarms would result in flashing (and/or sound based) messages.

Interviewees suggested that better orientation indication may help: in the current layout, the orientation is hinted in two manners: (i) through the top right hand corner global map view, and (ii) in the left side navigation tools. We agree however that more clues included in the main, central view would improve the perception of the orientation.

It was interesting to note that the proposed layout / disposition of the GUI components were not of paramount importance according to the interviewees: they claimed that they would learn how to make use of the provided interface anyway. We still consider that the GUI layout has a strong impact on the HMI experience fire fighters can have and on the overall performances, and accordingly further and more in depth design evaluation is planned.

III. Conclusion and Perspectives

The work described in this paper demonstrates the complexity and potential value of integrating user input into the design and development process. In particular the work addresses the complexity of working with highly trained and dedicated professionals in a safety critical context while target technology is not fully established. To help ensure that the user interfaces for highly specialized technology works the user interface technology has been developed with a view to being as flexible as possible. In this manner formative feedback from evaluation can be understood in a context of accumulated experience and it can be acted upon in order to develop new alternative or improved designs. This approach has been applied productively in both the design of the base station user interface and the fire fighters helmet.

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