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Conceptual Design Document for Human-Robot Swarm Interaction Schemes Analysis and Specification

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This document presents an analysis and specification of human-robot swarm interaction in search and rescue mission during fire in industrial areas as well as some metrics and methodology for evaluating the performance of the human-robot system.

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1 Introduction

In search and rescue mission during a fire in industrial warehouse or basement, the firefighters have a maximum of 20 minutes to enter the fire ground, search and exit the building safely. However, a such mission in such events is of high complexity and risk, which sometimes leads to casualties[1].

The GUARDIANS are a swarm of autonomous robots applied to navigate and search an urban ground. The application of such robotic system is meant to help firefighters in performing their tasks in a such dangerous situation. However, to ensure synergy among firefighters and robots, a comprehensive analysis of human-robot interaction is a compulsory. Thus, this document will present a taxonomy of human-robot interaction on which the analysis and specification for human-robot swarm interaction will be based.

In defining the specification of human-robot swarm interaction, a mapping of every possible interaction during runtime against the developed taxonomy will be done. This mapping process uses the scenario in which the system will be possibly deployed.

In GUARDIANS project, there are two types of human-robot interaction, direct and remote interaction. This document focuses on the earlier, which is on the direct interaction between human squad leaders and robots. The latter, which is concerning the interaction between human squad leaders or robots with the humans at the base station will not be discussed here because it will be covered by another document.

1.1 Document Structure

This document is structured as follow. Chapter 2 presents an overview of the scenario which will be tackled in this project. The scenario describes how the robot swarm will be deployed to work together with firefighters. In Chapter 3, an overview of the human-robot interaction will be presented. Chapter 4 present an analysis of the interaction likely to happen between the robot swarm and the firefighters in the case of fire in industrial areas. In Chapter 5, some metrics and methodologies used for measuring the performance of human-robot interaction will be presented. Chapter 6 presents the requirement and specification of the human - robot swarm interaction based on the scenario, the human-robot interaction analysis, and the important metrics. This document will be concluded in a short summary in Chapter 7.

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[1] In recent years, five fire fighters died in the UK, as they got disorientated in a warehouse search [FireBU91].

2 GUARDIANS Scenario

The major use-case scenario and test case is proposed by the Fire and Rescue Services and consists of searching an industrial warehouse or basement. The following is the situation in which the human-robot swarm system developed in the GUARDIANS project will operate.

> *Consider an industrial warehouse or basement containing a lot of and diverse material being in fire. In this situation, the temperature at the area is very high. Moreover, burnt material will likely release a lot of smoke, which has great effect on visibility of the firefighters as well as robot sensors. It is also possible that the smoke is coming from toxic substance, which is dangerous for human when get inhaled. Furthermore, there are a lot of noise due to burnt material, explosion, and falling debris. The debris may block the way in or out. Considering the situation, firefighters have to be equipped with special clothing to protect them from excessive hot temperature. Moreover, some other gears are also important to help them minimize the effect of such condition, such as gloves, masks, helmet, oxygen tube, radio communication, axe for making way, etc.*
>
> *In the event of fire in such areas, firefighters have a maximum of 20 minutes to enter the fire ground, search and exit the building safely. Considering the condition of the work environment and the constraints, this job is dangerous and in itself time consuming. To support this task, a swarm of robots are deployed to work together with firefighters that can adequately assist and safeguard them. Through the installed sensors and a certain level of intelligence, the robots are able to perform some tasks, such as detecting toxic chemicals, providing and maintaining mobile communication links, providing location of important objects, and assisting in searching.*
>
> *The swarm of robots are to access and assess scenes for dangers to human beings; they search for toxic chemicals under extreme conditions with poor visibility, high noises etc. The robots are equipped with a range of sensors for the registration of temperature, atmospheric pressure, and the presence of different chemicals.*
>
> *The robots navigate the site autonomously and serve as a guide for a human squad-leader in finding the target location or in avoiding dangerous location or objects. They connect to a wireless ad-hoc network and forward data to the squad-leader and the control station. The network, which are actually a chain of robots equipped with wireless communication module, is self-organising, adapts to connection failures by modifying its connections from local up to central connections.*
>
> *The autonomous swarm operates in communicative and non-communicative mode. In communicative mode, automatic service discovery is applied: the robots find peers to help them. The wireless network also enables the robots to support a human squad-leader operating within close range. In the case of loosing network signals, the robot swarm can be still functioning with non-communicative mode and continue serving the firefighters.*

Depending on the situation, the robots swarm can be deployed with or without a human squad leader. Without a human squad leader, they can search and navigate through the warehouse, maintain communication connections, designate one or more robots as positioning beacons, exchange position data with the base station, detect and possibly locate toxic agents, and possibly detect casualties. With a human squad leader the robots swarm can navigate the squad leader through the warehouse, exchange squad leader's position data with the base station, warn for toxic agents, call the squad leader's attention to objects of interest, and maintain the communication link between the fire fighter and the control base.

In some situation, a group of robots may be further split into several groups or individuals. For example, at first all robots might be involved in searching operation but when the swarm is advancing several robots might stay behind as positioning beacons and to maintain communication connectivity.

3 Human-Robot Interaction

Robots are now becoming more commonplace in human life. Not limited to industry or space application domain, robots are also used and exist in more areas of our daily life; there are already robots for weeping floor, mowing lawn, bomb searching, guiding visitors in museum, education, and entertainment, to name some.

To ensure successful deployment in human daily life, a good understanding on possible human-robot interaction is important. Human-robot interaction can be simple or complex. For different tasks, in term of complexity or risk, we may give the robots different level of trust, thus it effects the type of interaction we have with the robots. Moreover, environment condition has also influence on the way human and robot interact. Furthermore, the number of robots or agents may influence how we interact with them. Also, robots' autonomy level may need to be adjusted in some particular situations to solve problems or to improve the performance.

This chapter discusses in general about human-robot interaction. First it will present an overview of human-robot interaction. Second, some issues in human-robot interaction will be presented.

3.1 Human-Robot Interaction: An Overview

In the early stage of robotics, the main stream point of view on robotics were that of robot as human's servant, to do what human tell it to do. An obvious example is industrial robotics[1]. In this application domain, robots are doing a pre-programmed tasks such as welding cars, spraying paint or glue on appliances, assembling printed circuit boards, etc. There is hardly any intelligence on board the robots. They can perform the tasks only if the human provides the detail of movements, such as the position as well as the speed, they have to strictly follow.

However, such a robot is only a part of our imagination on robots. A robot should be able to think (intelligent) and to perform many tasks (versatile) as is thought by roboticists; it should be able to learn so that it can perform tasks it is not programmed to do in the first place. Moreover, it should also be able to work safely and securely among and with people. Perhaps it is still far away to achieve our ideal robots, but the progress in robotics is toward this direction, as shown by many results of research in robotics in relationship with human as well as in artificial intelligence (AI). Then, we come to the era of service robots.

Service robots are developed to interact with human beings. They include many different kinds of robot, which can be classified into subcategories based on application area: service robots for professional use and service robots for personal and private use [28]. Service robots for professional use include but not limited to cleaning robots, sewer robots, inspection robots, demolition

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[1] As predicted by *International Federation of Robotics* (IFR) [28], the number of operational industrial robots will reach 1,041,700 units, a significant increase from estimated 847,764 units in 2004.

robots, underwater robots, medical robots, guide robots, fire- and bomb-fighting robots, agricultural robots, etc. Service robots for personal and private use include domestic (home) robots for vacuum cleaning and lawn mowing, entertainment robots, education robots, etc.

The development of service robots have shown us the paradigmatic shift in human-robot interaction from *mechano-centric* to human oriented paradigm [26]. They have more interaction with human than their fellows, industrial robots. As noted in the previous paragraph, service robots are made to perform some human activities and at the same time to work and live together with human. Due to this fact, care must be taken in developing robots interacting with human; psychological approach in robot development is important to capture possible interaction between human and robot to ensure successful robotic system.

3.2 Issues in Human - Robot Interaction

Scholtz in [34] stated that the goal of research in human - robot interaction is *to have an efficient and effective team consisting of human and robots and which can benefit from the skills of others.* To achieve this goal, we need to understand clearly the nature of human - robot interaction.

Human-robot interaction can be simple or complex. For different tasks, in term of complexity or risk, we might give the robots different level of trust, thus it effects the type of interaction we have with the robots. The more trust we have on the robots, the less attention we give. Moreover, with the same capability the robots have, we might have different perception on the robots trustability in case of different environments in which the robots are operating. For example, we might not see the robots trustable in stochastic and dynamic environment compared to the same robots in static and predictable environment. It is natural because the earlier type of environment is difficult to predict or to anticipate during the robot development process, thus we cannot be sure how the robots will handle unpredictable events during runtime. As a result, we will put more effort in monitoring the robots operating in this kind of environment. Furthermore, the number of robots or agents might influence how we interact with them. Interaction between single human and a single robot is not the same as the one between single human and a group of robots. In the case of single-robot, we can have more flexibility in interacting with it. However, in the case of multi-robot system, our interaction is limited to our capability of handling multiple concurrent events. Last but not least, during runtime, we might need to change the level of autonomy of the robots due to problems the robots are facing and too difficult for them to solve.

There are several important issues in human - robot interaction, they are: *human - robot interaction taxonomy*, *human - robot interface*, *communication between human and robot*, *system architecture*, and *adjusting the level of autonomy*. We will see them in more detail in the following sub-sections.

3.2.1 Human - Robot Interaction Taxonomy

In the literature, we can find some attempts for classifying human-robot interaction [34, 46, 45, 9, 26, 37]. For example, Yanco and Drury [45, 46] have presented an extensive classification and distinguished HRI into eleven categories: *task type*, *task criticality*, *robot morphology*, *ratio of people to robots*, *composition of robot teams*, *level of shared interaction among teams*, *interaction roles*, *type of human-robot physical proximity*, *decision support operators*, *time/space taxonomy*, and *autonomy level/amount of intervention.* However, the taxonomy presented there is not complete

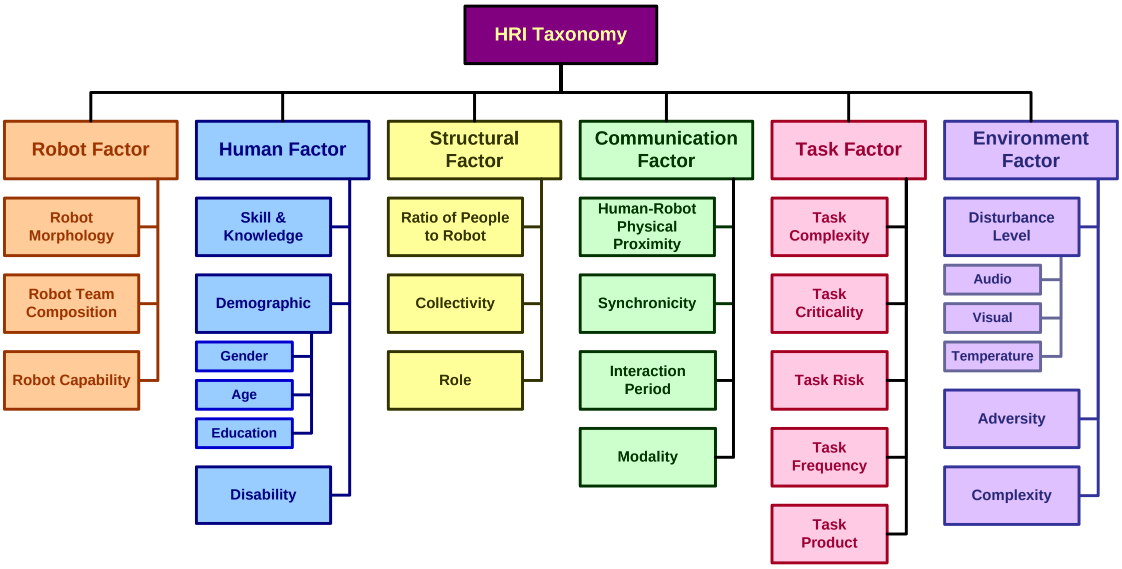

Figure 3.1: *The complete proposed taxonomy of human-robot interaction.*

yet. There are several aspects that can be added to complete the current taxonomy. Some of them are human factors (human skill and knowledge and human group and age) and environment factor (environment type, type and level of disturbance). By having a complete taxonomy, we can have *a better perspective on and a structural framework for tackling the issues in human-robot interaction.* While the taxonomy might not be able to be treated as a rule, but we can use it as a guideline.

For GUARDIANS project, we deem these two additional factors important. Earlier, we have presented the kind of environment in which the humans and robots will operate. Because of the environmental conditions, humans, in our case firefighters, need to equip themselves with special clothing, mask, gloves, etc, which will make it dificult for them to interact in a normal way. Thus, special attention is required to analyze the effect of environment condition in which interaction between humans and robots can occur.

Also, we notice that it is the first attempt to deploy robots for supporting firefighters during search and rescue mission. Thus, we need to ensure that the use of robots will bring benefit, not otherwise. To achieve our aim, it is important to have a good understanding on how humans will work together with the robots; we need to know what is their perception on robots, their thought about the role of the robots, or their skill and knowledge related to robots.

We have been developing a new taxonomy of human-robot interaction with those two aspects added. In general, it groups some categories based on several factors: robot, human, structural, interaction, task, and environment factor. The complete proposed taxonomy is shown in Figure 3.1. Figure 3.2 shows more detail description of the proposed human-robot interaction taxonomy.

3.2.2 Human - Robot Interface

Adams [1] argues that human-robot interface should be designed simultaneously as the robotic system development is started. Moreover, the inclusion of users during development phase is very important. Otherwise it is hard to claim that the developed interface is intuitive, easy to use, etc.

No	Key Dimension	Parameters		Possible Value
1	**Human**	Human Expertise		• elite • intermediary • end-user • layman
		Human Disability		• Cognitive disability • Physical disability
		Demographic	Age	• children • teenager • adult • elderly
			Gender	• female • male • unisex or gender-neutral
			Education	• un-educated • sufficiently-educated • highly-educated
2	**Robot**	Robot Morphology		• Anthropomorphic • Zoomorphic (Familiar Animal, Unfamiliar Animal, Imaginary Animal) • Functional
		Robot Team Composition		• homogeneous • heterogeneous
		Robot Capability	Reasoning	• reactive • deliberative
			Action	• direct-control • semi-automatic • fully-automatic
3	**Structural**	Ratio of People to Robot		• single human _ single robot • single human _ multi robot • multi human _ single robot • multi human _ multi robot
		Collectivity		• individual human to individual robot • individual human to a group of robots • group of humans to individual robot • group of humans to group of robots
		Role	Robot	• companion • worker • extension of human's sensing or organ
			Human	• Supervisor • Operator • Team-mates • Bystander • Mechanic → represent the power possessed by human during interaction

No	Key Dimension	Parameters		Possible Value
4	**Communication**	Human-Robot Physical Proximity		• Collocated • Non-collocated • remote
		Synchronicity		• Synchronous • asynchronous
		Interaction Duration		• Short-term • Long-term
		Intensity		• High • Medium • Low
		Modality		• Direct vs indirect • Audio, visual, gesture, haptic
5	**Task**	Task Complexity		• Simple • Complex
		Task Criticality		• Low-priority • High-priority
		Task Risk		• Catastrophic • Hazardous • Moderate • Minor
		Task Frequency		• Once • Seldom • Often • Always
		Task Product		• Abstract • Real
6	**Environment**	Adversity		• Catastrophic • Hazardous • Moderate • Minor
		Predictability		• Stochastic • Deterministic
		Complexity		• Simple • Complex
		Disturbance Level	Visual	• High • Medium • Low
			Aural	
			Temperature	

Figure 3.2: *List of factors of human-robot interaction and their possible values.*

Human-robot interface itself is an active research area. Even though human-robot interface is still in its infancy, it can adapt some result from human-machine interface or human-computer interface, due to its close relationship with these more mature research fields. Moreover, some results from research in human factors are also relevant for designing human-robot interface. There are also some issues in human factors that can be taken into consideration in developing efficient, effective, and usable human-robot interface, they are: human decision making, workload, vigilance, situation awareness, and human error.

In designing a good user interface, a deep analysis of human cognitive capability is very important to prevent cognitive overload due to overwhelming information displayed to the human operators. After knowing the human cognitive capability, we will be able to decide how we should display information from the robots effectively so that it is easily discernible. There are some examples on how to present information to human operators such as perspective display [18], ecological display [30], fusion display [11], virtual reality [42], and augmented reality [14]. Beside cognitive load, workload analysis is also important to ensure that the human operators can *always* control the robots. Behavioral entropy [18] is one example of how to measure workload on the human operators. To reduce workload, multi-modal user interface is believed to be a solution. There are some examples of multi-modal user interface: haptic display [20], communication with voice [38], [22], communication with gesture [29], and joystick with force feedback [36], [44]. Another important point is concerning the coordination of many human operators in controlling one or many robots at the same time, some refer as cooperative teleoperation or teleassistance [16], [15].

In the case of GUARDIANS project, a suitable human-robot interface is crucial for the mission success. During operation, firefighters are already under pressure: the task is critical and risky, the time for searching is limited, the environment is adverse, a lot of disturbance, etc. Therefore, the way information is provided to the firefighters must be designed carefully to avoid cognitive overload. There must be a prioritization of different level of importances of displayed information. Less important information must be less distracting than the higher one. Moreover, the thick clothes word by the firefighers can restrict the way the interaction is performed. If the interaction is done through widgets, they must be easily operationable, and at the same time, robust to unintentional activation.

3.2.3 Communication between Human and Robots

During communication between human and robot as well as among the robots, the aim is for exchanging information. Human requires information from robot to understand the situation the robot encounters, to know the actual state the robot is in, to acquire important information such as the video, temperature, radioactivity of the environment, as well as to obtain any request from the robot. Reversely, robot requires information from human to get the human knowledge to solve problems it is facing and to receive commands or tasks it has to perform.

In general, communication can be classified into several forms: *explicit*, *implicit*, and *state communication*. Two examples of explicit communication are spoken language and message. Implicit form takes place when the information is conveyed through the change in the environment, known as well as *stigmergy*. State communication is rather similar with the implicit state. However, the information conveyed not through the change of the environment, instead of the physical change (or behavior) of the agent. One example of this communication form is body language or gesture.

For communication, the information needs a medium that will transfer it from the communicator to the receiver. The medium can be of air (for spoken language), visual (gesture), light (e.g. infra-red), the environment (stigmergy), electric (e.g. via cable), electromagnetic (radio or wireless Ethernet), or the Internet. All of these media are not free from noise and disturbance, which means that there is a certain condition that will make these media failing to convey the information.

For humans to interact with a robotic system, it is argued that they prefer to do it in a similar way as they interact to other humans. Thus, it implies that the robotic system should be able to comprehend human language, either auditorially or visually. There are some attempts to achieve this [29, 43, 13]. While they show some promises in getting this goal, there are still a lot to do in this research area to develop a human-language-capable robotic system.

In GUARDIANS project, the robots communicate to each other or with the firefighters implicitly through stigmergy and explicitly through wireless communication. Also, they communicate with humans at the base station through wireless communication. In the environment where the operation takes place, there are a lot of disturbances and noises which make it difficult to communicate. Debrises and obstacles may obstruct the line of sight which may hinder them to sense the present of firefighters or other robots, thus the stigmergy may be difficult to achieve. Metals in the warehouse, which are commonly found, greatly effects the quality of wireless communication.

3.2.4 System Architecture

This issues deals with the relationship between human and robot hierarchically, whether a vertical (master-slave) or horizontal (peer to peer) relationship. This notion is important in determining the task and responsibility allocation as well as the level of autonomy of the robots. In a master-slave relationship, in one hand, the slave (robot) will always follow what the master (human operator) commands. On the other hand, a peer-to-peer relationship will allow the robots to refuse what the human operators say if the first parties think that the commands from the second parties are, due to some reasons such as bad timing or information misinterpretation, inappropriate. Most of the traditional telerobotics are of the first relationship. Recently, some research are directed to the second relationship. Two examples are mixed-initiative [27] and collaborative control [13], [12].

In the case of the GUARDIANS project, we want the robots to be able to operate autonomously to minimize monitoring and supervision by human operator. However, due to the nature of the operation, which is critical and risky, we need to ensure that the robots will always perform as we want them to, especially in some situation where error in action may lead to mission failure or even casualties. For example, in some situation humans decision is superior than the robots. In other words, during normal operation humans and robots will operate as peers. But in some situation, human will be the master and robots will be the slave. For this issue, we need to find the most suitable system architecture which is able to support both kinds of structural relationship between humans and robots.

3.2.5 Adjusting the Level of Autonomy

Traditional multi-robotic system is normally designed with a fixed autonomy. This approach, while simple, has two drawbacks. First, human-robot interaction requires varying level of autonomy, depending on situation. Thus, fixed autonomy is definitely unable to accommodate such purpose.

Second, fixed autonomy requires that a robot must be designed as such that it will be able to perform many tasks with a certain fixed amount of human assistance. However, this requirement is very hard to achieve, at least for the current technology we possess.

Adjustable autonomy is defined as the ability of an entity - agent or robot - to dynamically adjust its own level of autonomy based on the situation. With adjustable autonomy, an entity need not make all decisions autonomously, rather it can choose to reduce its own autonomy and transfer decision making control to other users or agents. The concept of adjustable autonomy are that for humans to adjust the autonomy of agents, for agents to adjust their own autonomy, and for a group of agents to adjust the autonomy relationships within the group.

Adjustable autonomy has several advantages. The first advantage is that it can makes a system more flexible because it allows human to aid the system as it is facing problems or situations it cannot solve. The second advantage is that adjustable autonomy can make the system design process easier. The last advantage is that adjustable autonomy makes the system user friendlier. This is possible while a system with adjustable autonomy can increase user understanding, control, and trust of autonomous systems by providing users, during system runtime, with an ability to do experiment with the system in order to know how the system works.

However, there are some basic questions in implementing adjustable autonomy in robotic system: when it should/must be done [5, 8, 19, 23] and how to do it in a seamless way [5, 19, 33].

For the GUARDIANS project, we think it is important to analyze the situation which will be tackled by the firefighters and robots during the operation. In general, each robot may need to perform the task it is required to do at any time and any situation. For example, a robot may be switched from semi-/fully-autonomous mode to direct control when human operators need it to inspect a certain area or object without disrupting the currenly-pursued exploration task. In this event, the taken-over robot must be able change its level autonomy smoothly. Moreover, the robot group must adjust themselves due to the loss of one of its member. This adjustment can be done automatically. If it is not successfull, which can happen due to unexpected events, humans can help them to re-adjust. There are several possible situation which require autonomy level adjustment, and it is important to analyze them carefully.

4 Human-Robot Swarm Interaction Analysis

This chapter presents the analysis of human-robot swarm interaction. To have a structured analysis, we will analyse the scenario based on the developed human-robot interaction taxonomy presented earlier.

4.1 Scenario - Revisited

Chapter 2 presents the scenario which will be tackled by this project. In this section, we will map the scenario to the human-robot interaction taxonomy presented earlier.

Table 4.1: *Mapping the scenario to the human-robot taxonomy.*

Group Factor	**Factor**	**Issue**	**Description**	**Value**
Environment	Noise / Disturbance Level	Fire	Fire-protecting gears may reduce the movement flexibility of the fire fighters	High
			Critical and Risky	High
		Smoke	Low visibility	High
			Problem with respiration	Medium
			The need for gears to help respiration, thus reduce the movement flexibility	
		Burnt material, explosion	Audio impairement (difficulty in aural commuincation)	Medium ??
			Critical and Risky	High

Group Factor	Factor	Issue	Description	Value
		Toxic substance	Problem with breathing, thus requires breathing apparatus	High
	Complexity	Falling debris, rubble of building structure	The environment changes as debris or rubbles of building structures are falling. Thus, the previous information on envrionment condition may not be valid anymore.	High
Task	Task complexity	Search and rescue mission is complex: localization, navigation, coordination, target allocation. Moreover, environment condition makes it more complex.	SAR mission itself is stressful for firefighters. The additional task to work together with robots may add additional workload, if the interaction and interface is not designed carefully.	Medium, High
	Product of the task	Incorrecly assigned task product to each agents	To assign a certain task product to agents who can't produce such product may lead to inefficiency or event jeopardize mission accomplishment.	Information of the environment from robot, Physical work done by firefighters.
	Frequency	Repetive tasks, such as checking the floor, remotely control the robots, for firefighters during the mission.	Firefighters are already in stressful situation with high workload. Thus repetitive tasks must be avoided to reduce work load. Whenever possible, such tasks must be delegated to robots.	High[1]
	Risk	Failures by humans or robots in performing the task	Safety of firefighters, Safety of the victims	High
	Criticality	Limited time duration of the mission[2]	All the tasks must be done as efficiently as possible. Any lateness will impact mission accomplishment, even the safety of the firefighters.	High

---

[1] I put the value to high because of some tasks in SAR mission are repetitive in nature.

[2] A list of critical tasks may be useful. Also, related to task allocation requirement, we need to determine who will do which tasks.

Group Factor	**Factor**	**Issue**	**Description**	**Value**
Human	Expertise	The skill and knowledge of operating or interacting with the robots	Lack of skill or knowledge will lead to inefficiency, thus endanger mission accomplishment or even the safety of the firefighters.	End user[3]
Structural	Role (Robot)	Three possible different roles of robots during the mission.	Different roles require different expectation or mental model of the robot. If expectation or mental model different from reality, it will lead to frustration or stress.	Human's sense extension[4], Companion[5], Communication Node[6]
	Role (Human)	Two possible roles of firefighters during the mission	Different roles may mean different information availability, different control capability, different interaction, etc.	Team mates[7], Bystander[8]
	Ratio of number of people and robots	Human limited cognitive capability	Some results in literature show that the more robots to control, the more workload for human operators. In some critical tasks, such as SAR, it is common that some human operators operate one single robot. However, in GUARDIANS, many humans will interact with many robots, thus robots must be designed as autonomous as possible, and if direct control is required, human cognitive capability must be taken into consideration.	Single-Human – Single Robot Single-Human – Multi-Robot Multi-Human – Single Robot Multi-Human – Multi-Robot[9]

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[3] We must try to ensure that people within the "End User" can interact with or operate the robot. Thus, training is required to build understanding on the robots' behavior (mental model of the robots).

[4] To provide firefighters with information about the environment, such as hazardous objects or way out.

[5] To assist firefighters to manage their direction to the scene operation and the exit point.

[6] Some robots will be responsible for keeping the communication infrastructure operating by acting as communication node.

[7] Firefighters and robots can work together as peers.

[8] Firefighters have no control of the robots' behavior. This can be the case when people at the base station directly control the robots for some particular tasks.

[9] One team comprises two firefighters and more than 4 robots surrounding them.

Group Factor	**Factor**	**Issue**	**Description**	**Value**
	Collectivity	The source and target of the control.	It does matter how the control is originating and will be executed. If there are more than one source of control, how the control should be treated; how should it be combined. In another case, if the target is more than one, how these targets should execute it, as a group or individually?	Individual human to individual robot, Individual human to a group of robots, Group of humans to individual robot, Group of humans to group of robots
Robot	Robot Capability	Robot capability can be at a particular point of autonomy spectrum: direct-control – fully-autonomous.	The question here is how autonomous the robots can operate? Robot sensing capability may not work normally in the incident area, especially in such an environment. Without well-working sensing capability, how robots can perceive the world or humans correctly, thus to interact smartly?	Direct Control, Semi-autonomous, fully-autonomous
	Robot Team composition	Different type of robots in the team (physically or functionally)	Different type of robots, whether in term of physical or functional factor, may effect the expectation or the mental model developed by humans, in our case the firefighters. Moreover, due to environment condition, it may be difficult to differentiate one robot to the others. Thus expected behaviour may be different from the actual one due to misidentifaction. As a result, frustration may develop during the mission, which may lead to additional workload.	Homogeneous[10]

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[10] All robots will be equiped with the same equipment (communication and sensor devices)

Group Factor	Factor	Issue	Description	Value
Communication	Human-robot proximity	In our case, the issue is more about visibility due to smoke or obstacle	During operation, robots will track the firefighters so that they can keep their position around the FFs. However, the present of obstacle may introduce problem, to keep the formation as required. Thus, another communication channel is necessary as back-up.	close and direct[11]
	Interaction Duration	It seems that interaction intensity is more relevant to the project.		Medium[12]
	Intensity	Intense interaction during some period of time in the mission.	Intense interaction may lead to heavier workload to the FFs. Thus, care should be taken during system design to ensure that there will be no long-intense interaction during the mission which requires solely the action from FFs.	Low[13], Medium[14], High[15]
	Modality	Considering the environment noises, we need to find the most suitable communication modality	Employing only one communication modality may increase the cognitive load. More modality may reduce the cognitive load.	Aural, Visual, Tactile
	Synchronicity	Whether the information and command will be processed immediately or after some time.	It is related to expectation, when to receive the response from the other party during communication. If it's supposed to be a synchronous one, the other party is expecting to receive the response immediately. Any delay may lead to frustration or lack of trust.	Synchronous[16], Asynchronous[17]

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[11] although it is still possible that human and robot will communicate via the provided communication channel

[12] Equals to the mission duration.

[13] in fully autonomous

[14] in semi-autonomous mode

[15] in direct control mode

[16] the information and command are processed immediately

[17] the information and command are processed after some time

5 Human Robot Interaction (HRI) Metrics and Evaluation Method

To evaluate and validate the effectiveness of the interaction between robot and human in general, we need to have some metrics (what to measure) and standardized methods (how to measure). These issues are regarded essential but somehow unexplored in the area of human robot interaction. Because of the very broad applications of human-robotic systems, it is difficult to have common metrics. Some metrics may be suitable in some applications, but may not in others.

There have been many efforts to establish common metrics for HRI. One of the most comprehensive one is the work of Fong et al. [10]. In their paper, they summarize some existing metrics which can be used as standard measurements for a wide range of tasks and applications. Crandall and Cummings have also presented a set of metrics that measure the effectiveness of a certain aspect of a human-robot team (HRT), which they call metric classes [4].

The issue concerning methods for evaluating HRI is also not trivial. Although some existing methods from human-computer interaction (HCI) domain may be applicable in HRI, but care should be taken because there are some aspects that greatly differentiate robots to computers. Robots are real objects that can physically interact with their environment and effect it accordingly. Moreover, they are usually operating in real-time condition. Thus, debugging robotic system is also another research field of its own.

Scholtz [34] mentioned two issues in evaluating human-robot interaction. The first one is that we need to evaluate not only the state of the robot system after performing an action but also the state when the action was given. It is because it is important to ensure the synchronization between the specified and the actual behavior. The second one is the importance of separation between the performance of the HRI system and the usability of the interface.

In the following sections, we will take a closer look on these two issues, which are the “things” to be measured and the “way” they can be measured.

5.1 “Things” to be measured (Metrics)

In the following sub-sections, some metric classes will be presented. They will be presented in groups based on the work of Fong et al. [10], they are: system, operator, and robot performance.

System performance is the measurement on how well the human(s) and robot(s) perform as a team. Basically, system performance can be measured either quantitatively or qualitatively. Operator performance is a measure on how well the human(s) can handle the interaction. There are three important aspects in measuring operator performance: situational awareness, workload, and accuracy of mental models. The last is the robot performance. This performance measures how well a robot can accurately asses itself during runtime, how well a robot is aware of the human presence, and how high is the capability of a robot, or in other words, the level of autonomy of a robot.

Crandall and Cummings [4] argue that the metrics class should have the following three atributes to effectively evaluate HRTs:

- containing metrics that identify the limit of all agents in the team (human or robot).
- possessing predictive power that can estimate the effect of changes in environment, mission, and team composition on the team’s effectiveness.
- containing key performance parameters (KPPs) that indicate the overall effectiveness of the team.

Basically, the idea of having a human-robotic system is to combine the strength of each so that we can get an emergence from their action. Thus, a deep understanding of strengths and weaknessess of human and robot in some particular tasks is important. In our case, we need to analyze which tasks during search and rescue operation are more suitable for robots and which are for humans. In relationship to this issue, the work of Rodriguez and Weisbin [31] is important to be mentioned. They propose a quantifiable measurement for deciding who will perform which tasks in what situation. This method can quantify the tasks’ complexity, and on which a decision can be made to determine whether the tasks suit more to robot or human.

5.1.1 System Performance

This metric class measures the performance of robots and humans as a team. It is indeed task specific, which means that it is difficult to have a common metrics. However, Fong et al [10] propose a metric that is task-independent; it can be used for evaluating human-robot team and human-robot interaction. They propose three kinds of metrics for system performance: *quantitative performance*, *subjective ratings*, and *appropriate utilization of mixed-initiative*. However, we argue that the last metrics can be regarded as subsets of the first one. Thus, for the GUARDIANS project, we group the system performance into two groups: the quantitative and qualitative metrics.

5.1.1.1 Quantitative Metrics

This metric can provide a quantitative, thus comparable, performance measurement. In general, it assesses the effectiveness and efficiency of human-robot teams’ performance in performing tasks.

Effectiveness Fong et al [10] state that this metrics require the knowledge of the level of autonomy of the system. Thus, we must know in advance the percentage of the desired human intervention on the system. In other words, the capability of the robots for performing the tasks. However, this requirement may not suitable for systems with adjustable autonomy or mixed-initiative[1]. Thus, to make this metrics as generic as possible, we define effectiveness as the percentage of mission accomplishment. To further clarify, we list out aspects that may influence the mission accomplishment.

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[1] This must be the reason that Fong et al put the metrics for system with mixed-initiative in another group.

- The number of completed tasks.

  In search and rescue mission, there are several tasks that have to be completed by the human-robot team (firefighters and robot swarm), e.g. explore the area, locate dangerous substance, find victims, etc. Given a certain amount of tasks, we will record how many tasks can be fully completed by the team.

- The number of failures.

  Given the number of tasks to be completed, we will record how many failures occur during the mission.

- The total interaction duration and number between humans and robots.

  During mission we need to measure how long the total duration of interaction between firefighters and robots. Moreover, it is also important to know the number of times the interaction takes place. Too frequent interaction with short duration may distract the firefighters during the operation.

Efficiency Fong et al define efficiency as the time required to complete a task. However, we consider also other aspects, such as communication bandwidth and other important resources. Thus, in general, we define efficiency as the amount of resources required to complete a task.

- Time completion.

  Due to the nature of event, the operation time for search and rescue mission is limited to a certain period. Thus, it is important to ensure that all tasks can be completed as fast as possible within the allowed time window.

- Communication bandwidth.

  Due to the computing and power limitation, robots cannot carry computing- and energy-hungry devices on board. In term of communication device, communication bandwidth is effecting the computing and power requirement. The higher the bandwidth, the higher the computing and power requirement. As a result, we need to ensure that the interaction between humans and robots can be done with minimal communication bandwidth.

- The ratio of actual time of action and preparation (negotiation, delegation, coordination, etc).

  During the mission, the less time required for other things but the interaction itself, the better. This means that all information exchanged is easily comprehended, thus the overhead of the interaction can be kept minimum. This measurement is closely related to the quality of the communication protocol between involved parties (robots, firefighters, mission commanders, etc).

- Interaction Delay

  During interaction, there may be a delay between perception and action, either on humans or robots side. This delay occurs due to the need for processing the information and making the decision. Delay can lead to frustration; the higher the delay the higher the frustration. Moreover, in situations as ones faced by the firefighters in search and rescue mission, the slow response of the robot will impede the goal achievement. For example, sluggish reaction of the robot swarm on the movement of the firefighters will force them to always wait for and monitor the movement of the robot swarm, which in turn will lead to more workload on their part.

5.1.1.2 Qualitative Metrics

This metrics cover other measurements which cannot be quantified, such as the quality of the interaction, the provided information, etc. The metrics are of subjective nature; it is compiled from all parties involved, directly or not.

- **Usability of the user interface**

  Usability, as defined by ISO 9241, is the effectiveness, efficiency, and satisfaction with which specified users achieve specified goals in particular environments. With regard to user interface, this metric measures the easiness to use the interface to interact with machines (computers or robots): to understand the information from or to send commands to the machine.

- **Information quality**

  This metric measures how easy the displayed information is for users. Data sensed by robots are raw data and it is difficult to understand them in their original form. Moreover, some data may support others in describing a certain situation. Thus, such related data may be better combined in a way that the information can be presented comprehensibly.

- **Interaction quality**

  This metric measures how easy to interact (related to modality), considering the preferences of humans and the environment condition. This value can be gained by interviewing the users' impression after the interaction.

5.1.2 Human Performance

This metric class measures some aspects from human point of view. Fong et al [10] mentioned three aspects in this metric class, they are: situational awareness, work-load, and accuracy of mental models of device operation. However, there are also two other aspects, as pointed out by Adams in [1] that can be added to this metric class: vigilance, and the human-error.

5.1.2.1 Situational Awareness (SA)

Situational awareness as defined by Endsley [7] is:

> "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future".

In other words, situational awareness refers to the knowledge of things happening in the surrounding. Endsley in [7] presents three levels of situational awareness.

- Level One of SA is the basic perception of information in the surroundings.
- Level Two of SA is the ability to comprehend or to integrate multiple pieces of information and determine the relevance to the goals the user wants to achieve.
- Level Three of SA is the ability to forecast future situations events and dynamics based on the perception and comprehension of the present situation.

In the case of GUARDIANS project, firefighters need to obtain Level Three of SA due to the nature of search and rescue mission. In such mission, the environment changes abruptly, which means that previous information may become invalid in a snap. Thus, the information provided to the firefighters must be comprehensive and detail enough so that they can determine the most approriate actions for a certain situation.

5.1.2.2 Workload

Hart and Staveland [21] define workload as: "*a hypothetical construct that represents the cost incurred by a human operator to achieve a particular level of performance*". There are several factors that can influence workload: task difficulty and complexity, stress, mental effort, time pressure, fatigue, physical effort, own performance, etc. In the same work, Hart and Staveland present 10 bipolar rating scale, which are: **Overall Workload** (OW), **Task Difficulty** (TD), **Time Pressure** (TP), **Own Performance** (OP), **Physical Effort** (PE), **Mental Effort** (ME), **Frustration** (FR), **Stress** (ST), **Fatigue** (FA), and **Activity Type** (AT). Table 5.1 shows this rating scale.

This framework, also called NASA-Task Load Index (NASA-TLX) has been widely used to measure human performance and workload in several types of application scenarios. In general, workload is subjectively lower as the level of system autonomy increases.

In human-robot teams consisting of many robots, such as the scenario tackled by GUARDIANS project, workload is assumed to be higher as the number of robots increases, as shown in Humphrey et al. [24]. In their work, they use NASA-TLX to measure workload to control many robots (up to 9 robots) simultaneously. They present six factors that they consider to contribute to overall workload: *mental demand*, *physical demand*, *temporal demand*, *performance*, *effort*, and *frustration*. In the case search and rescue mission, the task factor is likely to increase the workload because of its nature: highly critical and risky. Moreover, environment condition and limited time will impose higher stress to firefighters. Thus, a carefully and wholistically designed human-robot interface is very important for this project to ensure effectiveness and efficiency of human-robot interaction.

One issue concerning workload measurement is to have a non-intrusive methodology that can capture the real workload value of humans without interfering the process of performing the task. This issue may relate to the knowledge in physiology; some physiological measures (cardiovascular, respiratory, etc) can be used as indicators of workload[3].

5.1.2.3 Human Error

There are several definition of human error found in the literature. The one that mostly relevant to this project is defined by Sanders and McCormick [32]. They define human erros as

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[3] We may need to find some suitable physiological measurement which can be used for this purpose.

Table 5.1: *Ten bipolar Rating Scale description, adapted from Hart and Staveland [21].*

Title	Endpoints	Descriptions	Issue in GUARDIANS[2]
Overall Workload	Low, High	The total workload associated with the task, considering all sources and components.	
Task Difficulty	Low, High	Whether the task was easy or demanding, simple or complex, exacting or fogiving	
Time Pressure	None, Rushed	The amount of pressure you felt due to the rate at which the task elements occured. Was the task slow and leisurely or rapid and frantic?	
Performance	Failure, Perfect	How successful you think you were in doing what we asked you to do and how satisfied you were with what you accomplished.	
Mental/Sensory Effort	None, Impossible	The amount of mental and/or perceptual activity that was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)	
Physical Effort	None, Impossible	The amount of physical activity that was required (e.g., pushing, pulling, turning, controlling, activating, etc.)	
Frustration Level	Fulfilled, Exasperated	How insecure, discouraged, irritated, and annoyed versus secure, gratified, content, and complacent you felt.	
Stress Level	Relaxed, Tense	How anxious, worried, uptight, and harresed or calm, tanquil, placid, and relaxed you felt.	
Fatigue	Exhausted, Alert	How tired, weary, worn out, and exhausted or fresh, vigorous, and energetic you felt.	
Activity Type	Skill Based, Rule Based, Knowledge Based	The degree to which the task required mindless reaction to well-learned routines or required the application of known rules or required problem solving and decision making.	

> “an inappropriate or undesirable human decision or behavior that reduces, or has the potential for reducing effectiveness, safety, or system performance”.

The situation faced by firefighters during the incident is of critical nature. They are introduced to high workload, mentally as well as physically. Moreover, the environment condition is not supportive either, which is dynamic, adverse, and complex, which can potentially bring more stress to them. Thus, human errors occur easily.

The measurement of human error is a good representative of the quality of human-robot interface of human skill and expertise. Well design interfaces will display enough information but at the same prevent cognitive overload. However, no matter good an interface is, without proper training, it may fail to achieve its goal. Especially, we are aware that it may be the first attempt to employ robots to assist firefighters in fire incident. It means that in-depth introduction to and training on the robotic system is important for the firefighters to minimize human error during missions.

To understand human error, we need to know types of action that may lead to human-error. In general, there are four types of such actions:

- Errors of omission - forget to do something
- Errors of commission - doing the task incorrectly
- Sequence errors - out of order
- Timing errors - too slow - too fast - too late

Moreover, it is also important to have a classification of error. There are three types of error, which are:

- Skill based - controlled by sub-conscious behavior and stored patterns of behavior
  - usually errors of execution
- Rule based - applies to familiar situations - stored rules are applied
  - errors involve recognising the salient features of the situation
- Knowledge based - occur in unique & unfamiliar situations
  - errors result from inadequate analysis or decision making

5.1.3 Robot Performance

5.1.3.1 Self-awareness

Self-awareness is defined as the ability of a robot to accurately assess itself. To achieve a 100% functional robotic system is hard. Failures are likely to happen. Thus, instead of maintaining 100% functional reliability, we may simply maintain 100% error-reporting reliability. It means that the robots should be able to sense any failure occuring inside themselves (self-cognizant). An issue to follow is what to do with the knowledge of such events.

It is believed that the more a robot possesses self-awareness, the more it is able to recognize problem encountered, in turn, the less human needs to monitor or control it. Related to the GUARDIANS project, robot swarm must be able to detect any failure within themselves as well as among themselves. As they can identify failures, they can re-organize autonomously without humans' intervention. Or, if required, they can ask human advice on what to do, given a certain failure.

5.1.3.2 Human awareness

Human awareness is defined as the ability of a robot to recognize human presence and be able to communicate with him/her. In relationship with GUARDIANS project, several capability of the robots are required, such as:

- human detection and tracking
- gesture and speech recognition
- human modelling and monitoring
- adaptable behavior to human

5.1.3.3 Autonomy

Autonomy is a word commonly used but somehow not clearly defined. However, for the purpose of this project, we define autonomy as the ability of robots to function independent of external influence, which can be humans or other robots. The function can be decision making, environment exploration, environment sensing, etc.

Goodrich et al. [17] introduce the neglect graph (see Figure 5.1) representing the relationship between level of autonomy and robot performance in term of effectiveness. They argue that robot's performance is proportional to the amount of human's attention given to the robot, regardless the level of autonomy, although the effects are different from one level to the others. However, the results of Ali in his dissertation show that this is not always the case [2]; the effect of human intervention on robot performance depends on several factors, the type of the task, robot capability, user interface to name a few. However, the model proposed by Goodrich et al. seems to be generic enough, thus it is worth to mention here as a rule of thumb.

Another attempt to measure the level of autonomy is done by Barber and Martin [3]. They model autonomy as the amount of control each agent posseses for a particular goal. In this regard, the amount of control is equals to the number of decision made. Suppose that an agent must decide 16 times to achieve its goal. During the course of goal achievement, apparently the agent can only make 8 decisions by itself, the rest are delegated or transferred to other agent. Thus, from the model of Barber and Martin, the agent level of autonomy is said to be 8/16 or 50%.

5.2 "Way" to measure (Method)

In relationship with the GUARDIANS project, we will need to find some suitable methods with which we can evaluate and validate the end product of the project. In the previous section,

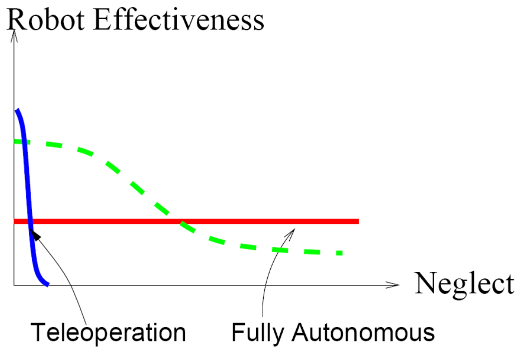

Figure 5.1: *Neglect graph representing the effect of human intervention on robot performance for particular levels of autonomy (Taken from [17]).*

some metrics classes that closely related to the human-robot interaction in this project have been presented. In this section, we will discuss some existing methods and tools that can be used for analyzing the interaction.

5.2.1 Methods

In this sub-section, some methods for evaluating HRI will be presented. Scholtz et al. [35] mentioned several common methods for evaluating situational awareness. We think that all of these methods can be used simultaneously, and together with the metrics previously proposed, we can have a comprehensive evaluation of the human-robot interaction.

5.2.1.1 Performance-Based Method

This type of method measures the result or the outcome of the interaction, whether the system consisting of humans and robots performs correctly in achieving the goal. However, such method is not comprehensive enough; there are factors that may make it invalid because it lacks analysis during the goal-achieving process. Some "*lucky*" factors may have a role during the process and this method is likely to fail to capture it.

5.2.1.2 Knowledge-Based Method

This type of method is done in experimental conditions to isolate particular components and assesses them individually. This method is regarded to suit better at uncovering declarative information than procedural information.

5.2.1.3 Subjective-Rating Method

This type of method can be used to capture the impression or opinion of the users, in our case the firefighters or people at the base station, during the interaction with the robot swarm. This is commonly done through the use of questioner during or after the evaluation period. However, this method may not be able to show the missing information which may be required for the successful interaction.

5.2.1.4 SAGAT

The Situational Awarenes Global Assessment Technique or SAGAT [6] is a tool for measuring situational awareness. It uses a goal-directed task analysis to construct a list of the situational awareness requirements for an entire domain or for particular goals and sub-goals. It is done during a direct experiment with some queries asked at a certain task. At a specific time, the task is frozen and then users need to answer some questions that can determine their situational awareness at that particular time. Afterward, the task is resumed.

5.2.2 Tools

During experiments or field tests, we need to record a lot of data of different types for analysis purpose. For example, video or audio data may be stored to capture human and robot behavior during interaction. In addition, such data is not enough because it cannot provide information about the reason that the robots behave accordingly as recorded on the video. Thus, we need also to record the internal state or information of the robots.

Considering the amount and type of data recorded, it is delicate to combine and present them in a comprehensive manner. Thus, some tools may be helpful for us in analyzing the result of the experiments or tests. One example of such tools is presented by Kooijmans et al. [25]. They have developed a tool called “Interaction Debugger”. This tool can be used for collecting data during interaction between humans and robots and presenting it in a comprehensible way using graphical representation.

In relationship with GUARDIANS project, this kind of tool may help us in providing some qualitative as well quantitative measurement on the performance of the human-robotic system. In the work of Tanoto et al. [40, 39], an integrated platform for setting-up, executing, and analyzing experiments in multirobotics can be also useful for analyzing human-robot interaction. This platform, called Teleworkbench [41], is able to record all information and events coming from the robots or external systems (GUI or other computers) and then to generate videos with all information and events embedded. Moreover, the use of MPEG-4 video standards allows some level of interaction between users and the video. For example, users are able to display some specific information only, to reduce cognitive load during analysis.

6 Human-Robot Swarm Interaction Requirement and Specification

This chapter presents the requirement and specification of human-robot swarm interaction. It is developed based on the analysis of human-robot swarm interaction (Chapter 4) and the metrics (Chapter 5).

6.1 Functional Requirements

For the purpose of clarity, we will group this requirement into system, human, and robot.

6.1.1 System

This requirement emphasizes the interaction inside the system in general.

6.1.1.1 Humans-robots interaction

1. *Ratio of number of humans and robots.* The system must support different ratio of number of humans and robots: *single human – single robot*, *single human – multi robot*, *multi human – single robot*, *multi human – multi robot.*
    a) *single human – single robot.* One human will interact directly or indirectly with one robot. In this project, an operator at the base station or the firefighter, in urgent situation, may control one robot to do a certain task. Most probably when one robot is in trouble, needs guidance, or gets out of the path. In this case, the most possible autonomy level is *direct control.*
    b) *single human – multi robot.* One human will interact directly or indirectly with some robots. In this project, an operator at the base station or the firefighter, in urgent situation, may control several robots to do a certain task. For examples, the robots are asked to explore unexplored area, to lead the way, or to maintain communication infrastructure. In this case, the most possible autonomy level is *semi-autonomous* or *fully-autonomous*, such that human just need to give high level request or command and the robot will do accordingly without needing more detail command.
    c) *multi human – single robot* . Several humans will interact directly or indirectly with one robot. In this project, several operators at the base station may control one robot to do a certain task, such as scrutinizing a suspicious object which requires detail analysis of information from different sensors. In this case, the most possible autonomy level is *direct control.*

   d) *multi human – multi robot.* Several humans will interact directly or indirectly with several robot simultaneously. In this project, several operators at the base station may control several robot to do a certain task, such as describe in 6.1.1.1 #1c. However, the situation requires information from different places simultaneously. Thus, some robots are needed.

6.1.1.2 Communication

1. *Modality.* The communication channel between firefighters and robot swarm must be of several modalities to reduce cognitive workload. Some possible modalities can be employed are aural, visual, and tactile.

   a) *Gesture.* Due to visual adversity in the incident area, visual communication mode can be supported by the use of special devices which can emit lights[1] that can be detected by robots' sensor. In this way, communication by gesture can be accomplished.

   b) *Audio.* Robots must be able to understand some important commands as speech, e.g. navigation commands such as “Go Left”, “Turn Right”, “Go one meter straight”, “Stop”.

   c) *Widget.* Widgets must be sufficiently separated one to the others and easy to reach and activate. Its sensitivity must be within the range of X to Y[2].

2. *Duration & Intensity.* The communication must be kept as concise, comprehensive, and unambiguous as possible, to avoid repetitive message.

3. *Synchronicity.*

   a) The communication protocol must be of synchronous type. Every command or request must be answered, to inform the command or request iniator that the transferred message is received. Moreover, the answer must be specific to the command or request, to show whether it is understood or not.

6.1.1.3 User interface

1. *Clarity.* The information provided to the firefighters must be unambiguous.

2. *Succinctness.* The information displayed must be succinct but at the same time comprehensive.

3. *Non-distracting.* The information displayed must not distract the firefighters from their main task. Moreover, the user interface must be able to differentiate between information of different priority. Information of higher priority must be more catchy.

4. *Usability.* The user interface must be as easily used as possible. The widgets must be easily reachable. Moreover, they must be sufficiently separated and big to avoid mis-activation or activation-difficulty due to protecting gears.

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[1] The required value of light power can be put here.
[2] We need to find these numbers, if they exist.

6.1.1.4 Autonomy Level Adjustment

1. *Subject.*
    a) Operators at the base station and the firefighters are allowed to initiate the autonomy level adjustment of the robot swarm.
    b) Due to the nature of the mission, which is of high risk and critical, other robots are not allowed to initiate autonomy level adjustment of the robot swarm.
    c) However, the robot itself is allowed to initiate autonomy level adjustment of itself.
2. *Object.*
    a) During operation, the autonomy level adjustment may manifest in a form of either
        i. decision,
        ii. command,
        iii. asking for advice, or
        iv. advice.
3. *Reason.*
    a) Human knowledge and skill cannot be disregarded in such a mission.
        i. Because the environment is unpredictable and human experiences and instict play are still the important factors in such an environment, the main decision maker is still human.
    b) Lack of trust on robots' capability for the mission.
        i. The mission is too risky or too critical to be dependent on the robots.
        ii. Sensor reliability factor due to adverse environment.
    c) To increase effectiveness and efficiency.
        i. There are tasks which are more suitable to robots, and some to humans, depending on the situation.
        ii. Repetitive tasks which robot can do reliably are better assigned to robots.
        iii. Risky and critical tasks must be assigned to humans, and the role of the robots is to support them, e.g. provide more information to help making decision.
4. *Context.*
    a) Robots need help. There is a situation in which robots knows they face problem which they cannot solve by themselves, e.g. trapped in an area, or in a position to choose between two or more branches. In this situation, robots can lower its autonomy level, from semi-autonomous to direct control, and allow humans to provide low-level control on them.
    b) Unexplored area. There is a situation in which robots think they have cover all area while actually there is one part of the area which is not explored yet. In this situation, humans can tell the robots to explore that area by giving high-level command, such as the point of entry to that area.

   c) Object analysis. There is a situation in which humans want to scrutinize a suspicious object. Thus, in this situation, they will take over the control of one or more robots to go to the object location and taking some data using sensors on board the robots to study the object. During this time, robots must let human to have control over them.
   d) Decision making. The role of robot swarm is to guide firefighters to safely navigate the incident area. During the time, robots will operate autonomously. However, there is a situation in which robots' guidance does not suit the squad leader's intention. In this situation, the squad leader's decision overrides the robot's guidance, and the robots must follow the decision.

5. *Method*[3].

6.1.1.5 Task

1. *Task allocation.* There must be a clear definition of tasks that must be done by robots and ones by humans[4].
   a) *Task risk.*
   b) *Task criticality.*
   c) *Task product.*

6.1.2 Human

6.1.2.1 Human Skill & Expertise

1. Firefighters must have knowledge on the communication protocol used for communicating with robots.
2. Firefighters must have knowledge on robots' capability; what they can and they cannot.
3. Firefighters must be able, if necessary, to directly control one or several robots[5].

6.1.2.2 Role of Human

1. *Team mates.* In this role, firefighters and robots work together as peers. The control is shared among them.
2. *Bystander.* In this role, firefighters have no control over the robots behavior. This role happens when people at the base station directly control the robots for some particular tasks.

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[3] At the moment, this requirement is still not clear.

[4] I think the requirement in this group needs further discussion with the end user because they know better of the kind of tasks that will be involved during the mission.

[5] We should give an exact number here, how many robots maximum must be controlled by the firefighters.

6.1.3 Robot

6.1.3.1 Robot capability

1. *Level of autonomy.* The robots must be able to operate at minimum three different levels of autonomy: direct control, semi-autonomous, fully-autonomous.
2. *Formation keeping capability.* Each robot must be able to recognize its position in reference to other robots and the firefighters.
3. *Failure detection capability.* Each robot must be able to recognize failure within itself, and as much as possible to inform it to human operator.

6.1.3.2 Robot's Role

1. *Human's sense extension.* Robots must be able to provide firefighters with information about the environment, such as hazardous objects or way out.
2. *Human's companion.* Robots must be able to assist firefighters to manage their direction to the scene operation and the exit point.
3. *Communication node.* Robots must be able to maintain the communication infrastructure during the operation by turning themselves as communication nodes.

6.1.3.3 Robot Team Composition

1. The requirement in this group will be further defined later.

6.2 Non-Functional Requirements

In this sub-section, we will analyze each requirement to derive possible problems out of it.

6.2.1 Flexibility

This requirement maintains that the system is open to future extension, supports scalable number of entities, and is portable.

6.2.1.1 System Interface

1. The components of the system have to have common communication protocol.

6.2.1.2 Platform

This requirement is closely related to the Base-Station Architecture and Robot Architecture Requirement.

6.2.2 Efficiency

This requirement explicitly says that the system must be resource-friendly.

1. The robots must be able to operate with maximum performance within the maximum time duration of the mission[6].
2. The interface used to interact with robots must be able to operate at maximum performance within the time duration of the mission.

6.2.3 Dependability

This requirement requires that the system must be able to provide reliable performance in doing its task in the condition the system is designed for (*reliability*), and in case of failure, the system must be able to recognize the failure (*cognizant failure*) and take appropriate actions to ensure that it will not endanger people and itself (*safety*). Moreover, since the robotic system is allowed to be controlled by other agents, either human operators or software agents, it is important to prevent any malicious agents, unauthorized person or viruses, to take control over the robotic system (*security*).

1. The system as a whole must be able to guarantee X % success rate[7].
2. The robots and the user interface must be able to *ALWAYS* detect failure.
3. The robots must be equiped with safeguard mechanism to guarantee safety of humans, other robots, or itself, in case any failure or unexpected situation.

6.2.4 Maintainability

This requirement underlines the system ability to function normally although some robots of the system are temporarily not available due to maintenance[8].

1. The system must be modular.
2. The modules must be easily de-/installed from the others.
3. For each module, there must be a documentation explaining the installation and maintenance.

6.2.5 Self-configurability

This requirement requires that the system is robust against failure of one of its elements, either human operators or robots[9].

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[6] It would be better to put an actual number here. We can get it from the maximum duration of the mission.

[7] I think this measurement is important. The question is how high we expect it to be?

[8] I put some examples here on maitainability aspect. But other people from other work package can contribute.

[9] This requirement is closely related to the swarming and its reconfigurability in case one or some of the components fail.

6.2.6 Usability

This requirement is basically related to the quality of user interface issue covered in the functional requirement.

7 Summary

This document presents:

- the scenario tackled in GUARDIANS project,
- an overview of human-robot interaction, including some important issues of it,
- the analysis of human-robot swarm interaction for GUARDIANS project based on the developed human-robot interaction taxonomy and the scenario presented earlier,
- some metrics and methodology that can be used for evaluating and validating the project, and
- the human-robot swarm interaction requirement and specification.

Further elaboration is needed to make this requirement and specification document more specific.

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