Chapter 2
Artificial Intelligence Based Framework for Robotic Search and Rescue Operations Conducted Jointly by International Teams

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Abstract Many countries suffer from various natural disasters, including heavy rains, that are associated with further flood and landslide disasters. Based on our experiences of different disasters response, we develop a joint international operation framework for a disaster site management with distributed heterogeneous robotic teams that consist of unmanned aerial, ground, surface, and underwater vehicles. The artificial intelligence-based information collection system, which is targeting to become a worldwide standard, contains interaction protocols, thematic mapping approaches, and map fusion processes. The project provides a new working framework and control strategies for heterogeneous robotic teams' cooperative behavior in sensing, monitoring, and mapping of flood and landslide disaster areas. In this paper, we present an overview of the system and a first stage toward robot interaction protocols development and the system modeling within robot operating system's Gazebo environment.

Keywords Robotics · Information system · Urban search and rescue · Usar · Ros · Gazebo · Heterogeneous robotic teams

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2.1 Introduction

A long-standing goal of rescue robotics is to construct and employ robots operating in environments that are considered to be unreachable or dangerous for humans. A wide range of rescue robotics applications includes the exploration of volcano craters, wilderness, labyrinths of dangerous underground tunnels and communication pipes' networks, tasks in high pressure and poisonous environments with nuclear or chemical contamination, replacing human teams in scouting and mine clearing, and supporting antiterrorist operations. Rescue robots extend capabilities of human rescuers while significantly increasing their safety. One of the particular rescue robotics applications is urban search and rescue (USAR) domain. USAR is probably one of the most dangerous environments that are characterized by disaster victims often being buried in locations, which could not be easily reached for a human rescuer.

A growing number of emergencies are caused by natural disasters. East Asia, including Asian part of Russian Federation, is a vulnerable to natural disasters region. There are over 30 types of dangerous natural phenomena, and floods are among the most frequent and costly phenomena in terms of human and economic loss. Therefore, it is highly important to create and experimentally validate technological solutions that could deal with such disasters. Science and robotic technologies can play a key role in disaster risk assessment and prevention, and the role of artificial intelligence and robotics technologies increases yearly together with successes of robotic research and development around the world. Modern technologies collect global data for natural hazards assessment and disaster prediction with remote sensing, GIS, and satellites. Yet, in order to support real-time disaster management, the development of an artificial intelligence-based information system is required, which will allow using effective information exchange and robotic technologies, communication systems, and decision-making systems in combination with various types of robots [1, 2].

Our long-term international project includes research teams from Russia, Japan, and Thailand, and each team contributes unique experience and special expertise of the past and the ongoing research activities toward a joint goal. The Japanese team contributes its expertise in robotized urban search and rescue field, including Geological Information Systems (GIS), graphical user interfaces, and design of control strategies for heterogeneous robotic teams [3]. The Russian team concentrates on the development of specialized robot simulators in ROS/Gazebo programming environment, simultaneous localization and mapping technologies, and path planning algorithms [4]. The Thailand team has a strong expertise in unmanned aerial vehicles (UAV), unmanned ground vehicles (UGV), and unmanned surface vehicles (USV, unmanned ships) development, teleoperation systems for various types of robots and heterogeneous robotic teams as well as applied issues, including improving reliability of rescue robots [5]. Our collaborative project targets for the development and verification of an artificial intelligence-based operational framework for disaster site management with the help of distributed heterogeneous UAVs, UGVs, unmanned underwater vehicles (UUV), and USVs' teams. In this framework, robotic teams will construct a large collaborative thematic map of a disaster site, which will help human rescue teams to speed up the process of extracting survivors from a disaster site and evaluating dangers of construction collapse and environment pollution while increasing the safety of human rescuers and survivors.

This paper presents an overview of the artificial intelligence-based operational framework and is organized as follows. Section 2.2 describes motivation and related work. Section 2.3 familiarizes a reader with our approach to the framework development. Section 2.4 briefly discusses requirements for a proper simulation of the framework and USAR environments in robot operating system (ROS)-based Gazebo simulator. Section 2.5 demonstrates a prototype of data exchange and interaction protocols that will be used by robotic teams within the operational framework. Finally, we conclude in Sect. 2.6.

2.2 Motivation and Related Work

The governments of those countries that are at a high risk of natural disasters pay great attention to improving emergency preparedness. When various natural disasters occur in populated areas, regional and, in the case of a massive catastrophe, the national government needs to organize search and rescue teams to deal with the effects of natural disasters and emergency management. To identify (possible) places where victims need to be evacuated and identify the most dangerous areas, rescue teams need to receive timely information about the situation in the disaster area in order to be able to respond quickly and effectively. At the same time, untimely and/or poor-quality information about a disaster scale and current situation in the disaster area significantly reduces the efficiency of interdepartmental organizations in dealing with the disaster aftermath [6, 7].

One of the ways to improve the emergency management system is to automate data management processes and to robotize data collection processes. Today, much attention is paid to the development of situational centers, which, as a rule, are equipped to simultaneously monitor a huge amount of data, receive and analyze operational information, manage disaster relief processes, and coordinate search and rescue operations. An example of a prototype information system is WIPER (Wireless Phone Based Emergency Response System [8]) system that was developed and implemented using the Dynamic Data Driven Application Systems (DDDAS, [9]) concept. The WIPER system is designed to use real-time cell phone call data in a specific geographic region to provide increased situational awareness of disaster prevention centers. WIPER-like decision-making systems can also be used to study the dynamics of water resources, simulate forest fires and disasters in coastal areas.

The idea of using robots for rescue operations arose in the early 1980s, but until the 1990s, they did not cause a wide resonance due to the insufficient level of robotic technologies. The great Hanshin-Awaji earthquake (7.3, the Richter scale) of 1995 in Kobe city, Japan, during which 6434 people died, 200,000 buildings were destroyed and Japanese economy suffered general damage of 2.5% GDP, has become one of the largest earthquakes in Japanese history. The disaster aftermath investigation demonstrated many problems in buildings' constructions as well as in rescue work process [10]. Thus, it was this catastrophe that stimulated a transformation of an abstract scientific concept of "search and rescue robotics" into the realm of applied scientific research, which were further actively funded by the state [11]. The tasks of the robotic systems during search and rescue operations were defined as victims search in hard-to-reach and most dangerous zones of a disaster area, automatic debris processing, data collection about a disaster area from the air (using UAV groups), from the water (at a moderate level of landscape flooding, with a help of USVs), and from under the water (with large-scale flooding, with a UUVs).

For the first time in history, search and rescue robots were tested under real conditions during the aftermath of terrorist attack on the World Trade Center in the USA on September 11, 2001. Within 6 h after the attack, Center for Robot-Assisted Search and Rescue CRASAR launched equipment deployment and study of debris using three small-sized mobile robots Inuktun microVGTV, Inuktun micro-Tracks, and Foster-Miller Solem, which were used there until October 2, 2001. The robots worked in narrow vertical spaces and each robot was equipped with an escape cable, while connection with an operator was made via fiber optic cable in case of interruption of wireless communication [12]. During a search and rescue operation after a landslide in La Conchita, California, in 2005, the CRASAR used improved UGV models, one of which was lost due to the issues with mobility and maneuverability [13]. For emergency examinations of building structures after Catherine hurricane CRASAR used UAVs [14] and concluded that for such situations, it is critical to use a group of miniature UAVs that could cover a large disaster area. In the aftermath of Sago mine explosion, a tracked UGV V2 was used [15]; however, he was able to penetrate the mine only 700 meters, which also emphasized a need for further improvements in maneuverability and mobility of the robot. In [16], the authors presented SENEKA project that aimed at optimizing information support processes for search and rescue teams. The project idea was to form dynamic networks using sensors and heterogeneous robots (UAVs and UGVs), which could allow rescue teams to obtain more detailed information about the situation in disaster zone, as well as to speed up response to emergency situations.

Analysis of the current state of research in the field of search and rescue robotics showed that introducing information technologies and robotic systems will improve monitoring and accelerate the response process of rescue and medical services. There is a clear need for artificial intelligence-based support systems and data transmission from a disaster site to emergency management centers, which in many cases can be achieved solely through robotic systems use. Today, it is important that during USAR missions robots of heterogeneous teams interact not only directly with their teleoperators [17] but also with each other [18, 19]. When developing protocols and standards for the interaction of robots that act as a single team, it is critical to consider possible limitations of wireless communications that occur spontaneously in certain areas [20] or permanently in the entire area of operation [21]. Therefore, for example, when such group of robots is engaged in a task of localization relative to landmarks and/or each other [22, 23] and mapping [24, 25], rapid integration of data in place [26] could be significantly difficult [27], and therefore it is done via centralized control using information, which is collected by individual robots. At the same time, scientific groups offer various approaches data integration, including combinations of occupancy grids [28], Hough transforms [29], using a graph that is based on positions and orientations of robots relative to natural landscape or artificial marks [30], and others.

2.3 Approach

Based on a theoretical abstract scheme for managing a robotic search in a disaster area [31] and broad experience of our joint international team, we plan to develop and implement an information system for disaster management so that it could become an open international standard in the future. The framework of a joint international operation for a disaster site management contains interaction protocols between robots of a team as well as between robots of different teams, agreements on thematic mapping requirements and approaches, map fusion processes, and other collaborative features. Thematic maps will cover such data as color, texture, heat emission, and chemical pollution information as well as dangerous locations, victims, survivors, animals, and potential voids for rescue team entrance.

We started from the development of theoretical path planning and disaster area coverage algorithms, control strategies, and multi-robot simultaneous localization and mapping (SLAM) technologies design for heterogeneous teams of UAV/UGV/UUV/USVs. The robotic teams include wheeled and crawler UGVs, quadrotor UAVs, a snake-type UUV, and a USV. While all teams use SLAM-based approach for the mapping task, since every team uses different robots, this requires different modifications of SLAM algorithms [32], which should be adjusted accordingly to the sensors and locomotion capabilities of the robots as single units as well as a team. Figure 2.1 presents an overview of the proposed project. Various heterogeneous robots work as a large international team, supplying the informational system with data, which is obtained through sensing and mapping activities from water surface, underwater, air, and rough terrain.

A microsimulator in robot operating system and Gazebo environment is currently under developed and is presented in some more details in Sect. 2.4. Its goal is to verify the above-mentioned algorithms and strategies after their prototyping in MATLAB. The microsimulator contains a feature of adding sensory input errors and sensor failures in order to simulate real-world uncertainty. Even though every team uses its own robot models in simulated disaster scenarios, the framework itself and simulated environments are common, while a large joint thematic multi-layer map of a disaster site is constructed by fusing together separate maps of different robots and teams.

Finally, we will develop a macrosimulator, including graphical user interfaces for monitoring a disaster site by a human operator and Geological Information System that can update and handle information about the disaster site. Practical evaluation of the macrosimulator will be performed involving citizens of Kochi prefecture (Japan) in cooperation with Kochi government within the artificial drills conditions. Only an

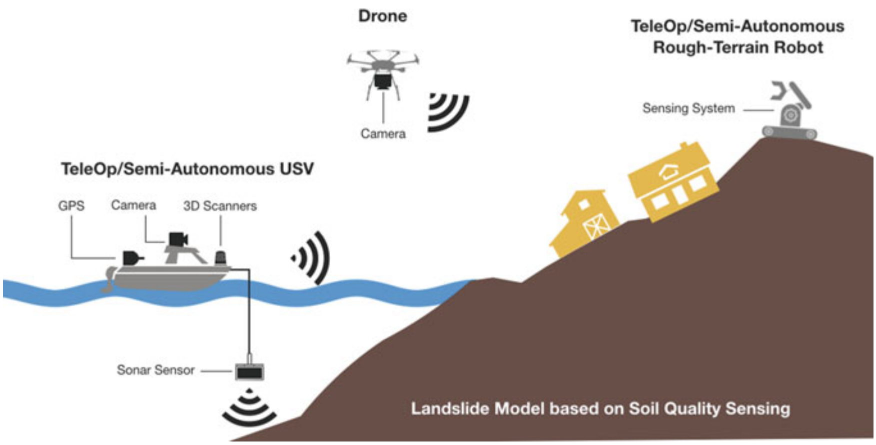

Fig. 2.1 An overview of the operation: heterogeneous robots work as an international team

appropriate level of synergy of the teams' expertise and joint research activities will allow us to successfully construct a joint informational system of a disaster site.

2.4 Simulation in ROS/Gazebo Environment

The Russian research team is responsible for the development of interaction and data exchange protocols between the heterogeneous robots within the teams as well as inter-teams' communications, development, and setup of joint ROS-based simulations framework, joint ROS-modules' architecture and implementation, testing methodology for ROS-based simulations and area coverage path planning algorithms. The developed by the Russian team simulator and a set of simulated testing environments will be further used by Japanese, Russian and Thai teams for strategies and algorithms evaluation.

The simulation is constructed in Gazebo environment, which is a ROS-integrated simulator [33]. Initially, a number of environments for our project were constructed using models of existing solid objects. Figure 2.2 shows an example of a virtual USAR environment map, which we called "an accident in a science city." The environment contains several partially destroyed buildings, regular buildings, cars, people, and other objects. While such type of an environment contains attractive colors and object textures, it could hardly be used for our purposes. We can still exploit these environments for path planning and coordinating robotic teams in external map constriction, but because all objects are sold models, they do not allow any interaction with their inner parts, e.g., a robot cannot enter a building and perform search and rescue activities inside buildings and other objects.

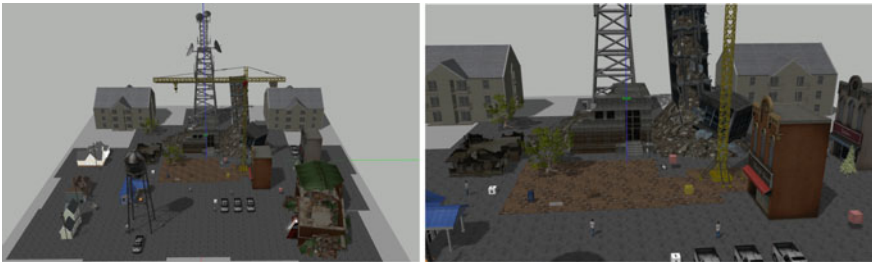

Fig. 2.2 Virtual USAR environment "xan accident in a science city"

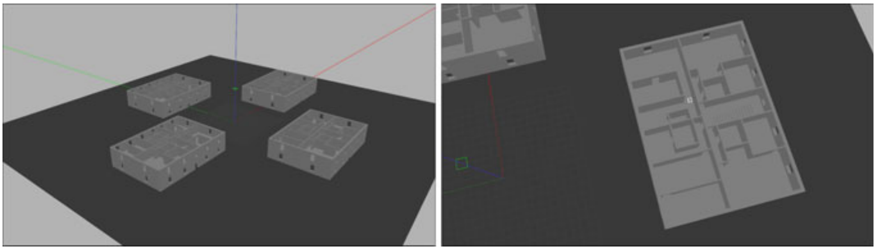

Fig. 2.3 Virtual USAR environment "two-store cottages": four symmetrically located identical two-floor buildings (on the left) and an enlarged picture of a second floor of the building, where a human location is shown with a small white cube (on the right)

To enable activities inside buildings constructed a virtual environment map, which we called "two-store cottages" (Fig. 2.3). Each building consists of walls, doors, windows, and stairs and allows a robot to operate inside. Yet, each of the above-mentioned objects is represented by a solid model without a texture. The modeling was performed with Intel(R) Core(TM) i5-3210 M 2.50 GHz PC with DDR3 6 GB RAM memory and AMD Radeon HD 7500 M/7600 M Series 2 GB graphic card. We constructed several environments with two types of buildings: two-store cottages and storage buildings without windows. Even though a relatively powerful computer was used for this simulation, the largest environment, which we succeeded to construct, contained only seven storage buildings and five two-store cottages. Gradual increase of number of objects in the environment immediately reduced a real-time factor (RTF) of the simulation, which rapidly converged to zero as an executing computer went out of RAM memory. Since RTF is a ratio of a simulation (calculation) time to execution time (real time) for a particular task, it is important to keep it high in order to allow path planning, SLAM, robot interaction, and other robot activities inside buildings. A suggested solution is to place models through plugins connected to the world and to exploit plugins for interacting with the models. Finally, the environment was constructed using a specially written position plugin.

The latest version of Gazebo introduced an atmosphere that allows to set and use a temperature parameter in addition to previously existing lightening (attached to meshes) and underlying surface condition parameters. However, these parameters are not enough for a proper simulation of a USAR scenario. Therefore, one of our goals is to create special layers or thematic maps that will store additional environmental information, which will be available for robots via sensory input. Table 2.1 presents several examples of parameters that are associated with particular layers and play an important role in USAP environment simulation. First column contains a parameter, followed by its description and attribute layer; last column specifies sensors that could be applied for the parameter detecting and evaluating. The information about parameters was obtained via analysis of the research publications in USAR field, e.g., [34–36]. For example, the first line of Table 2.1 presents noise parameter, which may interfere with microphone arrays of the robot and thus decreases its ability to determine the location of victims. Noise belongs to sound layer and could be detected using vibration sensors or microphones. Table 2.1 presents only few parameters, while general concept of additional layers covers also light condition, pollution, communication, human victims and life organism presence, weather and surface conditions, etc.

Table 2.1 Example of some parameters that should be considered in USAR environment model

Parameter	Description	Layer	Detecting sensors
Noise	Interferes with a microphone, deteriorates the ability to determine the location of victims	Sound	Vibration sensors, microphones
Radiation	Affects human health. It must be determined. Introduces minor irregularities into sensor readings (low level). Destroys electronics (average and high levels)	Radiation	Radiation sensor (Geiger counter)
Temperature	Hints of fire and potential chemical pollution. Areas with high temperatures can destroy a robot and have low probability of alive victims' presence	Temperature	Temperature indicator or thermal camera
Smoke	In case of fires, heavy smoke may occur, which influences visual conditions for cameras and causes poisoning of alive victims	Air	Smoke detector

2.5 Pilot Protocols for Data Exchange and Robot Interaction

The disaster site management framework includes interaction protocols between robots within a single team as well as between robots of different teams. To initialize the framework with a number of pilot protocols, we analyzed standard data exchange protocols, typical tasks of robotic teams and robots' onboard sensors. Various options for wireless communication were considered, including Bluetooth, UWB, ZigBee, and Wi-fi [37]. After comparing them for average speed, range of work, a number of connected devices and power consumption, Bluetooth protocol was selected. Moreover, this is a justified selection because most robots have Wi-fi and Bluetooth modules, as well as USB slots, which could be used for communication module attaching.

Since we target to use ROS as a backbone of our framework, the output of most sensors was reduced to the types that are defined by *sensor_msgs* package. The priority was given to *LaserScan*, *Image*, and *PointCloud* types. These types will be further optimized with regard to message volume taking into account Bluetooth package payload and applying compression, archiving, splitting into several packages, and partial discarding of data. A mesh network was selected as the most suitable topology for our task since it takes into account that its devices may not be always in a static state but may be mobile as well [38].

A pilot set of commands was selected in order to expand them into formal protocols of control commands and data exchange. Table 2.2 presents several examples of the selected commands; the first column contains a command name; the second and the third columns specify a robot that may send this command and a robot that could be a recipient of the command, respectively; the last column shows parameters of the command. Figure 2.4 demonstrates a prototype of the protocol for "Follow" command with data exchange between a sender (Robot 1, on the left) and a receiver (Robot 2, on the right). After Robot 1 establishes communication with Robot 2, it sends its current coordinates to Robot 2 in a loop and verifies that Robot 2 is following it until stop signal is delivered and confirmed by the recipient. Note that at some point, the protocol allows the communicating robots to disconnect from each other for a short period of time in order to listen the network for other incoming communications.

Table 2.2 Examples of commands that could be transferred within robot teams

Command	Sender	Receiver	Parameter
Follow	Any robot	Any robot	Coordinates, speed, and acceleration limits
ShowCam	Any robot	Any robot that has a camera	Frame, repeat, period
LandOnTop	UGV/USV	UAV	Coordinates
ForwardMsg	Any robot	Any robot	Target robot, message

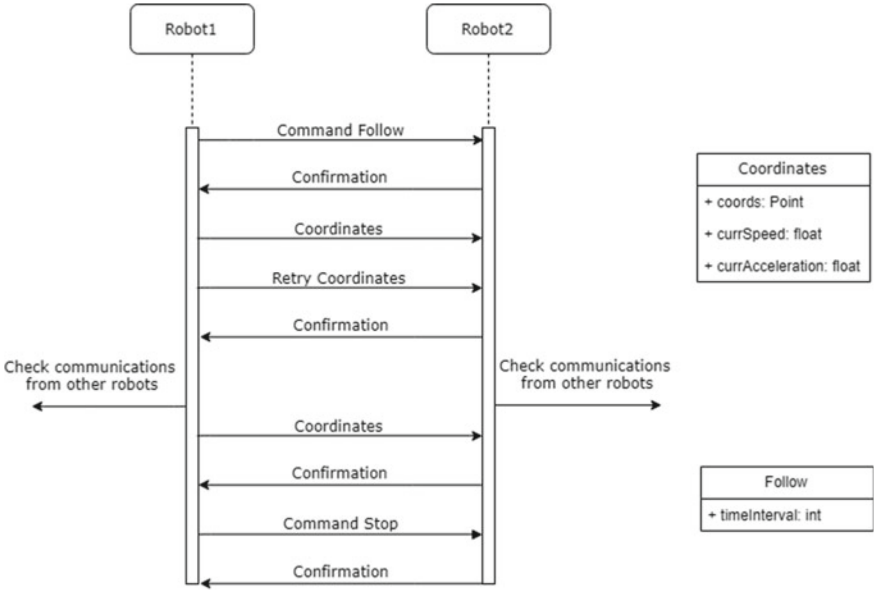

Fig. 2.4 Diagram for "Follow" command protocol

2.6 Conclusions and Future Work

Many countries around the world suffer from various natural disasters, which cause human live losses and significant economic losses. Recent developments in artificial intelligence and robotics help improving speed and quality of search and rescue operations, while simultaneously increasing the safety of involved rescue teams.

In this paper, we presented an overview of our ongoing work toward the international operation framework for a disaster site management with distributed heterogeneous robotic teams that consist of unmanned aerial, ground, surface, and underwater vehicles. The artificial intelligence-based information collection system, which is targeting to become a worldwide standard, contains interaction protocols, thematic mapping approaches, and map fusion processes. The project provides a new working framework and control strategies for heterogeneous robotic teams' cooperative behavior in sensing, monitoring, and mapping of flood and landslide disaster areas. This paper revealed concepts and examples of robot interaction protocols and system modeling within robot operating system's Gazebo environment, which serve as a backbone of a virtual microsimulator that will allow verifying ideas, concepts, and approaches toward a large-scale robotized operation framework for a disaster site management.

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