Collaborative robotic framework for emergency situations management in areas of flood and landslide disasters

Evgeni Magid[1[0000-0001-7316-5664]], Tatyana Tsoy[1[0000-0002-5715-7768]], Fumitoshi Matsuno[2[0000-0001-9685-3267]], Jackrit Suthakorn[3[0000-0003-1333-3982]] and Mikhail Svinin[4[0000-0003-2459-2250]]

[1] Laboratory of Intelligent Robotic Systems (LIRS), Intelligent Robotics Department, Institute of Information Technology and Intelligent Systems, Kazan Federal University, 35 Kremlyovskaya street, Kazan, 420008, Russia
[2] Mechanical Engineering and Science Department, Kyoto University, 3 Kyoudaikatsura, Nishigyo-ku, Kyoto 615-8540, Japan
[3]Biomedical Engineering Department, Mahidol University, 4, 999 Phuttamonthon, Salaya, 73170, Thailand
[4]Robot Dynamics and Control Laboratory, College of Information Science and Engineering, Ritsumeikan University, Noji Higashi 1-1-1, Kusatsu 525-8577, Japan
E-mail: dr.e.magid@ieee.org

Abstract. Southeast Asia region is vulnerable to extreme precipitation that increases negative impact on human lives and infrastructure caused by hydrological natural disasters. Rapid reaction measures require search and rescue activities within a stricken area. Rescue robotics application in such hazardous environments replaces human rescuers with robots and provides humans with supplementary capabilities. Information on victim whereabouts and area map is crucial for effective rescue efforts and real-time rescue management. Therefore, a development of an information systems using an artificial intelligence is required. This paper presents an outline of an international framework that will contribute to effective actions using heterogeneous robotic teams and development of information collection system for a hazardous site rescue management. A novel approach is based on expertise in urban search and rescue robotics and previous collaborative work of roboticist teams from Japan, Thailand and Russia, the countries that constantly suffer from high precipitation level and climate change consequences. The joint research targets to provide a new framework and control strategies for international robotic teams' cooperative behavior applying interaction protocols between heterogeneous robots within a team and between robots of different teams, agreements on mapping, data fusion and other collaborative features. The robotic teams consist of various types of wheeled and crawler unmanned ground vehicles, unmanned aerial vehicles, unmanned underwater vehicles and unmanned surface vehicles. These robotic teams provide the informational system with local data that are obtained by applying sensing and mapping activities from water surface, under-water, air and terrain to assemble a large collaborative map of a disaster site. The collaborative robotic framework is based on path planning and disaster area coverage algorithms, control strategies and multi-robot joint SLAM technologies for heterogeneous robot teams. For modelling and algorithms' validation Robot Operating System (ROS) and Gazebo simulator were used.

Keywords: Robotics, Information System, Urban Search and Rescue, USAR, ROS, Gazebo, Heterogeneous Robotic Teams, Interaction Protocols, SLAM

1 Introduction

Annual natural disasters turned into critical issues at the Emergency Situation Institutes' agenda of East and Southeast countries. Particularly hydrological natural disasters negatively affect human lives and cause considerable economic losses due to geographical peculiarities and climate changes. To manage the damage caused by the hazards throughout large areas it is crucial to develop and apply fast-growing technologies that would assist stakeholders. Moreover, saving human lives is a top priority task in emergency situations and therefore rapid reaction measures based on situation awareness are irreplaceable. Robotic technologies application becoming actual in forecastable disasters, climate and pandemic unpredictable circumstances [1].

Rescue robotics specializes in designing and developing robots for implementing in extreme environments that are life-threatening for human, e.g., searching victims in wild areas and labyrinths of tunnels, exploring volcano craters and pipe networks, running reconnaissance tasks in high temperature and poisonous environments under nuclear or chemical contamination, replacing human teams in scouting and mine clearing etc. Rescue robotics solutions improve human safety by supplementing rescuers in search missions or replacing them when applying limited human capacities are not enough for a successful task performance. Urban search and rescue (USAR) field presents application of rescue robots in hazard and extreme environments where survivors could detected with a higher speed and probability by robotic technologies [2].

Stakeholder institutes upgrade measures and increase emergency preparedness by refining protocols of rescue actions and using advanced equipment to cope with a disaster. However, identifying victims and conducting missions in hard to access areas that endanger human life still remain a critical issue when natural disaster occur in urban area for the reason that post-disaster extreme environment creates a large number of debris-type obstacles. Taking rapid and effective measures depends on timing when rescue center headquarters possess correct information on a situation. However, when the information on the current situation is untimely and has a poor quality it scales down speed and progress of a rescue operation [3, 4]. Therefore, the development of an information system (IS) for managing a process of mitigating consequences of natural disasters that permits increasing the efficiency and speed of taking care of the post-disaster aftermath is one of the high-priority tasks facing the scientific community today.

Considering increasing number of accidents occurred due to hydrological hazards, employing advanced technologies for global data collection, Geological Information

System (GIS), satellites and other equipment is required. To assist in creating a map of a large-scale post-disaster hazard area we proposed robotizing data collection and automating data management processes. For managing disaster in real-time, the IS should effectively organize a communication and information exchange, and employ capabilities of AI-based decision making systems in combination with mobile robots [5, 6].

Our international project was launched in 2019 by teams from Russia, Japan and Thailand. The project develops a new framework and strategies for managing a cooperative behavior of heterogeneous robots while performing tasks of information collecting, monitoring and mapping large-scale disaster zones, including terrestrial and underwater areas of a hydrological disaster site, e.g., a flood site or/and landslide site that are caused by an extreme precipitation level [31]. Within the project, new control strategies, interfaces and communication protocols were tested in Matlab, Unity, and Gazebo simulations, and will be further verified in field experiments [32]. At a lower level of the project hierarchy, new path planning algorithms for efficient coverage of a post-disaster unstructured environment, autonomous return of robots in case of communication loss and other algorithms were developed. Thailand team concentrates on development of robots' hardware for landslide conditions in order to provide a new class of mobile vehicles. Japanese team develops a macro simulator based on GIS and GUI, deals with practical issues of control strategy for monitoring a dynamically changing flood area by using a group of unmanned aerial vehicles (UAV), decentralized navigation for a group of unmanned ground vehicles (UGV) and UAVs, and others.

Fig.1. Principles of the proposed international framework.

A joint goal of the project is to develop and verify a framework for post-disaster site management by applying distributed heterogeneous UAVs, UGVs, unmanned underwater vehicles (UUV), and unmanned surface vehicles (USV) groups (Fig.1). Within this framework heterogeneous robotic teams generate a large collaborative thematic map of a post-disaster site, which targets to assist in decreasing time of a decision-making process, taking rapid reaction measures, increasing a number of survivors and general safety of human rescuers.

2 Robot Applications in Urban Search and Rescue

Rescue robotic technologies used in USAR have significantly increased general robotic technology capabilities, have been upgraded in design, and increased in variety since their initial application in real world rescue operations in 2001 [7, 8]. Nonetheless the progress in rescue robotics extends with increase of autonomy level, to the best of our knowledge, yet no existing robot is capable to accomplish a rescue task in a completely independent manner without a full or a part-time human guidance or an intervention. Considering this fact, a part of the rescue process should be performed by joint human-robot teams [9], with a clear preliminary roles' distribution and delegation of dangerous and challenging for a human tasks to robotic assistants. In particular, such tasks include:

Reconnaissance and mapping. Reconnaissance and mapping are used in wide-area search and rescue scenarios to assess a situation on the ground before a rescue operation launch [10, 11]. A swarm (or a team) of homogeneous or heterogeneous UAVs may accomplish this task conducting an automated scouting and mapping of large areas, saving time and collecting data that could assist in the situation awareness and shift to a decision-making stage [12, 13]. UGVs could also be used for reconnaissance and mapping as they might contribute in creating more accurate maps, however they lack the ability to cover vast areas [14]. Methods using UAV and UGV swarm applications necessitate an implementation of appropriate for a particular task and environmental conditions collaborative and coverage algorithms [15, 16]. UUVs and USVs could be employed to support or replace UAVs in maritime rescue scenarios.

Debris penetration. Small sized mobile UGVs could complement a human or replace a rescue canine by penetrating debris or narrow spaces deeper while searching for survivors [17]. In our project we apply a number of various types of UGVs for debris penetration tasks, including Servosila Engineer crawler robot [10] (Fig. 2).

Structure inspection. UAVs and UGVs could be used for inspection of damaged constructions by employing multiple on-board sensors combined with data fusion algorithms that allow to receive a significantly more complete and accurate building view comparing to human capabilities [34]. UUVs and USVs should be applied when a construction or its supporting surface have sections that are located under water [35, 36].

Debris removal. This procedure in USAR missions differs from removal operations in civil construction or demolition. Personal involved in debris removal should always be aware of a possibility to encounter heavily buried victims who might be out of sight or unconscious at the time of the operation. Moreover, there is a high risk of unexpected collapses of visually formed yet unstable ruins and debris during removal activities. Exoskeletons and powerful mobile manipulators may be used to remove debris, but these types of robots are still in the early stages of development [18].

Victim Search. Timing is crucial in discovering victims after a disaster occurred, because victim survival rates drop rapidly. For example, after two days under a collapsed house, a human's chances of survival drop to less than 40%, and after five days under a rubble, a chance of extracting the person alive becomes extremely low. To be effective in a search for victims, a robot should compliment the performance of a human rescuer or a specially trained rescue dog [19].

Telepresence. This robot feature allows for faster inter-team communications for rescue team members inside rubble, as well as a possibility of providing a psychological or medical assistance to a discovered victim while a rescue team prepares the victim extraction [20].

Hazmat situations. “Hazmat” refers to hazardous materials. Frequently during anthropogenic disasters, a rescue site might get contaminated by nuclear or chemical agents. In such situations, human rescuers are unable to operate effectively on-site, and the planning and aftermath phases of a rescue operation take a longer time. Such hazmat catastrophes as the Chernobyl nuclear power plant and the Fukushima Dai Ichi nuclear disasters could have been handled more effectively if robotic technologies readiness had been better developed and used right after the disaster [21]. Some of the applications listed above are similar to military or police robot usage, but many of them are specific only for rescue purposes. Robots that were designed for other purposes are modified for employment in search and rescue operations. Usually, during a robot assisted rescue, a rescue robot is deployed on site for an initial exploration, and a human tele-operator remotely controls the robot from a secure location outside of the site using a wireless communication link [22].

Fig.2. Servosila Engineer rescue robot in a random step environment (RSE, [33]), at Laboratory of Intelligent Robotic Systems (LIRS), Kazan Federal University.

3 Collaborative Robotic Framework

Rapid measures of a response to a disaster comprise a number of challenges: a large-scale site for operation, limited human and equipment resources, unreachable and life hazardous areas to inspect, weather and post-disaster conditions of on-site infrastructure etc. Frequently attempts to solve one problem immediately create obstacles for finding a solution of another. Therefore a success of the disaster management as an overall process is a challenging and resource consuming task.

For effective operations and reduced casualties, rescue operations necessitate a high degree of situation awareness among disaster management stakeholders aiming at reducing human loses. One of the main milestones in the outcome of an emergency response operation is full and correct incoming data. An obvious way to improve the emergency management system is the automation of management processes and robotization of data collection. Today in most cases robotic technologies are used via a teleoperation for information gathering and in a narrow number of applications in short-term missions at a disaster site [33]. At the same time, much attention is paid to the development of situational centers, which, as a rule, are equipped to simultaneously track a huge amount of data, receive and analyze operational information, manage disaster relief processes and coordinate search and rescue operations [5, 6]. An example of a prototype IS is the WIPER system (Wireless Phone Based Emergency Response System, [29]), developed and implemented using the Dynamic Data Driven Application Systems (DDDAS, [30]) 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 employees of disaster prevention centers [4]. WIPER-like decision systems can also be used to study water dynamics, simulate forest fires and coastal disasters [29].

There are yet no common definitions of disaster management cycle stages and they vary depending on a country and institutions. Robin Murphy in [27] defined a four-stage disaster management cycle, which includes the following activities:

- rescue activities during a disaster or in an immediate aftermath;
- reconstruction of property and infrastructure, support for rebuilding social, economic, and health aspects of affected communities;
- future disasters or mitigation of their effects;
- ongoing activities.

Thorstensson et.al. in [28] proposed a Detect-Assess-Decide-Act (DADA) cycle, which describes internal information handling process in a command team and consists of the four following steps:

1. **D**etection of an evolving situation using data from an operation area;
2. **A**ssessment of the situation in order to analyze its probable future development and expected consequences of alternative actions;
3. **D**ecisions based on data analysis;
4. **A**ctions with respect to the decisions that have been taken.

Our project aims to establish and incorporate an IS for disaster management based on a theoretical abstract scheme for managing a robotic search in a disaster area [9] and the broad experience of our international team, aiming at framework that will contribute to effective actions using heterogeneous robotic teams and development of information collection system for a hazardous site rescue management. Under the DADA paradigm our proposed framework corresponds to the first step when a full scale and accurate information on the situation is required in order to proceed toward the next steps. Moreover, recent success in AI domain allows delegating some tasks of the second and the third steps to intelligent assistive systems, while heterogeneous groups of robots could be broadly involved in the fourth step. The proposed IS targets to collect data using distributed heterogeneous groups of robots, including various types of UAVs, UGVs, USVs and UUVs. Separate maps, built by distributed groups of robots, need to be combined into a single multi-layered thematic map of the disaster zone, which could help search and rescue teams to speed up the evacuation of survivors. The collected data allows assessing a level of danger and a probability of a further destruction of buildings and environmental pollution. Such situation awareness in turn significantly increases chances of rescuing survivors and increases the safety of rescuers during the search operations.

At a higher level of the system hierarchy, collected by heterogeneous robotic teams data should be fused and unified in a way that it could be further efficiently analyzed both by AI-powered assistance system and by human experts in order to allow proceeding to the second and the third steps of the DADA. To tackle these issues during a research stage we develop a GIS-macro simulator that includes graphical user interfaces for monitoring a disaster area by a human operator and allows updating and processing information about the location of the incident [37]. The practical assessment of the macro simulator will be carried out in the framework of an artificially created natural disaster conditions with the participation of citizens of Kochi prefecture (Japan) and in agreement with the prefecture government.

At a lower level of the system hierarchy algorithms for simultaneous localization and mapping (SLAM) for a heterogeneous group of robots in a natural disaster, path planning algorithms to effectively cover areas in an unstructured environment after a natural disaster and mechanisms for autonomous return of robots in case of loss of communication are required. These new control strategies, interfaces, protocols, robot models, algorithms and software developed within the framework of the project, after a thorough testing within simulations should be carefully validated in the field experiments. A selected number of the developed low-level approaches are briefly presented in the next section.

4 Heterogeneous robotic teams

After several decades, applications of heterogeneous robotic groups are still in the early stage of development, even though there is a significant progress in a variety of their potential employment areas. Today a broad diversity of robots allows assembling heterogeneous robot teams for different purposes, including search and rescue tasks.

Operating multiagent heterogeneous groups of robots for a particular mission is a challenging task. In [7] the authors summarized opinions of several top experts in USAR field in order to conclude desired requirements for a search and rescue robotic platform. The proposed list of requirements includes ease of use, logistical concerns, capabilities and robustness, robot’s applicability as a tool, situational awareness and remote sensing, levels of autonomy and data management. Unfortunately, nowadays

most of existing commercially available robots do not fully satisfy these requirements.
Yet, further expending of the list is necessary in order to define desired requirements for a swarm or for a team of robots.

Each of the three teams uses their own robots to simulate a disaster scenario operation within a common platform under development. The robotic teams include UAVs (quadcopters, e.g., Russian team uses PX4-LIRS, Fig.3, left), tracked (e.g., Servosila Engineer, Fig.2) and wheeled (e.g., TIAGo Base, Fig.3, left, and Avrora Unior Fig.3, right) UGVs, USVs, UUVs (robotic snakes). Despite the fact that for mapping tasks all teams use SLAM-based approaches, in order to implement this task various modifications of SLAM algorithms are required since a particular algorithm selection is performed in accordance with sensory and locomotion capabilities of robots, both as individual units and as part of its team. Semi-autonomous teleoperation systems allow delegating some low level tasks to control system of a robot (e.g., communication failure or autonomous return [22]) while keeping a human operator in the loop for all important decisions. To allow an efficient control, improved graphical user interfaces, in addition to standard locomotion control and direct sensory input display functionality, are required to provide cognitive data that are derived from raw sensory input (e.g., a precise description of the robot posture in a form of its 3D model) and to support operator's requests for more detailed data that describe current state of each joint and servo [38].

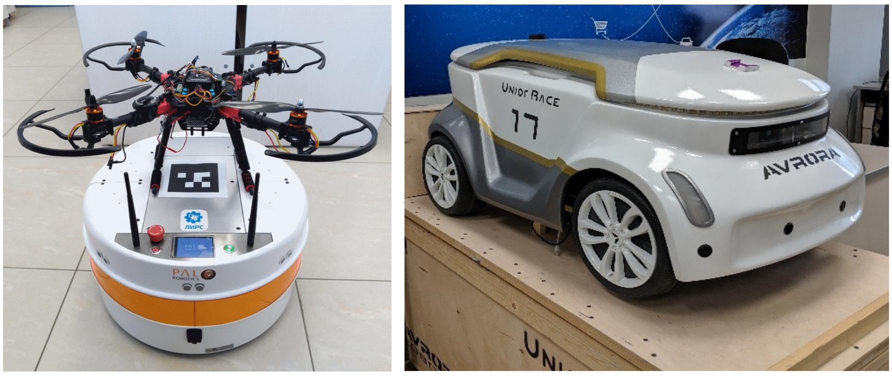

Fig.3. TIAGo Base UGV with ArUco marker and PX4-LIRS UAV on its top (left) and Avrora Unior UGV (right), Laboratory of Intelligent Robotic Systems (LIRS), Kazan Federal University.

Employment of multiple types and models of rescue robots allow maximizing the variety of onboard sensors available for a rescue mission, which enable capturing and tracking color, shape, texture, sound, heat emission and temperature, radioactive and chemical pollution, humidity, wind direction, smoke and other multimodal data, each forming a particular type of a thematic map, that reflects the corresponding data.

These in turn allow creating a large-scale multi-layer thematic map of the disaster zone, combining separate thematic maps obtained by individual robots [2]. Thematic maps include not only low-level sensory data and their analysis, but also derived information, e.g., dangerous locations, unstable structures, detected survivors, animals, available for rescue team entry voids etc.

During USAR missions, it is critical that robots within heterogeneous teams could communicate not solely with their teleoperators [23], but also with one another [24, 25]. Two main challenges are interaction protocols and communication. To develop communication protocols for our framework, standard data exchange protocols and typical tasks that require several robots to work as a team were analysed. Comparing such options as Bluetooth, Wi-Fi, ZigBee, and UWB [39] with regard to their average speed, operating range, power consumption, and a limitations on a number of connected devices, the Bluetooth protocol was chosen. This selection seems optimal because mobile robots are usually equipped with onboard Wi-Fi and Bluetooth modules, which are commercially available in a large range of options, including USB-connected external plug-and-play modules.

Robot Operating System (ROS) serves as a backbone of the framework, which allows unifying sensory data collection and representation within the *sensor_msgs* package conventions. Three types of data were selected as prioritized (*LaserScan*, *Image*, and *PointCloud*) and adapted for Bluetooth package payload capabilities involving compression, splitting into packages, and partial discarding of data. For robotic teams' network a mesh network was selected since it allows for mobile and static devices [40]. A pilot set of commands was selected in order to expand them into formal protocols of control commands and data exchange was presented in more details in our previous work [10]. The performance of pilot set of protocols was evaluated in the Gazebo simulator, using an existing model of TIAGo Base and our own models of Servosila Engineer, PX4-LIRS UAV, and Avrora Unior. Moreover, the protocols were further validated in a joint task of constructing an indoor environment map by the real TIAGo Base and Servosila Engineer UGVs.

5 Conclusions

Natural disasters annually take human lives and cause economic damage and losses. Recent advancements in robotics have increased the productivity of search and rescue operations while also the safety of rescue teams that are involved in mitigation with a disaster. This paper overviews typical tasks in USAR scenario and our continuing work on the implementation of the international framework for a disaster site management using heterogeneous robotic teams comprised of UAVs, UGVs, UUV and USVs. The aim of the project is to develop a new practical framework and control methods for multiagent heterogeneous robotic teams communicating disaster zones suffered from flood and landslide.

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