Report of the Korea-US/US-Korea Joint Workshop on

“Toward the Next Generation of Robotic Humanitarian Assistance and Disaster Relief: Fundamental Enabling Technologies”

Executive Summary

Robotic technologies are expected to raise the efficacy of humanitarian assistance and disaster relief to a new level beyond the current practice. This is especially so for the first responders to carry out time critical missions, such as search, rescue, hazard warning and first-hand damage control, under the severe deficiency in accessibility, in-situ information, infrastructural support and safety assessment. However, the application of robotic technologies to humanitarian assistance and disaster relief tasks has not been as successful as anticipated to date. On the contrary, a large gap has been found to exist between what current robotic technologies can offer and the harsh demands of real disaster environments. A breakthrough is seen imperative to have robotic technologies being effectively integrated into real-world relief operations. It includes, but not limited to, a radical improvement in the effectiveness, robustness, endurance and survivability of disaster response robots, a drastic upgrade in the capability of human-robot interaction, especially, for enabling not only immersive situational awareness but also mobile and power tele-manipulation with a full cognitive capacity of human operators, and a major enhancement in the performance of sensing, recognition and modeling for real-time assessment of, spatiotemporally varying, theater-wide and location-specific disaster situations.

Recognizing the need to identify the fundamental enabling technologies to be developed for such a breakthrough, the US-Korea/Korea-US joint workshop, “Toward the Next Generation of Robotic Humanitarian Assistance and Disaster Relief: Fundamental Enabling Technologies,” was organized under the sponsorship of Ministry of Trade, Industry and Energy (MOTIE), Korea and Department of Defense (DoD), US. The workshop was held in Incheon, Korea, Oct. 31 - Nov 2, with 31 concerned researchers from the US and South Korea participated in two parts of workshop activities: the presentation of selected white papers with open/panel discussions and the group-wise summarization and reporting of the fundamental issues to be addressed. For the latter, the participants were divided into three working groups according to the key areas to investigate: 1) novel platforms for search and rescue, 2) advanced human-robot interaction (HRI) for command and control, and 3) sensing, recognition and modeling for monitoring and planning.

This report represents an integrative summary of the workshop, based largely on the reports from three working groups. The report aims at addressing current problems and technical challenges to overcome and defining the fundamental enabling technologies necessary for further development. The fundamental enabling technologies identified in this report will serve as the basis for developing a jointly funded program for US-Korea/Korea-US collaborative research projects sponsored by DoD/US and MOTIE/Korea. In what follows, the fundamental enabling technologies thus identified as necessary for further development are briefly summarized:

1) Novel Platforms for Search and Rescue

- To radically evolve and revolutionize the effectiveness, dependability, endurance, performance and survivability of robots for disaster response toward higher technology

readiness levels.

- To upgrade the dependability in highly unstructured task environments by being able to adapt to large environmental variations and to be gracefully degraded and/or recover from unexpected disturbances, adverse weather conditions and communication failures.
- To develop more effective platforms for terrestrial, aerial and/or marine missions that broaden capabilities for disaster response and/or recovery with sufficient operational range and duration, reliability, durability, transportability, easy-maintenance and affordability.

2) Advanced Human-Robot Interaction (HRI) for Command and Control

- To endow robotic agents with a new capability of tele-manipulation, including whole-body tele-manipulation, especially, for mobile and power manipulation, utilizing a full cognitive capacity of human operators.
- To establish multi-modal perceptual immersion with visual, auditory, olfactory and kinesthetic feedbacks for a high fidelity of multi-scale and multi-modal situational awareness.

3) Sensing, Recognition and Modeling for Monitoring and Planning

- To have the capability of real-time collection of multi-resolution and multi-modal, spatiotemporally varying, data on disaster sites under extreme disturbance and ill-conditioned accessibility, e.g., for locating and rescuing victims, evaluating infrastructural damages, identifying geological changes, and monitoring the release of hazardous chemicals, biological and nuclear materials, etc.
- To provide site commanders, relief workers and/or assistive robots with theater-wide intelligence and location-specific information in real-time, whenever necessary for their operations associated with monitoring, planning and execution, by integrating and modeling the collected data.

Organizing Co-Chairs

1. Background

As robotic technologies continue to advance, a high level of expectation arises for robots to serve as pivotal facilitators toward the next generation of humanitarian assistance and disaster relief systems. In the near future, robots with superior adaptability, intelligence and autonomy are expected to team with human relief workers to prevent and relieve potential consequences from both natural and man-made disasters. Rapidly deployable yet highly effective robotic systems may become available to support a broader scope of relief activities in response to, but not limited to, such disasters as earthquakes, volcanic eruptions, floods and tsunamis, storms, nuclear contaminations, wild and urban fires, bio--chemical emergencies, structural collapses, shipwrecks, oil spills, droughts and famines, mining disasters, epidemics, mine explosions, et. al. It is desirable that these robotic missions be designed to assist, starting from detection of early warning signs to intervention and recovery once the event has transpired. These systems are critically needed as first responders in harsh, dangerous and unreachable environments in addition to promoting the safety and quality of service of human relief workers.

Past attempts at utilizing robots to support humanitarian assistance and disaster relief for major disasters such as the Deepwater Horizon oil spill in the Gulf of Mexico and the Fukushima Daiichi nuclear disaster have not been as successful as anticipated in achieving their objectives. One fundamental reason behind such disappointment is due to the large gap between what current robotic technologies can offer and the harsh demands of disaster environments. In particular, robots deployed at the disaster sites often exhibit brittleness, exposing deficiencies in robustness and adaptability in their performance as well as in user acceptability. In order to overcome these deficiencies and enable successful robotic missions in the near future, it is imperative to identify existing gaps and shortcomings in robotic systems and promote fundamental breakthroughs in key technological areas to bridge those gaps.

2. Objective

The objective of this report is to identify a list of fundamental enabling technologies necessary for bridging the existing gaps between current robotic systems and the demanding realities at disaster sites. The fundamental enabling technologies identified in this report will serve as the basis for developing a jointly funded program for US-Korea/Korea-US collaborative research projects sponsored by DoD/US and MOTIE/Korea.

The emphasis is given to addressing key fundamental scientific and technical issues to solve for making breakthroughs in real--world deployment. More specifically, the issues to be emphasized in this report include, but are not limited to:

- In-situ adaptability to wide environmental variations in terms of morphology, mobility, perception, manipulation, decision-making, and interaction with relief workers, including self-repair and reconfiguration.
- Expanded capacity of intelligence and autonomy to be shared with operators, including shared perception and understanding as well as collaborative teamwork with human operators.
- Advances in perception, information management, reasoning and understanding, as well as in the dexterity of mobility and manipulation for integrated contextual decision-making and decision support.
- Ensuring on-site robustness and adaptability in terms of tools, sensor suites, methodologies and platforms with enhanced rapidity, responsiveness, efficiency and ease of use.
- Scalable teaming of autonomous systems and human workers with shared mission intent and execution.

The solutions for the fundamental scientific and technical issues developed are expected to impact on enabling the following real-world capabilities of robotic applications to humanitarian and disaster relief:

- Surveillance and reconnaissance for disaster prevention and early detection.
- Perception and modeling for improved situational awareness.
- Search and rescue support for post-disaster and emergency relief operations.
- Sliding autonomy for operator control and human-robot interaction.
- Rapid delivery of life saving supplies and equipment to victims.
- Evacuation assistance from remote locations.

3. Research Areas

To explore what should be done more beyond the current state-of-the-art in robotic applications to humanitarian assistance and disaster relief, this RFP is seeking for proposals dealing with the technical challenges and fundamental issues associated with the following three research themes:

1) **Novel platforms for search and rescue.**
2) **Advanced human--robot interaction (HRI) for command and control.**
3) **Sensing, recognition and modeling for monitoring and planning**.

The motivations, challenges, and fundamental issues to be addressed in these three areas are summarized in the following sections.

3.1 Novel Platforms for Search and Rescue

3.1.1 Motivation

First generation robot platforms for disaster response were ground based ones tele-operated mainly to give incident commanders situational awareness. Equipped with cameras, wheeled or tracked platforms would survey damage. During the last decade, the inventory of robot platforms has been extended to include those that can crawl or climb areas hard to access, fly in and around structures, and swim in flooded and underwater regions. Today's terrestrial, aerial and marine robot platforms have demonstrated missions like localizing causalities, clearing debris, breaching walls and operating tools. Unmanned aerial vehicles quickly survey wide disaster areas, remotely operated underwater vehicles repair leakage of subsea oil plants, and unmanned ground vehicles work in contaminated areas of damaged nuclear power plants. Two decades ago, unmanned aerial vehicles could gather information remotely from sky up. At present, they can approach to structures of interest in close proximity, providing detailed visual inspection for maintenance, and can even enter damaged buildings through narrow entrance for searching victims. Moreover, unmanned ground vehicles with heightened autonomy and intelligence can integrate gathered information with measured 3D information into GIS as a powerful support for human decision, while reducing the physical load of responders. At this pace of development, the potential for robots to revolutionize the resilience to disasters is profound. For this reason, specialists predict that robotics will become an essential tool for preparedness, response and recovery in the coming decade. Disasters are chronic but robots that augment mitigation and accelerate recovery are not only realizable but globally urgent and important.

However, the record of robot platforms to disasters in the last decade shows gaps that have be filled in order to materialize more effective, reliable and extended usage of robotic solutions. Current terrestrial, aerial and marine platforms are still too limited and fragile for practical deployment. Further advancement in the performance of mobility, manipulation, sensing, recognition, situation awareness, communication, human interface, autonomy, as well as compliance to disaster conditions including chemical, radiation, temperature and/or explosion hardening has to be sufficient in the context of an overall system consisting of robots, relief workers and organizations.

3.1.2 Challenges

There is no comprehensive ontology listing the types of disasters and incidents, but obvious ones include earthquakes, floods, fires, hurricanes, tornadoes, tsunamis, and winter storms. Others are accidents or terrorism involving man-made facilities such as buildings, bridges, or tunnel collapses, chemical or radiological waste spills, and train, ship or airplane wrecks. Each disasters and incident is unique but all pose challenging problems that occur at several exceptionally stressful scales simultaneously including:

- Time: Disaster management encompasses preparedness and prevention (past), real-time response (present), and cleanup/recovery (future). Events can be discrete and short lived like tornadoes or long-term, as with nuclear accidents.
- Space: Damage can be highly localized, like bridge collapses, or spread over states in for example, hurricanes or earthquakes. Economic impacts can be national or even global.
- Stakeholders: Citizens, governments (municipal, county, state, and federal), industry, and non-governmental organizations all play roles.
- Data: Information is heterogeneous, takes many forms and content, comes from different sources, arrives in different volumes at different times, contains different levels of uncertainties, and exhibits different priorities for different phases of the disaster.

Nonetheless, robot platforms need to be flexible enough to perform broadly, endure, and survive in the face of uncertainty. Fundamental research and designs for robotic platforms to serve increased roles in disaster response and recovery are mandatory. Envisioned missions include, but not limited to: breaching, shoring, and extraction for tasks like protection, patrolling, building entry and/or room clearing; reconnaissance for tasks like damage assessment, inspection, searching and/or mapping; and unit support for tasks like supply distribution, communication relays, clearing and sorting debris, and/or damage control.

3.1.3 Fundamental Issues

There is profound need to radically improve, evolve and revolutionize the effectiveness, dependability, endurance, performance and survivability of robot platforms for disaster response toward higher technology readiness levels. In particular, a drastic increase in their capabilities of assisting responders physically with power mobile manipulation and mentally with integrated situational awareness, while adapting to large environmental variations, handling unexpected and harsh situations, recovering from failures, as well as executing a sufficient operational range and duration are critical. Furthermore, robustness in highly unstructured task environments by handling, recovering and/or being gracefully degraded from, unexpected disturbance, adverse weather and communication failure is required. In addition, platforms of low maintenance requirement that are reliable, durable, affordable and easily transportable are also in necessity. Mechanisms, actuators, algorithms and/or methods synthesizing into more effective platforms that broaden capabilities for disaster response and/or recovery must be of fundamental research objectives, such that platforms with enabling components will thus traverse, fly and/or swim for successful terrestrial, aerial and/or marine missions.

3.2 Advanced Human-Robot Interaction for Command and Control

3.2.1 Motivation

Robotic assistance to disaster relief requires advanced human robot interaction for agile and reliable mobile manipulation in harsh and unstructured disaster environments. The nature of disaster response tasks involves large situational variations, uncertainties, improvisations, time-dependencies and their combinations that require high adaptability, versatility and robustness in a large scale of disaster sites. However, current robotic technologies are yet to meet the critical engineering requirements of disaster response tasks as they are vulnerable to highly unstructured nature of, as well as a large scale of, operational space. In general, the current robotic technologies are lacking intelligence sufficient for enabling a certain level of autonomy required for disaster relief operations. They include:

- High-level reasoning in disaster situations with semantic/symbolic understanding of environments, including reasoning with a set of "common sense."
- Skills in real-time planning and control for optimal and stable dynamic performance of robots interacting with highly unstructured environments and under unexpected situations.

As such, transferring the intelligence and skills of a human operator to remote robotic agents so as to combine their strengths becomes essential.

3.2.2 Challenges

The advanced human-robot interaction for command and control faces the following challenges:

- To overcome limitations in situational awareness for operators. They include
  - Limitations in the bandwidth and network degradation for delivering sensory and environmental data.
  - Ineffectiveness in combining multi-modalities of sensory feedbacks for the given tasks in both macro and micro control point of view.
  - Difficulties in composing multi-modalities of supervisory control under the given network bandwidth.
- Lack of standardized evaluation criteria for teleoperation and human robot interaction for proper assessment and quantification of various teleoperation methodologies.
  - Quantification of shared autonomy
  - Quantification of human factors
  - Quantify cognitive workload and physiological state
  - Quantify performance of combined robot and human system
- Limits in needed functionality

- Limited stability for contact tasks
- Balance issues for dynamic tasks
- Lack of perceptual immersions
- Need for enhanced locomotion and mobility

3.2.3 Fundamental Issues

One major issue is the need to enhance the dynamic mobile manipulation capability of robotic agents in disasters utilizing the full cognitive capabilities of their human teammates. These situations require mobile and power manipulation under agile locomotion and environmental contact that is essential for rapid and reliable disaster response. Further improvements are required for ensuring stability under contact and balance under dynamic and power interaction, including whole body teleoperation. The establishment of multi-modal perceptual immersion with visual, auditory, olfactory and kinesthetic feedbacks as well as enhancing efficiency in control and training under high-level of command complexity is also critical.

3.3 Sensing, Recognition and Modeling for Monitoring and Planning

3.3.1 Motivation

To enable robotic facilitation of humanitarian assistance and disaster relief, the following broad categories of robotic assistance to disaster relief are defined:

> *Category One*: Robotic technologies that allow first responders and site commanders to offload important, but not necessarily time critical tasks, to robotic systems so that human first responders are more free to address immediate critical needs. Examples of such tasks include, but are not limited to: perimeter quick sweeps, area clearing; cleanup, road clearing, material handling; delivery and logistics; and establishment of critical infrastructure: e.g. communication networks, smart auto deploying structures, etc. under realistic yet benign and adverse environmental conditions such as poor weather, darkness, etc.

> *Category Two*: Robotic technologies that provide first responders and site commanders with augmented capabilities that increase their abilities to directly engage emergency situations that would otherwise be too dangerous for human intervention or of spatial or time scales too large or too small for direct human understanding and/or manipulation. Examples of technologies for augmented human capabilities include, but are not limited to, whole-theater intelligence gathering and knowledge inference, repairs of breeches causing active hazardous releases, ingress, intelligence gathering and inference of knowledge in hazardous environments such as contaminated, burning and submerged structures, etc. and/or in sub-human scale environments such as rubble fields, collapsed buildings, etc.

The motivation is to design technologies that exist at the intersection of the state-of-the-art feasibility and compatibility with the specific needs of first responders and incident commanders identified. Especially, the goal is to explicitly address how this intersection is achieved in realistic natural and/or man-made disasters.

3.3.2 Challenges

With the above broad categories of robotic assistance to disaster relief, the challenges involved in sensing, recognition and modeling for monitoring and planning are described as follows:

Category One

- Perimeter quick sweeps and periodic reassessment
- Area clearing
- Community requested quick checks for unaccounted persons
- Removal of debris, downed electrical wires, and road clearing
- Decontamination of areas and/or equipment
- Assembly of temporary structures (shelters or supports for compromised structures)
- On-site distribution of materials and supplies to responders
- On-site distribution of materials and supplies to members of the public sheltering in place
- Theater-wide delivery of materials and supplies to responders
- Theater-wide delivery of materials and supplies to members of the public sheltering in place
- Automated establishment of communications infrastructure
- Automated evacuation of casualties

Category Two

- Theater-wide intelligence gathering and knowledge inference at large spatial or temporal scales
- Mitigation and repair of hazardous releases
- Intelligence gathering and knowledge inference in areas too dangerous for direct human access
  - Areas suffering from chemical, biological, and/or nuclear contamination
  - Areas submerged, near collapse, and/or in flames.
- Intelligence gathering and knowledge inference in areas too small for humans to access or on temporal scales too short to be easily observed.

3.3.3 Fundamental Issues

It is essential for site commanders, relief workers and/or assistive robots to be able to assess in real-time the theater-wide intelligence and the location-specific information whenever necessary for their monitoring, planning and executing of relief operations, while coping with a large scale of spatiotemporally varying disaster situations. To this end, one fundamental issue to solve is how to collect a large scale of multi-resolution and multi-modal, spatiotemporally varying, data on disaster sites in real-time under extreme disturbance and ill-conditioned accessibility. The other fundamental issue to address is how to effectively integrate and model the collected data into the theater-wide intelligence and the location-specific information in such a way that they can be provided to site commanders, relief workers and/or assistive robots whenever necessary for their locating and rescuing victims, evaluating infrastructural damages, identifying geological changes, monitoring the release of hazardous chemical, biological and nuclear materials, delivering relief supplies, etc.

4. Example Technologies and Technical Capabilities

This section exemplifies technologies and technical capabilities necessary for tackling the technical challenges and fundamental issues defined above for the three research concentration areas. Note that the list introduced here represents only some of technical capabilities and approaches shown as examples, but may not necessarily imply prioritized item.

4.1 Novel Platforms for Search and Rescue

Technologies and technical capabilities of interest in the area of novel platform for search and rescue include, but are not limited to:

- Platforms designed, possibly with reconfigurable architectures, to adapt to widely varying and uncertain task environments in a highly unstructured disaster site, as well as to cope with many unexpected situations that could rise in disaster scenarios.
- Platforms with the capability of recovering from failures and faults in locomotion and manipulation during relief operations toward maximizing operational dependability.
- Extending serviceability by exploring the capability of mobile and power manipulation, including shoring or supporting of damaged structures, rapid and safe rubble removal, breaching, breaking through doors or walls to reach workspace or trapped victims, and rapid and low cost transportation of humanitarian supplies for safe search and rescue.
- Extending the length of operation based on efficient power management, for example, with energy storage and release mechanism in legs.
- A robot system that utilizes found materials (e.g. rubble) to shore damaged buildings, or create shelters and other useful structures. Hardware must include sensors to scan materials with ability to determine the important material properties of found materials.
- Unmanned Aerial Vehicle (UAV) or Drone that can be operational under strong wind and gust with increased endurance and reduced noise. For example, stable multi-step tilting of multi-rotor wings for overcoming strong wind and gust, endurance with novel wing morphology for drag reduction and efficient power management for endurance, efficient thrust with minimal number of rotors, etc.
- Maximizing the mobility of Unmanned Underwater Vehicles (UUV) under strong current and/or turbulence by maximizing thrust performance under energy limitations, minimizing underwater drag with full loadings and maximizing sensor stability while keeping the set motion.
- Precision docking and undocking capabilities with GPS/DGPS, ultrasonic sensors and mechanical locking systems for collaborative missions between UAV and Unmanned Ground Vehicle (UGV) as well as between UAV and Unmanned Surface Vehicle (USV).
- Extending mobility based on reconfigurable and/or multi--modal means of

movement, for example, jumping assisted by flapping flight, rotating shins for stair climbing and stepping over high doorsills, etc.

4.2 Advanced Human-Robot Interaction for Command and Control

Technologies and technical capabilities of interest in the area of advanced human-robot interaction for command and control include, but are not limited to:

- Enhancing mobile and power manipulation capability of robotic agents in disaster situation, focusing on high force manipulation tasks involving contacts, and balancing of the platform via advancement of human-robot interaction. Examples include manipulation or lifting of heavy objects, excavating, valve operation, etc. with the use of tools.
- Interaction of disaster relief workers with a team of cooperating robots in such a way as to overcome ineffectiveness in combining multi-modalities of sensory feedbacks for the given tasks in both macro and micro control point of view and difficulties in composing multi-modalities of supervisory control under the given network bandwidth.
- Multi-modal tele-presence, possibly, with wearable devices, to establish multi-modal perceptual immersion with visual, auditory, olfactory and kinesthetic feedbacks.

4.3 Sensing, Recognition and Modeling for Monitoring and Planning

Technologies and technical capabilities of interest in the area of sensing, recognition and modeling for monitoring and planning include, but are not limited to:

- Robotic swarm perception and autonomy: Deployment and formation control of a swarm of robots or heterogeneous robotic agents for optimally coordinated perception and manipulation, especially in a large scale of disaster site. This includes autonomous and/or supervisory trajectory coordination in dynamically varying disaster situations for, e.g. optimal deployment of sensors, accurate monitoring of hazardous materials such as gas-flow, as well as seamless communication amongst individual robots and relief workers. One particular example may be UAV based static/dynamic radiation or nuclear source localization for preventing potential nuclear terrorism and accidents by developing a compact & economical sensor package and source localization algorithms that are fully operation on conventional small size UAVs.

- Collecting a large scale of multi-resolution, multi-modal and multi-spectral (MMMS) yet spatiotemporally varying data on disaster sites in real-time under extreme disturbance and ill-conditioned accessibility. This includes methods of highly sensitive, accurate yet robust visual and/or acoustic sensing in visually and/or acoustically adverse conditions such as dark, fog, smoke, ego and external noise, unstable platform, etc. for detecting and localizing victims, as well as methods to prioritize what and when information to collect based on the models of temporally and spatially varying disaster scenes.

- Integrating the collected multi-resolution, multi-modal and multi-spectral (MMMS) data of a large scale into a hierarchy of multi-resolution model that provides site commanders, relief workers and/or assistive robots with both the theater-wide intelligence and the location-specific information. This includes constructing a multi-resolution multi-modal situation awareness map to be updated temporally for location specific damage assessment and global understanding of disaster situation in real-time, as well as exploring how a situational awareness map can be linked to 6D SLAM in a larger scale of complex and temporally varying disaster environments and how temporal features can be extracted for modeling and understanding the variation of disaster situation, possibly, in a semantic level.

5. Conclusions

A number of fundamental enabling technologies that need to be further developed to overcome deficiencies of current robotics systems for humanitarian assistance and disaster relief have been identified. These technologies have been listed according to their application to novel robotic platforms, human--robot interaction, and advanced perception and planning capabilities. We hope that this report will spur new research into these fundamental research areas in both South Korea and in the US and provide for the development of next--generation robotic systems.