Satoshi Tadokoro
Editor

Rescue Robotics

DDT Project on Robots and Systems for Urban Search and Rescue

Springer

Rescue Robotics

Satoshi Tadokoro
Editor

Rescue Robotics

DDT Project on Robots and Systems for Urban Search and Rescue

Springer

Satoshi Tadokoro, Prof.
Graduate School of Information Sciences
Tohoku University
6-6-01 Aramaki Aza Aoba, Aoba-ku,
Sendai 980-8579
Japan

ISBN 978-1-84882-473-7 e-ISBN 978-1-84882-474-4
DOI 10.1007/978-1-84882-474-4
Springer Dordrecht Heidelberg London New York

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Control Number: PCN applied for

Cover design: eStudioCalamar, Figueres/Berlin

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

To the more than 6,400 victims who died at the Great Hanshin-Awaji Earthquake on January 17, 1995.

Preface

Frequent outbreaks of natural disasters is a serious problem on a global scale. In 2008, when the author was editing this book, Sichuan earthquake attacked China and struck the lives of more than 70,000 residents. Recently, significant damage has been caused in Asian countries by a number of disasters such as the huge cyclone in Myammar and the tsunami in Sumatra. The United States has suffered damage from hurricanes, floods, tornados, and forest fires almost every year. It is reported in ancient documents that several catastrophes shattered urban cities. The human race has experienced a number of natural disasters in its history.

In Japan, the Great Hanshin-Awaji earthquake claimed more than 6,400 human lives in the center of the urban city of Kobe in the early morning of January 17, 1995. Japan is located in the area where huge earthquakes frequently occur. The Headquarters for Earthquake Research Promotion of Japan Ministry of Education, Culture, Sports, Science and Technology (MEXT) estimated that the probability that in the next 30 years, a Nankai-Tonankai earthquake of magnitude 8.5 will occur is 50–60% and that a Miyagi-offshore earthquake of magnitude 7.5 will occur is 99%. It has estimated that the Nankai-Tonankai earthquake will claim 17,800 human lives, and large areas of Tokai, Kinki, and Shikoku districts will be absolutely devastated by the tremor and tsunami up to 15 m high [1]. Disasters such as in Sumatra, which was widely broadcast on TV, might strike us anytime and anywhere. Earthquake disaster is not a past fact nor a distant occurrence, but an existing serious risk that might strike today.

It is important and essential to be prepared for such disasters in order to minimize the number of casualties. All possible measures must be applied to raise the survival rate, and the contribution of advanced technologies such as robotics is expected in the future.

An investigation research committee in the Robotics and Mechatronics Division of Japan Society of Mechanical Engineers, which was formed just after the Hanshin-Awaji Earthquake, showed that robotics would be highly effective for urban search and rescue [3]. The committee also reported that only a few researchers had been developing robots for urban search and rescue. Such rescue robots had appeared only in science fiction and played an active role only in children's cartoon movies. This fact meant that effective robots would never be invented even in the 22nd century if new initiative did not start. Human lives would never be saved by rescue robots although robotic systems are potentially the best solutions when secondary damage is possible.

The ability of first responders would be drastically improved by long-term research and development. In front of the rubble piles on a city-wide scale in Kobe, the members of the committee determined that they should initiate an effort to resolve the situation and should try to develop applicable technologies step by step. That was the genesis of rescue robotics in Japan. Many researchers began to apply their robotics and related technologies to urban search and rescue problems.

This book introduces the main results of *DDT Project* launched by MEXT, of which official name is "Special Project for Earthquake Disaster Mitigation in Urban Areas, III. Advanced Disaster Management System, 4. Development of Advanced Robots and Information Systems for Disaster Response." This project was managed by a nonprofit organization, International Rescue System Institute (IRS), and more than one hundred robotics researchers and students across the nation have contributed for five years from August 2002 to March 2007 [2].

I thank all the people and organizations that contributed to this project.

Sendai, Japan
December 2008

Satoshi Tadokoro
Tohoku University
International Rescue System Institute
Project Manager of DDT Project

References

1. Central Disaster Prevention Council, Cabinet Office of Japan (2003) http://www.bousai.go.jp/ (in Japanese)
2. Tadokoro S et al. (2003–2007) Reports of Special Project for Earthquake Disaster Mitigation in Urban Areas, III-4 Development of Advanced Robots and Information Systems for Disaster Response. Ministry of Education, Sports, Culture, Science and Technology, National Research Institute of Earth Science and Disaster Prevention, International Rescue System Institute (in Japanese)
3. Tadokoro S, Takamori T, Tsurutani S, Osuka K (1997) On robotic rescue facilities for disastrous earthquakes – from the Great Hanshin-Awaji (Kobe) Earthquake –. J Robotics and Mechatronics 9-1:46–56

Contents

List of Contributors

Satoshi Tadokoro
Graduate School of Information Sciences, Tohoku University, 6-6-01 Aramaki-Aza-Aoba, Aoba-ku, Sendai 980-8579 Japan, e-mail: tadokoro@rm.is.tohoku.ac.jp, and International Rescue System Institute (IRS), KIMEC Bldg 2F, 1-5-2 Minatojima-Minami, Chuo-ku, Kobe 650-0047 Japan

Hajime Asama
RACE, University of Tokyo, Kashiwanoha 5-1-5, Kashiwa 277-8568 Japan, e-mail: asama@race.u-tokyo.ac.jp

Fumitoshi Matsuno
Department of Mechanical Engineering and Intelligent Systems, University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Tokyo, 182-8585 Japan, e-mail: matsuno@hi.mce.uec.ac.jp, and International Rescue System Institute (IRS), 66-20 Horikawa-cho, Saiwai-ku, Kawasaki 212-0013 Japan

Masahiko Onosato
Division of Systems Science and Informatics, Hokkaido University, N14W9, Sapporo 060-0814 Japan, e-mail: onosato@ssi.ist.hokudai.ac.jp

Koichi Osuka
Department of Mechanical Engineering Kobe University, 1-1 Rokkodai, Nada-ku, Kobe 657-8501 Japan, e-mail: osuka@mech.kobe-u.ac.jp

Tomoharu Doi
Osaka Prefectural College of Technology, 26-12 Saiwai-cho, Neyagawa, Osaka 572-8572 Japan, e-mail: doi@ipc.osaka-pct.ac.jp

Hiroaki Nakanishi
Department of Mechanical Engineering and Science, Graduate School of Engineering, Kyoto University, Yoshida-Honmachi, Sakyo-ku, Kyoto 606-8501 Japan, e-mail: nakanishi@me.kyoto-u.ac.jp

Itsuki Noda
Information Technology Research Institute, National Institute of Advanced Industrial Science and Technology (AIST), ITRI, Central 2, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568 Japan, e-mail: I.Noda@aist.go.jp

Koichi Suzumori
Graduate School of Natural Science and Technology, Okayama University, 3-1-1 Tsushima-naka, Okayama 700-8530 Japan, e-mail: suzumori@sys.okayama-u.ac.jp

Takashi Tsubouchi
Department of Intelligent Interaction Technologies, Graduate School of System and Information Engineering University of Tsukuba, 1-1-1 Tennoudai, Tsukuba, Ibaraki 305-8573 Japan, e-mail: tsubo@roboken.esys.tsukuba.ac.jp

Yasuyoshi Yokokohji
Department of Mechanical Engineering and Science, Graduate School of Engineering, Kyoto University, Yoshida-Honmachi, Sakyo-ku, Kyoto 606-8501 Japan, e-mail: yokokohji@me.kyoto-u.ac.jp

Iwaki Akiyama
Department of Electrical and Electronic Engineering, Shonan Institute of Technology, 1-1-25 Tsujidonishikaigan, Fujisawa, Kanagawa 251-8511 Japan, e-mail: akiyama@elec.shonan-it.ac.jp

Tatsuo Arai
Department of System Innovation, Graduate School of Engineering Science, Osaka University, 1-3, Machikaneyama-cho, Toyonaka, Osaka 560-8531 Japan, e-mail: arai@sys.es.osaka-u.ac.jp

Teruaki Azuma and Masahiro Hatsuda
Nitta Corp.

Michele Guarnieri
Department of Mechanical and Aerospace Engineering, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550 Japan

Yasushi Hada
Information Security Research Center, National Institute of Information and Communications Technology (NICT), 4-2-1 Nukui-Kitamachi, Koganei 184-8795 Japan, e-mail: had@nict.go.jp

Michinori Hatayama
Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji, Kyoto 611-0011 Japan, e-mail: hatayama@imdr.dpri.kyoto-u.ac.jp

Takumi Hashizume
Advanced Research Institute for Science and Engineering, Waseda University, 3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8555 Japan, e-mail: hasizume@waseda.jp

Shigeo Hirose
Department of Mechanical and Aerospace Engineering, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550 Japan, e-mail: hirose@mes.titech.ac.jp

Takao Inoh
Hibot Corp, University Corporate Relations Bldg., 2-10-1-201 Kamata, Ota-ku, Tokyo 144-0052 Japan,

Yuko Kaburagi
International Rescue System Institute (IRS), 66-20 Horikawa-cho, Saiwai-ku, Kawasaki 212-0013 Japan, e-mail: kaburagi@rescuesystem.org

Tetsushi Kamegawa
Department of Systems Engineering, Okayama University, 3-1-1 Tsushima-naka, Okayama 700-8530 Japan, e-mail: kamegawa@sys.okayama-u.ac.jp

Kuniaki Kawabata
RIKEN (Institute of Physical and Chemical Research), 2-1, Hirosawa, Wako, Saitama 351-0198 Japan, e-mail: kuniakik@riken.jp

Kenji Kawashima and Takahiro Sasaki
Tokyo Institute of Technology, 4259 Nagatsuta-cho, Midori-ku, Yokohama 226-8503 Japan, e-mail: kkawashi@pi.titech.ac.jp

Tetsuya Kimura
Department of System Safety, Nagaoka University of Technology, 1603-1 Kamitomioka, Nagaoka 940-2188 Japan, e-mail: kimura@mech.nagaokaut.ac.jp

Eiji Koyanagi
Future Robotics Technology Center, Chiba Institute of Technology, 2-17-1 Tsudanuma, Narashino 275-0016 Japan, e-mail: koyanagi@furo.org

Masamitsu Kurisu
Department of Mechanical Engineering, Tokyo Denki University, 2-2 Kanda-Nishiki-cho, Chiyoda-ku, Tokyo 101-8457 Japan, e-mail: kurisu@cck.dendai.ac.jp

Hiroyuki Kuwahara
Sustainable Robotics, 11-9-A Sakuranamiki, Tsuduki-ku, Yokohama 224-0046 Japan, e-mail: kuwahara@sustainable-robotics.com

Shugen Ma
Department of Robotics, Ritsumeikan University, Faculty of Science and Engineering, 1-1-1 Noji-Higashi, Kusatsu, Shiga 525-8577 Japan, e-mail: shugen@se.ritsumei.ac.jp

Kiyoshi Maeda
Marine Technical College, 12-24 Nishikura-cho, Ashiya, Hyogo 659-0026 Japan, e-mail: maeda@mail.mtc.ac.jp

Ken'ichi Makabe
IRS-U, International Rescue System Institute (IRS), 66-20 Horikawa-cho, Saiwai-ku, Kawasaki 212-0013 Japan

Yasuhiro Masutani
Osaka Electro-Communication University, 1130-70 Kiyotaki, Shijonawate, Osaka 575-0063 Japan, e-mail: masutani@isc.osakac.ac.jp

Jun-ichi Meguro
Toyota Central Research Institute, Toyota, Japan

Kenjiro Miura
Graduate School of Science and Technology, Shizuoka University, 3-5-1 Johoku, Naka-ku, Hamamatsu 432-8011 Japan, e-mail: tmkmiur@ipc.shizuoka.ac.jp

Mika Murata
International Rescue System Institute (IRS), 66-20 Horikawa-cho, Saiwai-ku, Kawasaki 212-0013 Japan, e-mail: murata@rescuesystem.org

Kenzo Nonami
Department of Electronics and Mechanical Engineering, Faculty of Engineering, Chiba University, 1-33 Yayoi-cho, Inage-ku, Chiba 263-8522 Japan, e-mail: nonami@faculty.chiba-u.jp

Tomowo Ohga
Asia Air Survey Co., Ltd., 1-2-2 Manpukuji, Asao-ku, Kawasaki 215-0004 Japan, e-mail: tom.ohga@ajiko.co.jp

Kazunori Ohno
Graduate School of Information Sciences, Tohoku University, 6-6-01 Aramaki-Aza-Aoba, Aoba-ku, Sendai 980-8579 Japan, e-mail: kazunori@rm.is.tohoku.ac.jp

Ato Kitagawa
Department of Mechanical and Control Engineering, Graduate School of Science and Engineering, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550 Japan e-mail: kitagawa@cm.ctrl.titech.ac.jp

Noritaka Sato
Department of Mechanical Engineering and Intelligent Systems, University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Tokyo 182-8585 Japan e-mail: nsato@hi.mce.uec.ac.jp

Hiroki Shimora
Information Technology Research Institute, National Institute of Advanced Industrial Science and Technology (AIST), ITRI, Central 2, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568 Japan

Naoji Shiroma
College of Engineering, Ibaraki University, 4-12-1 Nakanarusawa-cho, Hitachi, Ibaraki 316-8511 Japan

Hiroshi Sugimoto and Noriyuki Matsuoka
Kyoto Kagaku Co., Ltd., 15 Kitanekoya-cho, Fushimi-ku, Kyoto, 612-8388 Japan

Toshi Takamori
International Rescue System Institute (IRS), KIMEC Bldg 2F, 1-5-2 Minatojima-Minami, Chuo-ku, Kobe 650-0047 Japan, e-mail: takamori@rescuesystem.org

Fumiaki Takemura
Okinawa National College of Technology, 905 Henoko, Nago, Okinawa 905-2192 Japan, e-mail: takemura@okinawa-ct.ac.jp

Kensuke Takita
Hibot Corporation, University Corporate Relations Bldg., 2-10-1-201 Kamata, Ota-ku, Tokyo 144-0052 Japan, e-mail: takita@hibot.co.jp

Osamu Takizawa
Information Security Research Center, National Institute of Information and Communications Technology (NICT), 4-2-1 Nukui-Kitamachi, Koganei 184-8795 Japan, e-mail: taki@nict.go.jp

Ikuko Tanimura
International Rescue System Institute (IRS), KIMEC Bldg 2F, 1-5-2 Minatojima-Minami, Chuo-ku, Kobe 650-0047 Japan, e-mail: tanimura@rescuesystem.org

Hideyuki Tsukagoshi
Department of Mechanical and Control Engineering, Graduate School of Science and Engineering, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550 Japan, e-mail: htsuka@cm.ctrl.titech.ac.jp

Taro Watasue
Kobe University, Kobe, Japan

Tomoko Yamaguchi
International Rescue System Institute (IRS), KIMEC Bldg 2F, 1-5-2 Minatojima-Minami, Chuo-ku, Kobe 650-0047 Japan

Atsushi Yamashita
Department of Mechanical Engineering, Facility of Engineering, Shizuoka University, 3-5-1 Johoku, Naka-ku, Hamamatsu 432-8561 Japan, e-mail: tayamas@ipc.shizuoka.ac.jp

Tomoaki Yoshida
Future Robotics Technology Center, Chiba Institute of Technology, 2-17-1 Tsudanuma, Narashino 275-0016 Japan, e-mail: yoshida@furo.org

Xin-Zhi Zheng
Advanced Software Technology & Mechatronics Research Institute of Kyoto (ASTEM), 134 Chudoujiminami-machi, Shimokyou-ku, Kyoto 600-8813 Japan, e-mail: zhengxz@astem.or.jp

Acronyms

AIST	National Institute of Advanced Industrial Science and Technology
ARS	Aerial Robot System Mission Unit
CBRNE	Chemical, biological, radioactive, nuclear, explosive
CFD	City Fire Department
DDT	Dai-Dai-Toku (MEXT Special Project for Earthquake Disaster Mitigation in Urban Areas, III. Advanced Disaster Management System, 4. Development of Advanced Robots and Information Systems for Disaster Response)
DaRuMa	Database for rescue management
D-GPS	Differential GPS
DiMSIS	Disaster Management Spatial Information System
FD	Fire Department
FDMA	Fire and Disaster Management Agency
FEMA	Federal Emergency Management Agency
FST	Flexible Sensor Tube
GIS	Geographic information system
GML	Geography Markup Language
GPS	Global positioning system
GPU	Graphic processing unit
ICP	Iterative closest point
IDR-R	Intelligent Data Carrier for Rescue
IIS	Information Infrastructure System Mission Unit
IRS	International Rescue System Institute
IRS	In-Rubble Robot System Mission Unit
IRS-U	IRS Unit
LCD	Liquid crystal display
L-in-R	Leg-in-Rotor
LRF	Laser range finder
MEPCM	Micro-encapsulated phase change material
METI	Ministry of Economy, Trade and Industry
MEXT	Ministry of Education, Sports, Culture, Science and Technology

MISP	Mitigation Information Sharing Protocol
MSTC	Manufacturing Science and Technology Center
MU	Mission Unit
NBC	Nuclear, biological, chemical
NBCR	Nuclear, biological, chemical, radioactive
NICT	National Institute of Information and Communications Technology
NIED	National Research Institute for Earth Science and Disaster Prevention
OGC	Open Geospatial Consortium
ORS	On-Rubbles Robot System Mission Unit
PARM	Pneumatic artificial rubber muscle
R-Comm	Rescue Communicator
RDBS	Relational database system
RFID	Radio frequency identification
RT	Robot technology
RTK-GPS	Real-time kinematic GPS
SLAM	Simultaneous localization and mapping
SOAP	Simple Object Access Protocol
UAV	Unmanned aerial vehicle
UGV	Unmanned ground vehicle
US&R	Urban search and rescue
USAR	Urban search and rescue
UWB	Ultrawideband
WFS	Web Feature Service
WORG	Window Organizer
XML	Extendable Markup Language

Chapter 1
Earthquake Disaster and Expectation for Robotics

Satoshi Tadokoro

Abstract In Japan, research into rescue robotics was triggered by the Great Hanshin-Awaji Earthquake in Kobe in 1995. Statistics data show that earthquake disasters pose a serious threat to many cities in the world, therefore, it is essential to be prepared for these disasters. In order to mitigate the damage, various countermeasures and key strategies have been investigated, determined, and are being implemented. Equipment and methods of search and rescue must be improved by advanced technologies because it is most important to save human lives in any disaster. Robotics can contribute toward (1) assisting search and rescue operations that are impossible or difficult to perform by humans, (2) reducing risk of secondary damage, and (3) improving speed of operations to raise survival rate, for first responders.

1.1 Frequent Occurrence of Large-Scale Earthquakes

The Great Hanshin-Awaji Earthquake (Kobe Earthquake) of magnitude 7.2 struck Kobe city at 5:46 am on January 17, 1995. It was one of the most devastating urban earthquake disasters in the 20th century in terms of the amount of damage. It claimed 6,432 human lives in total. The death rates were significant: 1,471/190,000 in Higashi-Nada waard, and 75/600 in Ohgi and Nishi-Ohgi region. The total number of people affected was 2,300,000. 104,906 houses completely collapsed, 144,272 suffered half collapse, and 530,000 houses were damaged. The area of heavy collapse formed belt 20×1 km. 285 fires were reported; in 14 incidents, more than 10,000 m^2 was burned; and 6,148 houses in total were burned down completely. The total cost of direct damage was 10 trillion JYE (= 100 billion USD), and the indirect economic damage was larger than that.

This catastrophe triggered research into rescue robotics in Japan. On the basis of the investigation into the search and rescue operations conducted in 1995–1996

Satoshi Tadokoro
Tohoku University, and International Rescue System Institute (IRS)

[11], the efforts of researchers and facilitating collaborations have promoted the development of rescue equipment, systems, and robots. The technology level has been gradually improved, and we expect some concrete achievements in the near future.

Table 1.1 shows the statistics for the various disasters that struck the world during 1995–2004 [8]. These statistics indicate that the most serious damage was caused by earthquakes and tsunamis in terms of casualties and the amount of damage. Of all the natural disasters, earthquakes caused the most deaths, 35%. Moreover this death toll exceeds that from transport accidents. The statistics also indicates that Asia incurred most of the earthquake damage.

Table 1.2 shows those earthquakes that occurred during 1944–2008 and had a magnitude of more than 7.0 or caused more than 100 casualties. These statistics show that on a global scale, large earthquakes happen quite frequently. Higher frequency of incidents is observed in the 21st century than in the 20th. This might be an effect of global heating.

Table 1.2 also shows that many earthquakes have happened in Japan. Many Japanese historical documents reported earthquake disasters. For example, Chomei Kamono wrote in his essay Hojoki in 1185, “As far as my eyes can reach, no buildings of temples and shrines in Kyoto could have the original shapes.”

Table 1.3 shows the risk indices of various cities in the world, which were estimated by Munich Re [14]. From these indices, it is learnt that major Japanese cities, Tokyo, Yokohama, Kawasaki, Osaka, Kobe, and Kyoto are exposed to high risks. The risks faced by San Francisco and Los Angeles are also high. These cities have the following common characteristics:

1. probability of large-scale earthquakes is high;
2. population density is high; and
3. they are centers of economic activities.

The Japanese Government has been making an effort to estimate the risk of earthquakes according to the following two categories [4]:

1. **Plate-Type Earthquakes** The island of Japan is situated at the edge of the Eurasian Plate and the North American Plate, under which the Pacific Plate and Philippine Plate are moving down at Nankai Trough, Suruga Trough, Sagami Trough, and Japan Trench. Plates are anchored to each other at asperities, and compression stress is accumulated as they move. When the energy is released by the slippage of asperities, an earthquake occurs. Because the velocity of plates is almost constant, this type of earthquake happens periodically. Nankai, Tonankai, and Tokai Earthquakes are the largest earthquakes of this type.

   The probability of the occurrence of Nankai and Tonankai earthquakes in the next 30 years is estimated at 50–60% according to their period and observation of the asperities, and their magnitude will be 8.0–8.5. A Miyagi-Oki earthquake of magnitude 7.5 is predicted to occur with a probability of 99% in the next 30 years. Because most of these earthquakes happen in the ocean, they pose a serious tsunami threat. When the epicenter is far from urban cities, a large-magnitude earthquake does not necessarily result in large-scale damage.

Table 1.1 Total number of people reported killed and total cost of damage by continent and by type of phenomenon (1995–2004) [8]. The upper number indicates the casualties; the lower number, the cost of damage in millions of US dollars

Criteria	Africa	Americas	Asia	Europe	Oceania	Total
Avalanches/ landslides	251 n.a.	1,742 194	6,219 138	416 26	128 n.a.	8,756 358
Droughts/ famines	4,551 445	59 3,447	270,923 14,435	n.a. 11,993	88 1,620	275,621 31,939
Earthquakes/ tsunamis	3,114 5,633	2,990 9,931	292,050 219,912	20,727 30,554	2,200 n.a.	321,229 266,029
Extreme temperatures	200 1	2,325 5,449	9,817 3,529	32,888 12,696	1 213	45,231 21,888
Floods	9,176 1,440	38,000 21,956	44,219 125,636	1,414 43,433	33 1,471	92,842 193,935
Forest/scrub fires	114 4	83 2,645	125 22,378	107 2,062	9 412	438 27,500
Volcanic eruptions	254 9	52 22	3 1	n.a. 23	4 n.a.	313 55
Windstorms	1,385 941	25,271 102,461	33,958 63,264	720 19,265	250 2,909	61,584 188,841
Other natural disasters	n.a. 6	3 129	448 n.a.	n.a. n.a.	n.a. 132	451 267
Total natural disasters	19,045 8,479	70,525 146,233	657,762 449,292	56,272 120,051	2,713 6,756	806,465 730,812
Industrial accidents	2,810 811	279 1,278	7,956 828	918 719	ndr ndr	11,963 3,635
Miscellaneous accidents	2,781 5	2,784 1,700	7,592 24	1,416 569	46 n.a.	14,619 2,298
Transport accidents	24,028 67	8,364 129	29,465 1,156	5,762 426	511 n.a.	68,130 1,778
Total technological disasters	29,619 883	11,427 3,106	45,013 2,008	8,096 1,714	557 n.a.	94,712 7,711
Total	48,664 9,362	81,952 149,340	702,775 451,301	64,368 121,765	3,270 6,756	901,177 738,523

2. **Fault-Type Earthquakes** The land of Japan has a number of active faults. They slip periodically with a cycle of long period, i.e., several hundred to several hundred thousand years. Hanshin-Awaji Earthquake is of this type.

   The Japanese Government has been estimating the probability and magnitude of the slippage of the known major active faults. However, it is impossible at present to predict the time when they will slide. Moreover, many active faults are covered by sedimentary layers and have not been discovered. For these reasons,

Table 1.2 Large-scale earthquakes that occurred during 1944–2008 and had a magnitude of more than 7.0 or caused more than 100 casualties

Year	Magnitude	Country/Region	Deaths
1944	8.0	Japan	1,223
1945	6.8	Japan	2,306
1946	8.0	Japan	1.443
1948	7.1	Japan	3,769
1952	8.2	Japan	33
1960	8.5	Chile	5,700
1960	7.2	Sichuan, China	
1964	9.4	Alaska, USA	131
1964	7.5	Japan	26
1975	7.3	Liaoning, China	1,328
1976	7.8	Hebei, China	240,000
1976	7.2	Sichuan, China	
1976	7.2	Sichuan, China	
1978	7.4	Japan	16
1983	6.9	Japan	104
1985	8.5	Mexico	5,900
1993	7.8	Japan	
1993	7.8	Japan	229
1993	8.1	Guam, USA	0
1993	6.4	India	30,000
1994	8.1	Japan	
1994	7.5	Japan	
1995	7.3	Japan	6,432
1999	7.4	Turkey	17,000
1999	7.6	Taiwan	2,405
1999	7.2	Turkey	
2000	7.3	Japan	0
2001	7.9	India	13,000
2001	8.1	Tibet, China	
2003	8.0	Japan	2
2003	6.6	Iran	40,000
2004	9.3	Sumatra, Indonesia	220,000
2005	7.0	Japan	1
2005	7.2	Japan	0
2005	7.5	Pakistan	80,000
2007	7.9	Peru	500
2008	8.0	Sichuan, China	87,449?
2008	7.2	Japan	23?

Table 1.3 Risk index of large cities estimated for natural hazards [14]

City	Risk index [a,b]	Hazard [c]	Susceptibility to loss [c]	Values [c]
Tokyo, Yokohama, Kawasaki	710	10.0	7.1	10.0
San Francisco, Oakland, San Jose	167	6.7	8.3	3.0
Los Angeles, Riverside, Orange County	100	2.7	8.2	4.5
Osaka, Kobe, Kyoto	92	3.6	5.0	5.0
Miami, Fort Lauderdale	45	2.7	7.7	2.2
New York, Northern New Jersey, Long Island	42	0.9	5.5	8.3
Hong Kong	41	2.8	6.6	1.9
Manila	31	4.8	9.5	0.7
London	30	0.9	7.1	4.8
Paris	25	0.8	6.6	4.6

[a] Risk = Hazard × Loss susceptibility × Values
[b] Total material loss, not the insured share
[c] Scaled to max. value = 10.0

risk estimation is very difficult. When a fault located in an urban area shifts, even a small-magnitude earthquake may cause serious damage.

1.2 Damage Caused by Earthquake Disasters

Characteristics of earthquake disasters are summarized as follows [9]:

1. Frequency of earthquakes is low; most people do not experience large tremors nor tsunami in their lives, although all of them suffer from windstorms.
2. Resultant damage can be extraordinarily massive; the world history records tragedies in which entire cities were devastated and wiped off the map by earthquakes. Large-scale incidents can ruin nations physically or economically.
3. They happen suddenly without clear predictors; it is difficult to predict when an earthquake will happen, although the probability of its occurrence in a certain period can be estimated quantitatively.
4. Large-scale damage includes complex natural and social phenomena; tsunami may be generated and fires may break out dependent on the circumstances, and secondary damage is sometimes serious.

An earthquake is the most critical disaster for which human societies must be prepared.

Tremors not only destroy buildings and generate tsunami but also cause fires, slope failures, debris avalanches, landslides, soil liquefactions, etc. These natural phenomena cause secondary effects to inhabitants, such as being buried alive, burned to death, and drowned; tangible secondary effects such as infrastructure damage, derailments, and traffic accidents; and intangible secondary effects such as property loss, economic recession and difficult living. Disaster damage propagates widely in this way and causes complex disaster phenomena.

Table 1.4 shows the estimated casualties if the Nankai and Tonankai earthquakes happen simultaneously [4, 2]. The history of Nankai, Tonankai, and Tokai earthquakes shows that these three types of earthquake have sometimes happened simultaneously. This estimation shows that a tsunami is the most serious threat and that inhabitants should promptly evacuate the area if they are fully aware of the threat. The number of casualties varies according to the time of the incident because human behaviors such as cooking and sleeping depend on the time.

Table 1.4 Estimated casualties and the seriously injured when Nankai and Tonankai earthquakes simultaneously occur [4, 2]

	Time of incident		
Item	5:00 am	Noon	18:00 pm
Casualties			
Tremor	6,000	2,900	4,000
Tsunami			
Well aware of evacuation	3,300	2,200	2,300
Vaguely aware of evacuation	8,600	4,100	5,000
Slope failure	2,100	1,100	1,300
Fire			
Wind = 3 m/s	100	60	900
Wind = 15 m/s	500	200	2,200
Large-scale landslide	Can be very large depending on the place		
Deaths in total	12,100–17,800	6,300–8,200	8,500–12,500
The seriously injured in total	20,400	16,100	17,300
Need rescue in total	40,400	22,400	26,900

1.3 Japanese Government Disaster Management Plan

In general, a disaster changes phase with time as follows [12]:

1. **Before Incident** Preparedness for disaster protection and mitigation is important. Damage prediction, countermeasures for mitigation, risk management plan, and training are important factors.
2. **Precaution by Predictors** Finding appropriate predictors enables us to avoid or mitigate damage by taking precautions.
3. **Response and Damage Control** Emergency management organizations must be promptly established, and provisions should be quickly made for information gathering and sharing, response planning, search and rescue, emergency medicine, evacuation, command and control, publicity, logistics, etc.

4. **Recovery** Recovery of citizens' mental, physical, and economic health and restoring their lives to normalcy is important.

In 2003, the Central Disaster Prevention Council (CDP), Japan Cabinet Office outlined the following countermeasures against a potential Tokai earthquake in 2003:

1. drawing an earthquake hazard map, making seismic diagnosis, and providing earthquake-resistant reinforcements to structures in order to improve earthquake resistance for mitigating damage;
2. active participation and collaboration of inhabitants, companies and nonprofit organizations to strength disaster response ability;
3. appropriate actions before the warning; and
4. wide-area disaster management institution of search and rescue, emergency medicine, firefighting, and transportation.

Task Force on Future Countermeasures Against Earthquakes of CDP reported the following key issues in earthquake disasters in 2002 [4, 3]:

1. **Unsolved problems in countermeasures after Hanshin-Awaji Earthquake:**

    a. fragility and impracticality of the response ability of the government and local governments in an unexpected disaster;
    b. lack of a scheme for services by individuals and private companies in a disaster; and
    c. lack of provision efficient and effective methods for improving earthquake reduction facilities.

2. **Problems caused by socioeconomic changes in Japan:**

    a. slowdown of economic growth;
    b. inactiveness of local community;
    c. growing citizens' awareness of safety and security;
    d. aging population and reducing birthrates; and
    e. rapid technology development, particularly the information technology.

The task force mentions that the following key strategies are essential to resolve the above issues:

1. On the basis of the developed systems and organizations established against earthquake disaster after the Hanshin-Awaji Earthquake, their substantial effectiveness should be enhanced by improving the efficiency of operations and social awareness.
2. Disaster mitigation functions should be established in ordinary social systems, because citizens' concern about the disaster problem is gradually fading after exhibiting a peak at the Hanshin-Awaji Earthquake.
3. Practical risk management systems, social cooperation in disaster, effective and efficient countermeasures, and full use of advanced technologies should be promoted.

This report advises the following actions as immediate measures:

1. **Establishment of practical risk management systems:**

   a. **Establishment of entirely practical systems for disaster reduction** Development of manuals showing concrete procedures, education of expert staff, improvement in the mobility of expert organizations, cooperation of organizations in medical services, emergency logistics, etc.
   b. **Wide-area disaster reduction systems** Development of collaborative action plans of multiple local governments in wide area for disaster mitigation, and standardization and sharing of disaster response systems, equipment, material, information, etc.

2. **Social cooperation in disaster:**

   a. **Local collaboration of governments with private sectors** Development of a disaster mitigation plan and an administrative plan utilizing local communities on the basis of local collaboration of governments with residents, companies, nonprofit organizations, etc.
   b. **Cooperation with volunteer activities** Development of systems for the participation of volunteers, training of coordinators, and providing specialists' support.
   c. **Disaster mitigation by private companies** Development of cooperation systems with companies that serve various functions in a disaster, such as supplying goods and services to the ground zero; evaluation of these companies from the viewpoint of (i) risk management for the safety and security of employees and customers and (ii) minimization of economic loss.
   d. **Information sharing in disaster** Development of information sharing systems among disaster mitigation agencies and between residents and the agencies.
   e. **Robustness of cities against earthquakes** Upgrading urban infrastructure for robustness against earthquakes, utilization of development tactics by which private companies and land owners benefit.

3. **Effective and efficient countermeasures for disaster reduction:**

   a. **Weighted countermeasures considering budget limitation** Development of upgrade indices and desirable levels of earthquake disaster mitigation facilities, guidelines for the objective evaluation of mitigation systems, and system for steadily implementing these plans.
   b. **Reinforcement of houses and public buildings of importance for disaster mitigation** Integrated program for the development of hazard maps, diagnosis of seismic qualifications, and refurbishment of structures for promoting earthquake resistance.
   c. **Introduction of economic principles into disaster mitigation** Development of performance metrics of effectiveness of products in a disaster, displaying disaster-resistant products, systems for evaluating disaster-resistant products on the market.

4. **Full use of advanced technologies:**

    a. **Advanced information systems** Development of advanced information systems for disaster mitigation that are effective from just after the occurrence of a disaster to the completion of recovery and reconstruction operations.
    b. **Technologies and systems eliminating various barriers** Development of technologies for information transfer and evacuation guidance to/for people who need assistance in a disaster, robots and systems that can work in inaccessible areas.
    c. **Technologies and systems for overcoming fragility of the convenient society** Development of robust infrastructure for guarding ordinary life against the disruption caused by the failure of electric power and communication.

In 2005, CDP determined a target of disaster mitigation to reduce the anticipated casualties and damage by half. For this purpose, the following countermeasures have the highest priority [4]:

1. renovation of houses and infrastructure to make them earthquake proof;
2. improvement in the awareness of evacuation from tsunami-hit place;
3. improvement in seashore safeguard facilities; and
4. reinforcement of steeply inclined slopes which may collapse.

1.4 Examples of Countermeasures

Various countermeasures have been proposed. Some distinguishing topics are introduced below.

The building code was revised in 1981 according to the analysis of the damage caused by the 1978 Miyagi-Oki Earthquake where 16 people lost their lives. It was observed in the Hanshin-Awaji Earthquake that most houses built after this revision did not collapse, although many older buildings had major damage. Earthquake-proof structure is a fundamental solution to prevent collapse of houses. However, it is difficult to force the general public to repair their houses. In addition, many public buildings such as schools have still not been renovated.

Automatic cutoff function has become popular in city gas valves of private houses. This function has effectively prevented fire in recent earthquakes.

The seismograph network has been improved and an Earthquake Early Warning System was started in 2007 [6]. On receiving the primary wave of an earthquake, the epicenter and the magnitude are estimated promptly. There is a time lag between the fast primary longitudinal wave and the slow secondary lateral waves; the latter cause structural damage. During the time lag, warning is sent out immediately, which reaches inhabitants before the secondary waves arrive. It was reported that in recent earthquakes in an ocean, the warning reached the inhabitants a few seconds before the tremors. The inhabitants could prepare for the disaster using this short period.

A Hyper Rescue Team was formed in 1996 in the Tokyo Fire Department [13], and similar teams have been built recently in major cities. These specialist teams have advanced equipment such as special-purpose vehicles, FLIRs, search cams, fiber scopes, microwave radars, spreaders, and air jacks. A wide-area firefighting collaboration has been started by reducing the barriers between municipal governments. Japan Disaster Relief Team has been put in action for international search and rescue.

In order to avoid traffic congestion in telephone and cellular networks, a Disaster Emergency Message Dial (171) system has been installed [5]. These systems record messages from inhabitants of the affected area, and automatically reply to. Internet services that provide disaster information have become popular, such as RescueNow [10]. It sends out realtime disaster/accident information to cellular phones and internet by e-mail.

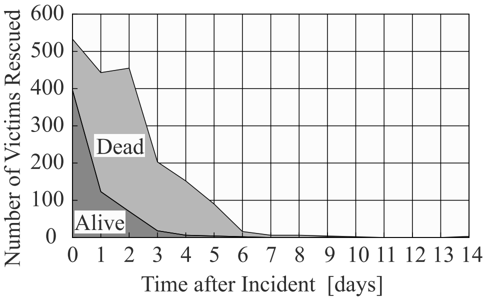


Fig. 1.1 Numbers of survivors and casualties who were rescued by Kobe Fire Department in the Hanshin-Awaji Earthquake

1.5 Urban Search and Rescue (USAR)

Human lives are the most important. It is essential to improve the ability of urban search and rescue as a countermeasure against earthquake disasters.

Figure 1.1 shows the number of victims rescued by Kobe Fire Department in the Hanshin-Awaji Earthquake [1]. This figure indicates that immediate search and rescue are important since the survival rate gradually decreases as time passes. It is desirable to be rescued within 3 hours. The survival rate drastically decreases after 3 days. This period is called “golden 72 hours” by first responders.

A medical report on the Hanshin-Awaji Earthquake mentions that 80% of casualties were crushed to death within one hour after the incident. However, many witnesses said that they had heard many voices calling for rescue after the tremor for a few hours. If those victims were rescued quickly, many of them would have survived.

A typical process of urban search and rescue (USAR) is as follows [7]:

1. **Awareness** Become aware that survivors remain in a rubble pile, in many cases by direct voice from the rubble pile or by a report from their family and residents.
2. **Situation assessment** Assess the risk of collapse of structures, existence of gases, oxygen, hazardous materials, and fire.
3. **Planning** Plan the procedure and task assignment, request backup parties, equipment and material, and arrange logistics.
4. **Search** Identify the positions of survivors in detail. Topological information based on characteristic landmarks is desirable for human rescuers. Absolute coordinates cannot be used in rubble piles where axes do not exist.
5. **Excavation** Remove rubble so that survivors can move. Appropriate treatment is necessary to avoid crush syndrome. The survivors must not be injured in the rescue process. The search process frequently needs simultaneous excavation.
6. **Secure** Secure the survivors.
7. **Emergency medicine** Medical examination is performed and first aid and psychological assistance provided. Confined space medicine is sometimes necessary, by which a medical procedure is performed while the victim is still in a rubble pile.
8. **Transfer** Transfer the survivors to medical institutions. Traffic jams and acceptability of medical institutions usually become a problem.
9. **Report** Report the operation.

The details of 4 and 5 are as follows, based on the observations during training of International Disaster Relief Team of Japan:

1. **Removal** Remove rubble on the approach path. Crowbars, pneumatic jacks, and hydraulic jacks are used.
2. **Prevention of collapse** Prevent collapse of the approach path. Supporting timber and hydraulic rescue supports are used.
3. **Search** Search for survivors. Search cams, fiberscopes, electromagnetic radars and acoustic probes are typical advanced equipments used.
4. **Confined medicine** Verbal contact is established and examination of survivors' conditions and triage are performed. Examination of external injury, heart pulse, and crush syndrome is important.
5. **Safety** Emergency evacuation and rotation of parties are necessary. Secondary disaster must be prevented. Planned rotation is essential in long-term operations.
6. **Command** Command parties; report situations; and request backup parties, equipment, and materials.

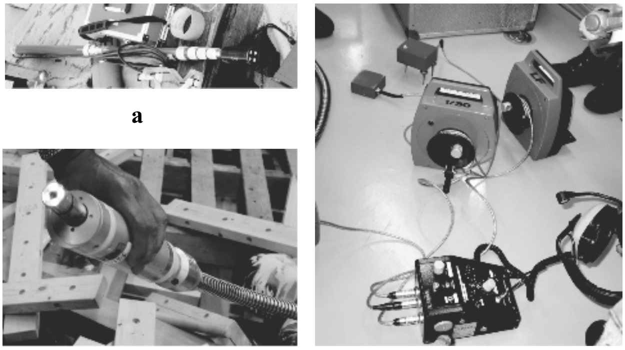
Among these steps, the search operation takes the longest time. Many first responders state that they can rescue if the victim's position is known. Often, search is beyond human ability.

The contribution of advanced equipment is expected in the following three areas:

1. assist search and rescue operations that are impossible or difficult to perform by human;
2. reduce the risk of secondary damage; and
3. improve the speed of operations in order to raise the survival rate.

1.6 Current Advanced Equipment for Urban Search and Rescue

At present, the hyper rescue team of TFD and Japan Disaster Relief Team for urban search and rescue utilize advanced equipment as follows [13]:



a

b c

Fig. 1.2 Advanced search tools. **a** Search cam. **b** Fiber scope (video scope). **c** Acoustic probe

1. **For search:**
   a. **Search cam** Bending camera head and light with a telescopic stick (Fig. 1.2 (a)).
   b. **Fiber scope (Video scope)** Bending camera head and light with a cable (Fig. 1.2 (b)).
   c. **FLIR** Infrared camera for human detection by means of thermal imaging
   d. **Microwave radar** Radar to detect heart beats and respiration under a rubble pile.
   e. **Acoustic Probe** Probe for listening to sound from victims under rubble pile (Fig. 1.2 (c)).
2. **For rescue:**
   a. **Air jack** Pneumatic jack for lifting structures (Fig. 1.3 (a)).
   b. **Spreader** Hydraulic tool to spread a narrow gap (Fig. 1.3 (b)).
   c. **Cutter** Air/engine tool for cutting structures (Fig. 1.3 (b), (c)).
   d. **Jack hammer** Air/engine tool for drilling holes in concrete structures (Fig. 1.3 (d)).
3. **Vehicles:**
   a. **Underwater robot** Teleoperated submarine robot for underwater search (Fig. 1.4 (a)).
   b. **RoboCue** Teleoperated rescue vehicle to capture victims (Fig. 1.4 (b)).
   c. **Fire Search** Teleoperated UGV for search in fire (Fig. 1.4 (c)).

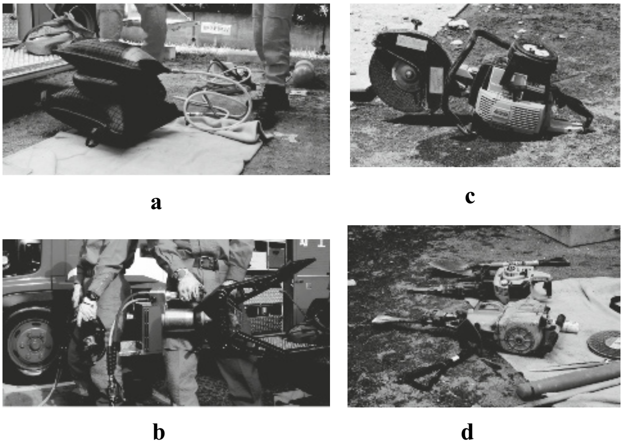


Fig. 1.3 Advanced rescue tools. **a** Air jack. **b** Spreader and cutter. **c** Enginer cutter. **d** Jack hammer

d. **Remote extinguishers** Vehicles for teleoperated extinguishers (Fig. 1.4 (d), (e)).

The current equipment is insufficient, and advanced technology is expected to improve this situations.

1.7 Expected Contribution of Robotics

Robotics is expected to improve the capability of advanced equipment and to introduce a breakthrough in the method of urban search and rescue [11].

On the other hand, the objectives of robotic systems are just the same as those of conventional equipment and are as follows:

1. assist search and rescue operations that are impossible or difficult to perform by humans;
2. reduce the risk of secondary damage; and
3. improve the speed of operations in order to raise the survival rate.

This implies that robots must be convenient tools of first responders. Autonomous superheroes are virtual creatures only in science fiction and animation and are not needed by first responders. Such robots are not practical in a short time period; even if they were, their cost would be astronomical.

Many applications of rescue robotics are expected, including but not limited to the following, in every process of urban search and rescue:

1. gathering overview information of a disaster;
2. gathering information about dangerous materials and environmental conditions;
3. search and diagnosis of survivors;

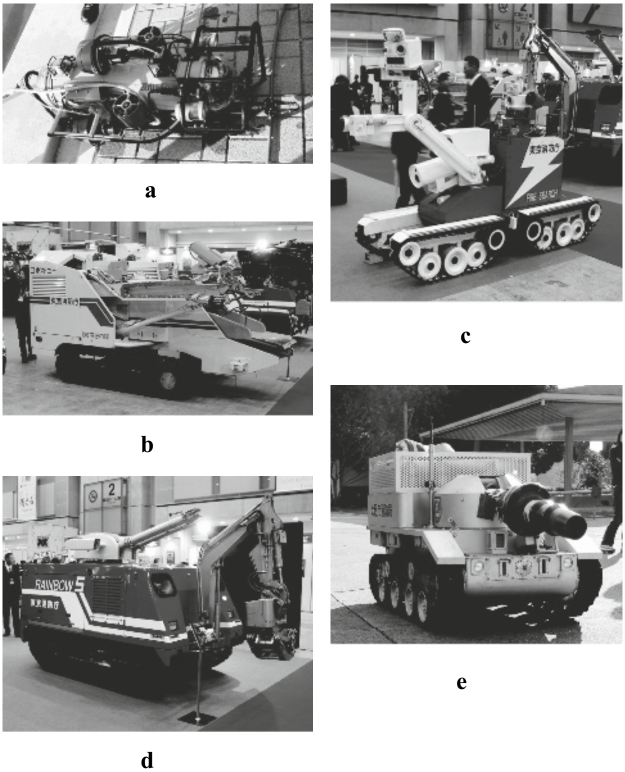


Fig. 1.4 Advanced vehicles for firefighting, search, and rescue. **a** Underwater robot. **b** RoboCue. **c** Fire Search. **d** Rainbow 5. **e** Teleoperated extinguisher

4. quantitative investigation of damage;
5. supporting recovery actions; and
6. supporting evacuation centers.

Collapsed structures, where rescue operation is performed, have various properties as follows:

1. **Type of structure** wooden structure, reinforced concrete, steel skeleton, etc.;
2. **Degree of collapse** full collapse, half collapse, damaged, or safe;
3. **Space** usable space around the collapsed structure, width of access road;
4. **Barriers** hazardous materials, gas leakage, water;
5. **Light** daytime or night;
6. **Sound** silent or heavy noise, for example, of helicopters;
7. **Weather** season, temperature, rain, snow, wind, etc.;
8. **Energy source** electric power source, hydraulic source, pneumatic source, etc.;
9. **Time of operation** risk of collapse, fire nearby; and
10. **Number of rescuers** professionals and volunteers.

The access path for entering a collapsed structure has the following characteristics:

1. **Size of clearance** compressed crush with a clearance of 0–30 cm, sparse crush with a clearance of 30–100 cm, damaged structure with a large clearance. Various clearances are observed in one building;
2. **Characteristics of clearance** angle of slope, lateral inclination angle, height of steps, width of gaps, necessary turning radius, etc.;
3. **Characteristics of obstacles in clearance** shape, overlap, weight, force for removal, iron nails, drooping cables, sharp edges, etc.; and
4. **Characteristics of floor surface** dirt, sand, dust, cloth, strings, net, glass, water, oil, etc.

The above characteristics determine the type of robotic systems that would be effective.

The evaluation of robots and systems is important. Various factors should be considered from the viewpoint of first responders and procurement authorities, at least the following:

1. Are the new robots and equipment better than the existing equipment and the other solutions?
2. In what situation are they better?
3. Are they compact and light weight?
4. Are they deployable in time?
5. What constrains their performance?
6. How robust are they in a disaster situation?
7. What are their purchase and running costs?
8. What is the training period?
9. Are they user-friendly?
10. What are the limitations of their functions and performance?
11. Can they be made available in sufficient number?

1.8 Conclusions

This chapter presented the following:

1. earthquake disasters and its damage;
2. disaster management by Japanese Government and various countermeasures;
3. urban search and rescue, and advanced equipment; and
4. expected contribution of robotics.

On the basis of the background outlined above, the DDT Project has been carried out as described in detail in later chapters.

References

1. Cabinet Office of Japan, Hyogo Earthquake Memorial 21st Century Research Institute (2000) Information packet of lessons in Hanshin-Awaji Earthquake. http://www.iijnet.or.jp/kyoukun/eng/
2. Central Disaster Prevention Council, Cabinet Office of Japan (2003) Handout at the 8th Meeting of TF on Tonankai-Nankai Earthquake. (in Japanese)
3. Central Disaster Prevention Council, Cabinet Office of Japan (2002) Report of TF on Future Countermeasures Against Earthquakes. (in Japanese)
4. Central Disaster Prevention Council, Cabinet Office of Japan (2008) http://www.bousai.go.jp/ (in Japanese)
5. Disaster Emergency Message Dial (171) (2008) http://www.ntt-east.co.jp/saigai_e/voice171/index.html
6. Earthquake Early Warning System (2008) http://www.jma.go.jp/jma/en/Activities/eew.html
7. Fire Supression Division, Tokyo Fire Department (2002) New firefighting strategies. Tokyo Horei Publishing (in Japanese)
8. International Federation of Red Cross and Red Crescent Societies (2005) World disasters report 2005, Focus on information in disasters.
9. Mizutani T (2002) Science and technology for natural disaster prevention, University of Tokyo Press (in Japanese)
10. RescueNow (2008) http://www.nescuenow.net/
11. Tadokoro S, Takamori T, Tsurutani S, Osuka K (1997) On robotic rescue facilities for disastrous earthquakes – from the Great Hanshin-Awaji (Kobe) Earthquake –. J Robotics and Mechatronics 9-1:46–56
12. Takizawa T (2005) Firefighting, disaster prevention and disaster management. Kindai Shobo Sha Press (in Japanese)
13. Tokyo Fire Department (2008) http://www.tfd.metro.tokyo.jp/eng/index.html
14. Voss S (2006) A risk index for megacities. Munchener Ruck, Munich Re Group

Chapter 2
An Overview of the DDT Project

Satoshi Tadokoro, Fumitoshi Matsuno, Hajime Asama, Masahiko Onosato, Koichi Osuka, Tomoharu Doi, Hiroaki Nakanishi, Itsuki Noda, Koichi Suzumori, Toshi Takamori, Takashi Tsubouchi, Yasuyoshi Yokokohji, and Mika Murata

Abstract The DDT Project on rescue robots and related technologies was carried out in Japan's fiscal years 2002–2006 by nationwide researchers, and was organized by International Rescue System Institute. The objective of this project was to develop practical technologies related to robotics as a countermeasure against earthquake disasters, and include robots, intelligent sensors, information equipment, and human interfaces that support emergency responses such as urban search and rescue, particularly victim search, information gathering, and communication. Typical tech-

Satoshi Tadokoro
Tohoku University, and International Rescue System Institute (IRS)

Fumitoshi Matsuno
University of Electro-Communications

Hajime Asama
University of Tokyo

Masahiko Onosato
Hokkaido University

Koichi Osuka
Kobe University

Tomoharu Doi
Osaka Prefectural College of Technology

Hiroaki Nakanishi and Yasuyoshi Yokokohji
Kyoto University

Itsuki Noda
National Institute of Advanced Industrial Science and Technology (AIST)

Koichi Suzumori
Okayama University

Toshi Takamori and Mika Murata
International Rescue System Institute (IRS)

Takashi Tsubouchi
University of Tsukuba

nologies are teleoperated robots for victim search in hazardous disaster areas, and robotic systems with distributed sensors for gathering disaster information to support human decision making. This chapter introduces the objective of this project, and a brief overview of the research results.

2.1 Objective of the DDT Project

On the basis of the background outlined in the previous chapter, the DDT Project was launched as follows [1]:

Project manager:	Satoshi Tadokoro, Tohoku University
Managing Institute:	International Rescue System Institute
Period:	August 1, 2002–March 31, 2007
Budget:	approximately 400 M JPY a year
Number of researchers:	more than 100

The following mission statement was defined so that disaster response problems can be solved using robots and related technologies.

> DDT Project will research and develop robots, intelligent sensors, information equipment, human interfaces, etc. to support victim search, information gathering, and communications for emergency response such as urban search and rescue in large-scale urban earthquake disasters. These systems and component technologies shall be useful for human disaster response activities and decision making by active intelligent information gathering and network-based information transfer and integration.

Robots are a type of advanced equipment for first responders such as firefighters, policemen, and Self Defense Corps. Such equipment serves the following purposes:

1. substitute for humans in risky tasks;
2. perform jobs that cannot be performed by a human; and
3. enable rapid and sure task execution without fail by humans.

Typical examples are substitution of robots for human tasks in explosive environments and search in inaccessible areas and in narrow gaps.

According to analysis of the Hanshin-Awaji Earthquake, information gathering was the most important issues for first responders. In addition, the technology review showed that robotics is better at information gathering than the other tasks at present and in the near future. Therefore, the DDT Project focused on solutions to the information gathering problem.

Consumer robots, which are expected to become more and more popular worldwide, can have rescue functions added and aid life support in an emergency, although first-responder robots are high-spec systems that are made available in only small numbers to fire departments. Their functions should, for example, complement to ordinary security sensors, alarms at catastrophes, measures for damage reduction, and gathering and transfer of disaster information. For this purpose, the DDT Project researched distributed sensor systems.

Robot technology (RT) has become a popular phrase, denoting technologies related to robots. Its market size is predicted to become 6 trillion JPY in 2025 in Japan. Rescue RT has many common parts with teleoperated or unmanned construction for disaster recovery, plant investigations, maintenance of old facilities, etc. Therefore, the development of rescue technology contributes to disaster mitigation and damage recovery.

2.2 Roadmap for Practical Solutions

The roadmap of the DDT Project is shown in Fig. 2.1. In the first 2–3 years, it concentrated on the trial of technologies that had not been well applied to the disaster problem; the purpose was to enhance the range of applicable technologies. In the last 2–3 years, potential technologies were intensively researched, and integrated systems were developed to serve the expected functions.

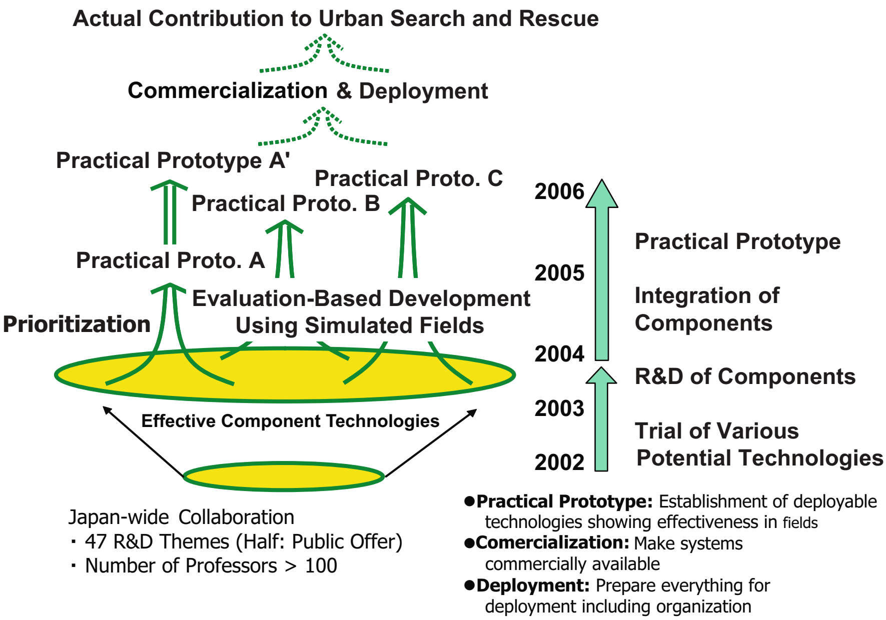


Fig. 2.1 Roadmap of the DDT Project

For this project, International Rescue System Institute (IRS) established two laboratories in Kawasaki and Kobe, as shown in Figs. 2.2 and 2.3. These laboratories have test fields for developed systems that simulate disaster situations. The Collapsed House Simulation Facility in the Kobe Laboratory, shown in Fig. 2.4, is a collapsed wooden house as observed in the Hanshin-Awaji Earthquake. The functions of these test fields are to conduct repetitive experiments and develop improved systems, in addition to the demonstration of developed systems and technologies in realistic situations at every stage of the project. In other words, the laboratories and facilities were used not only to achieve academic/technical results but also for practical deployment of systems and technologies in the future.

Fig. 2.2 Kawasaki Laboratory of International Rescue System Institute (IRS)

Fig. 2.3 Kobe Laboratory of International Rescue System Institute (IRS)

Fig. 2.4 Collapsed House Simulation Facility of IRS Kobe Laboratory

The DDT Project has performed intensive on-site experiments and demonstrations. Experiments at the site of Niigata-Chuetsu Earthquake, training site of Tokyo Fire Department Hyper Rescue, training sites of Federal Emergency Management Agency task forces, Collapsed House Simulation Facility, Kawasaki Laboratory, and Kobe Laboratory have produced a wide spectrum of lessons and knowledge for researchers and first responders. Practical demonstrations given at the World Conference on Disaster Reduction, training site of the International Disaster Relief Team of Japan, National Rescue Meet, Search and Rescue Workshop, disaster drills, expositions, and exhibitions have brought rescue robots to the recognition of first responders and general public.

This research aimed at creating various practical technologies to establish the fundamentals of disaster mitigation assisted by robots at the end of the project. The definition of the word *practical* in this project is to realize technologies applicable to disaster so that experiments at real or realistic test sites demonstrate the effectiveness of developed robots and systems. The following activities are necessary in order for these technologies to be used in a real disaster.

Research:	researchers create new functions.
Development:	first responders recognize satisfactory functions after improvement by researchers and engineers to practical level.
Commercialization:	cost and reliability are improved, and first responders can purchase the solution.
Deployment:	first responders and responding organizations can use the solution any time.
Training:	first responders can use the solutions effectively and smoothly.
Actual Results:	first responders have used the solutions and believe their good performance.

Most research members of the DDT Project were from universities. The market for developed robots and systems is not established at present, and private companies hesitate about commercialization. Procurement and deployment are dependent on government policies. First responders' opinions and evaluation are important. Under this situation, the duration of the DDT Project is too short to complete all the above activities, although it has made huge efforts on these items as part of the program. Further effort must be continued by company–government–academia–private collaborations.

The DDT Project consisted of the following four mission units as research groups in 2005–2006:

1. **Aerial Robot System Mission Unit (ARS)** Intelligent helicopters, balloons, image processing, and human interface.
2. **Information Infrastructure System Mission Unit (IIS)** Distributed sensors, RFID tags, integration protocol, database, and mapping.
3. **In-Rubble Robot System Mission Unit (IRS)** Serpentine robots, advanced rescue tools, advanced search cams, advanced fiber scopes, sensors, and human interface.
4. **On-Rubble Robot System Mission Unit (ORS)** Tracked vehicles, jumping robot, ultrawideband (UWB) radar, semi-autonomous movement, ad-hoc com-

munications, self-localization and mapping, human interface, and sensor data processing.

At the beginning of the project, 47 research themes were explored by 31 groups in order to assess various technologies according to the roadmap. In 2004, the themes were merged or abolished into nine tasks consisting of six task forces (TFs) defined by types of robots (Aerial Robot System TF, Information Infrastructure TF, In-Rubble Robot System TF, Advanced Tool TF, On-Rubble Robot System TF, Underground Robot System TF) and three TFs defined by common technologies (Control Human Interface TF, Communication and Data Format TF, Field and Evaluation TF) so that system integration is accelerated. In 2005, the TFs were integrated into the above four MUs in order to promote further collaboration of research members.

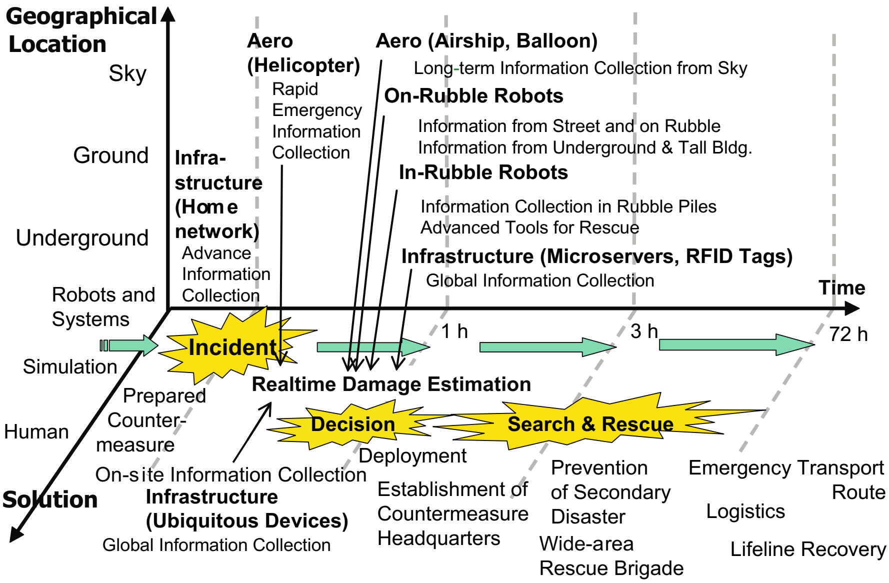


Fig. 2.5 Scenario by which research results are used in diaster

2.3 Disaster Response Scenario Using Developed Robots and Systems

The research results of the DDT Project are classified according to their usage as follows:

1. **Equipment and systems for first responders** Serpentine robots (Souryu, MOIRA, KOHGA, etc.), tracked vehicles (HELIOS, ACROS, Hibiscus, Alibaba, etc.), jumping robot (Leg-in-Rotor), advanced rescue tools (jack robot,

Bari-Bari, etc.), advanced search cam (KURUKURU, intelligent search cam, etc.), advanced fiber scope (Active Scope Camera, etc.), ultrawideband radar, wireless triage tags, etc.
2. **Technologies for equipment and systems** Methods for sensor information processing and image processing, algorithms for semiautonomous motion, human interface, etc.
3. **Equipment and systems for disaster response organizations** Intelligent helicopters (intelligent aerorobot, etc.), balloons (InfoBalloon, etc.), database (DaRuMa), protocol (MISP), etc.
4. **Infrastructure for houses** Distributed sensors (Rescue Communicator), etc.
5. **Information support for refugees** RFID tags, etc.

The phase of a disaster changes as time passes. The DDT Project assumes the following scenario for each phase, as shown in Fig. 2.5:

1. **Preparedness and detection of ominous presence** Watching for human existence in buildings using distributed sensors and home appliances.
2. **Response** Disaster information is quickly gathered by the distributed sensors and autonomous intelligent helicopters and is provided to emergency headquarters via GIS.
3. **Emergency countermeasures** Robots and advanced equipment are used for victim search in rubble piles and underground structures. Balloons and air ships perform fixed-point observation from the sky. IC tags support rescue activities.
4. **Recovery support** Moving state of refugees is monitored by IC tags.

If the research results are applied to a real earthquake disaster in the future, the following disaster response will be possible:

1. All the systems have been deployed and used in regular training. Common Geographic Information System (GIS) is ready in addition to the robotic systems.
2. Systems of IIS are continuously monitoring the situation in houses.
3. Large-scale urban earthquake disaster occurs.
4. Information about residents which has been gathered by distributed sensors, Rescue Communicators of IIS, is transferred to disaster response organizations immediately after receiving Earthquake Early Warning (EEW) [1] before the event.
5. Intelligent helicopters, intelligent aerorobot of ARS, automatically fly to gather overview information of the affected area by cameras and laser profilers rapidly within 30 min.
6. Human first responders make decisions on the basis of the information gathered. Human responders carrying the developed systems are put in action.
7. InfoBalloons of ARS fly and stop in the air or move slowly. They gather victim information using infrared cameras in cooperation with IIS Rescue Communicators and mobile phones, collect overview information using cameras and laser

[1] EEW system of Japan Meteorological Agency (JMA) provides advance announcement of the estimated seismic intensities and expected arrival time of principal motion using the difference of speed between the primary wave and the secondary wave of an earthquake.

profilers, and support human responders and the other robotic systems by position identification and communication transfer.

8. ORS Robots are brought by first responders to the disaster site. They move 50 m in rubble piles and on rubble piles to collect victim information and to investigate structural damage and hazardous materials using camera, infrared camera, temperature sensors, gas sensors, and so on, and report to the first responders. They enter 200 m into underground structures and buildings which have limited damage.
9. IRS Robots and advanced tools are carried by first responders to the side or the top of rubble piles. They enter 30 m into the rubble piles via narrow clearances using teleoperation to gather information by the sensors.
10. All the information gathered is recorded and mapped on to a GIS, DaRuMa, using a standardized protocol (Mitigation Information Sharing Protocol; MISP) so that the first responders and disaster managers can use it for decision making and operational support.

2.4 Brief Overview of Major Results

Major results are briefly introduced in this section. Details are given in other chapters and in papers in references.

2.4.1 Aerial Robot System MU

MU leader: Masahiko Onosato, Hokkaido University
MU subleader: Hiroaki Nakanishi, Kyoto University

2.4.1.1 Intelligent Helicopter, Intelligent Aerorobot

The small-size autonomous unmanned helicopter shown in Fig. 2.6 takes off immediately after the shake to gather information at less altitude with lower noise than manned helicopters. Technologies for stable flight in strong wind and simple teleoperation have been developed.

2.4.1.2 Balloon for Stationary Measurement, InfoBalloon

InfoBalloon, shown in Fig. 2.6, is airborne for a long period for stationary measurement and information support of ground operation. Robustness against wind is an advantage of this balloon.

Fig. 2.6 Experiments on intelligent aerorobot and InfoBalloon in Yamakoshi Town, which was struck by Niigata-Chuetsu Earthquake in 2005

2.4.2 Information Infrastructure MU

MU leader: Hajime Asama, The University of Tokyo
MU subleader: Itsuki Noda, AIST

2.4.2.1 Distributed Sensor, Rescue Communicator

Rescue Communicators shown in Fig. 2.7 are installed in houses as distributed sensor equipment, and they gather survivors' information by verbal contact. The information is transferred to disaster mitigation organizations by a home network and an ad-hoc network.

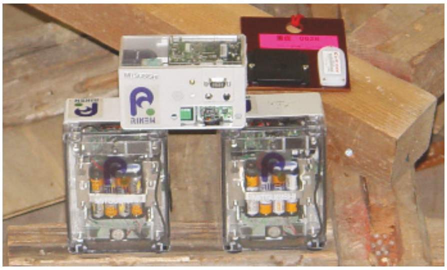


Fig. 2.7 Rescue Communicator and wireless triage tag (upper right)

2.4.2.2 RFID Tags for Triage Tag and Rescue Completion Tag

The wireless triage tag shown in Fig. 2.7 contributes to efficient logistics for rescued survivors using an RFID tag. The rescue completion tag is hung on the rescue site and stores the search and rescue information. This helps to avoid repetitive operations and thereby improves the efficiency of the overall operation.

2.4.3 In-Rubble Robot System MU

MU leader: Koichi Osuka, Kobe University
MU subleader: Koichi Suzumori, Okayama University
Tomoharu Doi, Osaka Prefectural College of Technology
Yasuyoshi Yokokohji, Kyoto University

2.4.3.1 Serpentine Robots, IRS Souryu, MOIRA, KOHGA, etc.

Various types of serpentine mobile mechanisms were researched and tested. The objective of these developments is to enable search in narrow clearances wider than 30 cm in collapsed structures. The developed robots have been intensively tested in rubble piles.

2.4.3.2 Hyper Souryu IV

A wide range of component technologies, which include a cable-type positioning system FST, a multi-camera system, a bird's-eye-view synthesis system using a past image, a multi-range finder, and a driving mechanism for pivot turn, were integrated into a new serpentine robot Hyper Souryu IV, as shown in Fig. 2.8. The mobility, teleoperability, position identification, and situation awareness were improved from its previous version, IRS Souryu.

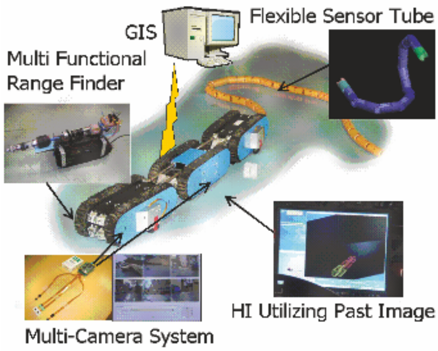


Fig. 2.8 Hyper Souryu IV with integration of component technologies

2.4.3.3 Advanced Rescue Tools

In order to improve firefighter's equipment, an intelligent search cam that measures the shape of a void in rubble piles, a search cam Kurukuru that is powered by hand electric generator, a jack robot for search and rescue inside rubble piles, another jack robot Bari-Bari for prying open a narrow clearance, a pneumatic jack, a cutter robot, etc. were developed.

2.4.3.4 Advanced Video Scope, Active Scope Camera

Adding actuators on to the surface of the cable of the rescue video scope gives Active Scope Camera (ASC) (shown in Fig. 2.9) which moves by itself into clearance more than 3 cm wide. The accessible distance was significantly improved.

Fig. 2.9 Experiments on Active Scope Camera at the Collapsed House Simulation Facility of IRS Kobe Laboratory

2.4.4 On-Rubble Robot System MU

MU leader: Fumitoshi Matsuno, The University of Electro-Communications
MU subleader: Takashi Tsubouchi, University of Tsukuba

2.4.4.1 Mobile Vehicles for Rough Terrain, HELIOS VIII, HELIOS Carrier, ACROS, FUMA, Hibiscus, Ali-baba, etc.

HELIOS VIII is an information gathering tracked UGV for damaged buildings with large space and has high environment resistance. HELIOS Carrier shown in Fig. 2.10 was developed by connecting two tracked bodies in order to improve mobility at steps and by integrating component technologies, which include a bird's-eye-view synthesis system for teleoperation human interface using a past image shown in Fig. 2.11, an image vibration reduction system for avoiding virtual reality sickness, [2] autonomous 3D map generation, and a teleoperation interface using the 3D image. Various types of UGVs such as ACROS, FUMA, Hibiscus, and Ali-baba were developed.

2.4.4.2 Jumping Robot

A jumping robot Leg-in-Rotor-V with super mobility on rubble can move for a long period using a new type of pneumatic power source utilizing the triple point of carbon dioxide by which dry ice can supply a sufficient volume of air at constant pneumatic pressure.

Fig. 2.10 HELIOS Carrier climbing up steps

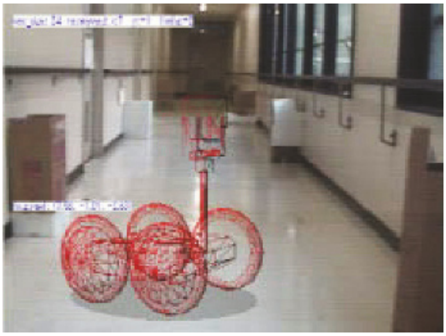


Fig. 2.11 Virtual bird's-eye-view synthesis system utilizing past image for tele-operation to enable easy navigation

2.4.4.3 Ultrawideband Radar

An ultrawideband radar sensor and signal processing technology improved the performance of detecting human breathing in rubble piles.

---

[2] When human uses virtual reality devices or makes teleoperation of moving vehicles for a long time, a symptom like car sickness sometimes appears. It is called virtual reality sickness.

2.4.4.4 Human Interface

A guideline for a human interface was developed aiming at future standardization.

2.4.5 Integration of Gathered Information

All the gathered data are integrated into the distributed database DaRuMa (DAtabase for RescUe MAnagement) via an XML-type standardized protocol MISP (Mitigation Information Sharing Protocol), and can be referred to and searched by SQL commands and viewers such as Google Earth^{TM}, as shown in Fig. 2.12. The information in the database can be attributed, added, and processed later via internet. It will improve the efficiency of decision making. Verification experiments in Yamakoshi Town and the Collapsed House Simulation Facility demonstrated the integration capability of data sent from various robots.

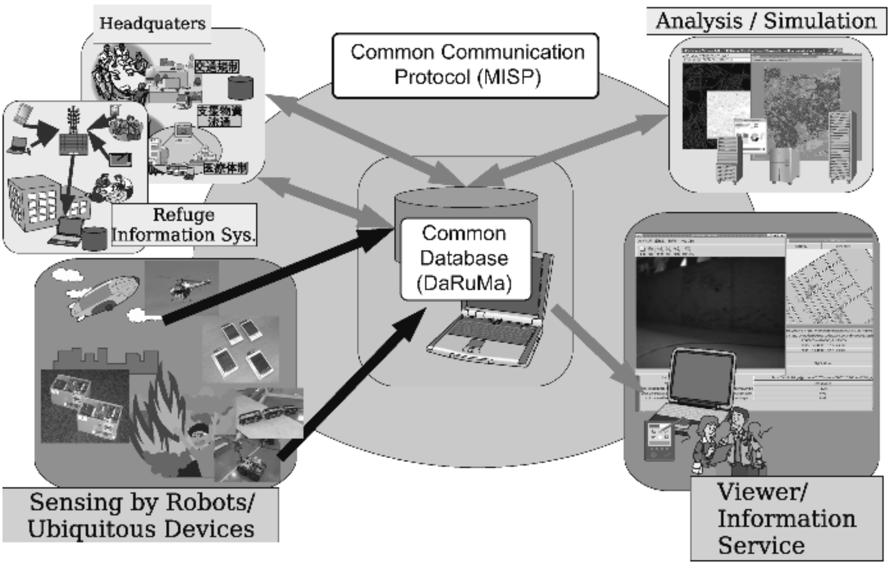


Fig. 2.12 Integration of data gathered by robots and systems using Mitigation Information Sharing Protocol (MISP) into the DaRuMa database

2.4.6 Verification Experiments and Exercise

A number of field experiments, demonstrations, and exercises were performed in order to enable the future deployment of the developed systems and technologies. Firefighters in active service organized a volunteer unit IRS-U, and carried out intensive tests and demonstrations to evaluate research results (Fig. 2.13). First responders in FEMA evaluated the robots at their training sites in meetings to standardize rescue robot evaluation methods and metrics organized by NIST and ASTM (Fig. 2.14). The general public has recognized rescue robotics research through the medium of many exhibitions and demonstrations, and via mass media.

Fig. 2.13 Volunteer unit IRS-U organized by firefighters in active service

Fig. 2.14 Experiments by FEMA first responders at the Texas TF-1 training site, Disaster City of Texas A&M University

2.5 Conclusions

This chapter introduced an overview of the DDT Project including a brief description of major results.

At the time of the Hanshin-Awaji Earthquake in 1995, the phrase “a rescue robot” meant a virtual creature in science fiction and cartoon animation. However, the DDT Project has established rescue robotics research field in Japan by proposing that the disaster mitigation problem is an important application area for robotics. Various systems and technologies have been developed and tested in real/realistic fields by four mission units (MUs): Aerial Robot System MU, Information Infrastructure System MU, In-Rubble Robot System MU, and On-Rubble Robot System MU.

Communication between robotics researchers, first responders and disaster scientists has become smoother through intensive experiments, demonstrations, and exercises.

The research and development of rescue robots and systems should continue to make a real contribution to disaster reduction. We hope this DDT Project has established the fundamentals for progress of this technology.

The authors thank all the people concerned and sincerely appreciate their contributions.

References

1. Tadokoro S et al (2003–2007) Reports of Special Project for Earthquake Disaster Mitigation in Urban Areas, III-4 Development of Advanced Robots and Information Systems for Disaster Response. Ministry of Education, Sports, Culture, Science and Technology, National Research Institute of Earth Science and Disaster Prevention, International Rescue System Institute (in Japanese)

Chapter 3
Disaster Information Gathering Aerial Robot Systems

Masahiko Onosato, Satoshi Tadokoro, Hiroaki Nakanishi, Kenzo Nonami, Kuniaki Kawabata, Yasushi Hada, Hajime Asama, Fumiaki Takemura, Kiyoshi Maeda, Kenjiro Miura, and Atsushi Yamashita

Abstract This chapter introduces R&D results for aerial robot systems for urban search and rescue (USAR). Different types of aerial robot system have been developed and effectively combined so as to offer a quick and continuous service for disaster information gathering. First, autonomous helicopters collect disaster situation data from the sky for first decision making in USAR planning. Then, a blimp-type robot system and a cable-driven robot system survey victims under collapsed houses by detecting faint signs of life. As a continuous information service, a captive balloon system with a monitoring camera presents bird's-eye-views of the disaster area, and relays wireless communication among working teams on the ground.

Masahiko Onosato
Hokkaido University

Satoshi Tadokoro
Tohoku University,

Hiroaki Nakanishi
Kyoto University

Kenzo Nonami
Chiba University

Kuniaki Kawabata
RIKEN (Institute of Physical and Chemical Research)

Yasushi Hada
National Institute of Information and Communications Technology (NICT)

Hajime Asama
University of Tokyo

Fumiaki Takemura
Okinawa National College of Technology

Kiyoshi Maeda
Marine Technical College

Kenjiro Miura and Atsushi Yamashita
Shizuoka University

These robot systems and other developed technologies are integrated to provide a total solution for quick information gathering from the sky for USAR activity support. The availability of aerial robot systems was demonstrated in field tests conducted at Yamakoshi village.

3.1 Introduction

This paper reports the main research results on aerial robot systems, which has been organized for a national research project, DDT Project (Special Project for Earthquake Disaster Mitigation in Urban Areas, III-4 Development of Advanced Robots and Information Systems for Disaster Response [8]).

The Aerial Robot System Mission Unit, the AIR MU for short, was organized to realize disaster information gathering as quickly as possible by using aerial robot systems [6]. A large-scale disaster, such as the Hanshin-Awaji Earthquake that struck Kobe city and its environs on January 17, 1995, destroys a number of structures on the ground and makes it very difficult to access destroyed areas. Collapsed buildings often block the usual approaches to target points for moving ground vehicles. Much time is wasted in finding an accecssible route to a target by a trial and error process.

Aerial robot systems that can directly approach target locations are expected to be free from such chaos on the ground [5].

3.2 Aerial Robot Systems for USAR

3.2.1 Utilization of Aerial Robot Systems

Aerial robot systems can be utilized for the following USAR activities:

1. **Information gathering:** Information about the disaster area is collected using various media such as pictures, videos, sounds, and other sensing data by using measuring equipment.
2. **Information relay:** The communication between two ground sites is relayed by an airborne station that is free from the difficulties caused by the obstacles present on the surface.
3. **Information delivery:** Information about the disaster situation and USAR operations is quickly delivered to the people in the disaster area and rescue agents on the ground.
4. **Goods transport:** Goods for rescue support such as medical supplies and communication equipment are transported from one site to another site isolated by the disaster.

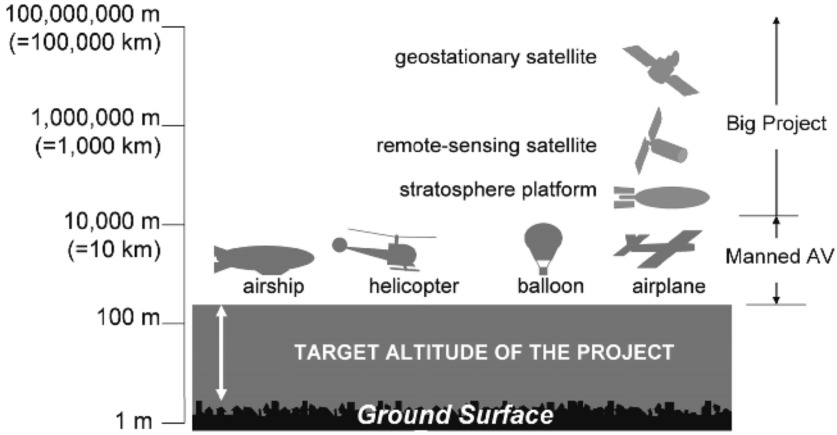


Fig. 3.1 Operating altitude of airborne systems

5. **Distribution of equipment and devices:** Equipment such as fire extinguishers and ubiquitous sensing devices are distributed by air to the disaster area.
6. **Other uses:** Lighting the ground from the air in the nighttime, identifying landmarks for refuge location, etc.

Among these various uses of aerial robot systems in USAR, the AIR MU has concentrated its R&D efforts on information gathering.

3.2.2 Information Gathering from the Sky

At present, several methods are used for information gathering from the sky. Figure 3.1 shows some typical systems for aerial surveillance. It is seen from this figure that no practical aerial system is available for use at low altitude under 150 m, where operating manned air vehicles is dangerous. Aerial robot systems working automatically in this space are expected to gather detailed information of the damaged areas quickly and safely. The AIR MU has set its main target to develop aerial robot systems that can be operated at low altitudes from the ground. Space satellites and manned airborne vehicles, which are effective approaches to collect information over large areas, are excluded from the AIR MU's research objectives.

3.2.3 Distinctive Aspects of Aerial Robot Systems

Compared with rescue robot systems working on the ground, aerial robot systems for USAR should satisfy more difficult requirements both from the technological

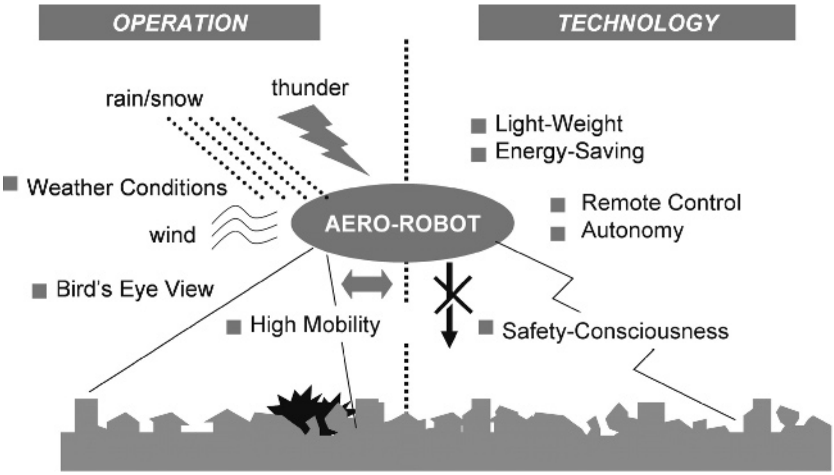


Fig. 3.2 Requirements in aerial-robot design

aspect and the operational aspect. For example, the following points should be carefully considered in the design and operations of aerial robot systems:

- **Weight reduction:** The most severe requirement in aerial robot design is to reduce the weight without violating the required functionality and safety.
- **Energy saving:** Most aerial robots are designed to self-contained in terms of power source. For long operational time, on-board equipment of aerial robots is required to have energy-saving features.
- **Safety consciousness:** Malfunctioning of an aerial robot in the air may cause a serious crash on the ground. Therefore, safety-conscious design and operations are most important criteria for aerial robot systems.
- **Remote control and autonomy:** Aerial robots are usually controlled by an operating agent on the ground with wireless communication. In the event of communication failure, aerial robots should autonomously maintain stability and take safe actions avoiding an unexpected crash.
- **Weather conditions:** Weather conditions affect aerial robots more than robots on the ground. Aerial-robot operators should consider temperature, wind, rain, snow, fog, thunder, and other weather conditions for successful operations.
- **High mobility:** Aerial robot systems have high mobility in three-dimensional space. This means that they should have high level functions to control its mobility appropriately.
- **Bird's eye view:** The bird's eye view is the most important advantage of aerial robot systems. Careless use of the bird's-eye-view from low attitude may raise privacy concerns.

These requirements for aerial-robot design and operation often make it difficult to realize both high mobility and long duration in a single aerial robot at an affordable price.

In other words, we cannot expect an aerial robot system that is always available for any purpose in any situation.

3.3 Designing Aerial Robot Systems

3.3.1 Three Phases of USAR Operations

The AIR MU divides USAR operations into the following three phases on the basis of requests for disaster information:

1. **Phase I:** The aim of this phase is to capture an overall image of the affected area immediately after the occurrence of a disaster. For USAR planning at disaster headquaters, the initial disaster information will be available 30–60 minutes after a disaster has occurred.
2. **Phase II:** The aim of this phase is to find victims who are buried under collapsed houses. The most important point of this phase is to determine primary search points with a high probability of victim existence for effective allocation of rescue teams on the ground. This phase will usually be carried on for more than 72 h.
3. **Phase III:** After the lifesaving rescue activity in the disaster area is completed, it becomes necessary for people in the area to continuously collect information about the damaged/recovered environments for safety confirmation and life support over the long term.

These phases are not exclusive and they usually overlap. For example, Phases I and II would be alternatively iterated in order to investigate a wide disaster area. The Phase III actions are desirable even in normal circumstances so as to confirm the safety of the community.

3.3.2 Aerial Robot Team for USAR

As discussed above, at present, it is very difficult for us to develop an aerial robot that can complete every mission in Phase I, II and III. A practical approach to the development of aerial robot systems for USAR is to organize an aerial robot team equipped with multiple aerial robots of different functionalities as follows:

1. **Phase I:** The aerial robot system for Phase I is a helicopter-based robot system. It takes off from the robot base immediately after the disaster and collects disaster information automatically. It has high mobility in the air, but its continuous operating time is usually less than one hour.

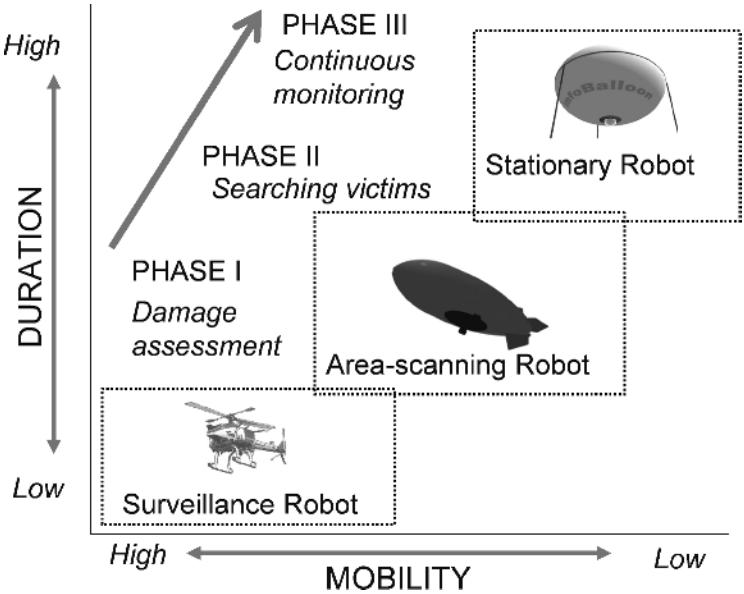


Fig. 3.3 Role-sharing of aerial robots for USAR

2. **Phase II:** The aerial robot systems for Phase II are a middle-sized autonomous blimp and a wire-driven balloon robot. These robots can sweep through the destroyed area at low altitude without generating interfering flight noise. Robots for Phase II have medium performance mobility and continuous operation time.
3. **Phase III:** The Phase III aerial robot system provides continuous information to the disaster-struck community. An aerial robot system based on a captive balloon is adequate to meet this requirement.

Figure 3.3 illustrates the role-sharing of aerial robot systems in USAR. Three different types of aerial robot systems are assigned, shown on a graph with two axes, mobility and duration.

3.3.3 Action Scenario of Aerial Robot Systems for USAR

Based on the discussion about the aerial robot team for USAR, six R&D groups in the AIR MU have developed various types of aerial robots to carry out the three phases.

Kyoto University group and Chiba University group have been developing intelligent autonomous helicopter systems [1, 3]. These aerial robot systems are expected to execute initial investigations collecting damage data from affected areas using their high mobility in Phase I.

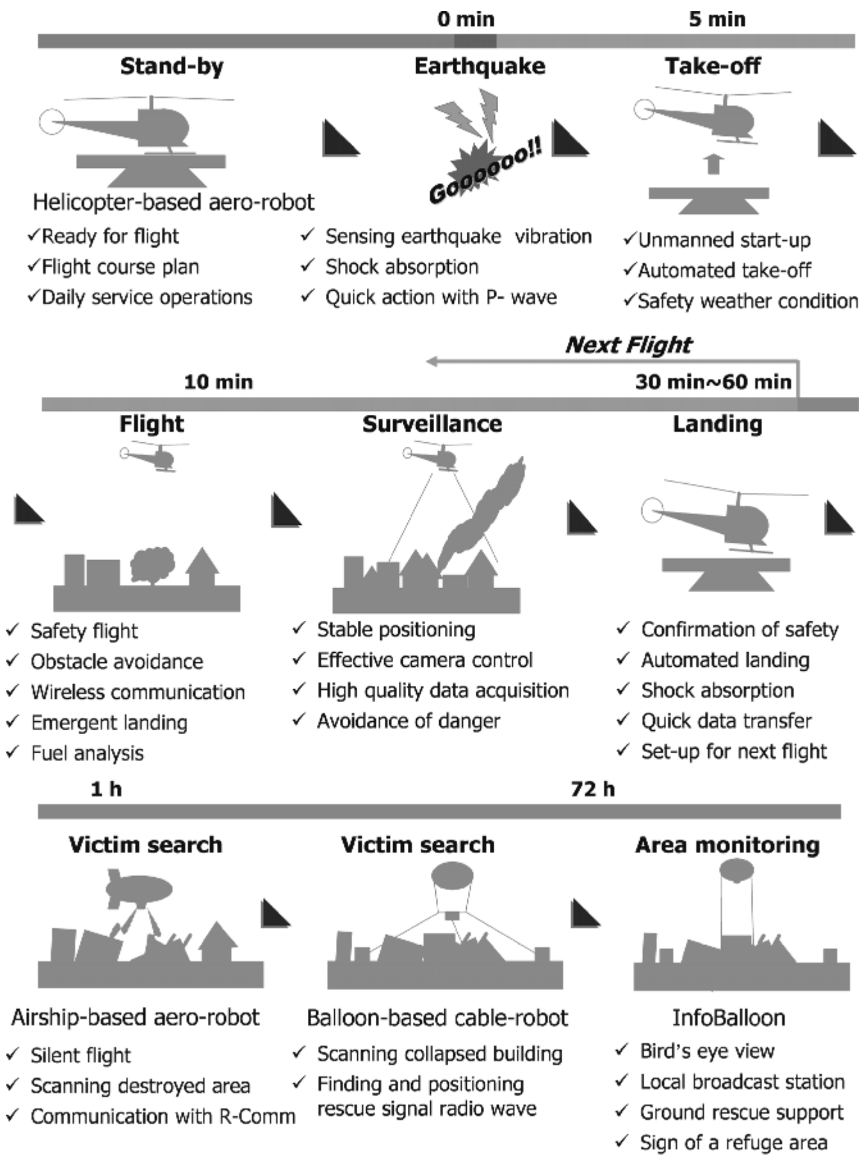


Fig. 3.4 Action scenario of aerial robot systems for USAR

A joint research group from RIKEN and the University of Tokyo has been developing a rescue request collection system using a blimp and intelligent communication devices named the Rescue Communicator (R-Comm) [2]. A joint research group from IRS, Machine Technical College, and Tohoku University has been developing an aerial robot system that is supported by three cables and lifted by a balloon [9]. This robot system has sensing devices to search for victims under the rubble. These two aerial robot systems are mainly used for USAR activities in Phase II.

Hokkaido University group has been developing InfoBalloon, which is a captive balloon with information acquisition and communication devices [7]. This system is designed for Phase III services such as continuous collection of local disaster situation data.

Shizuoka University group's mission is not robot development but the development of image processing with which low-quality camera images can be appropriately clarified. This method realizes a virtual wiper for monitoring cameras in dust-laden environments [10].

Figure 3.4 illustrates an action scenario of aerial robot systems developed by the AIR MU. In the following sections of this report, each aerial robot system is explained in detail.

3.4 Aerial Robot Systems Developed by AIR MU

3.4.1 Autonomous Unmanned Helicopter (Medium-Sized Vehicle)

An autonomous unmanned helicopter, named intelligent aerorobot, was developed by the Kyoto University group directed by H. Nakanishi. The platform of this intelligent aerorobot is an unmanned and middle-sized helicopter manufactured by Yamaha Motor Co. Ltd for agricultural chemical spreading. Based on this platform, an intelligent control unit with GPS and gyro sensor, a remote control camera system, wireless communication modules, and other additional equipment are mounted for extended capabilities of autonomous flight and adaptive information gathering.

The intelligent aerorobot is stably controlled by a hybrid control system combining GPS data and an inertial navigation system (INS) developed at Kyoto University.

The flight stability and accuracy achieved by the hybrid controller are superior to that achieved by expert human operators, particularly during hovering even in windy conditions.

The flight stability of the intelligent aerorobot contributes to the capture of high quality pictures and videos because of reduced motion of the loaded camera.

Figure 3.5 (a) and (b) show side and rear views of the intelligent aerorobot, respectively.

Fig. 3.5 Intelligent aerorobot developed by Kyoto University group: **a** intelligent aerorobot's side view. **b** Rear view. **c** Van for robot transportation, equipped with control and monitoring devices

In addition to better flight performance, the intelligent aerorobot has the advantage of easy operation compared with other remote-controlled aerial vehicles. The intelligent aerorobot can be monitored and controlled using a simple control panel on a notebook PC. An operator specifies only the flight target points on a GUI using a mouse and is not required to have knowledge about the flight mechanism and vehicle flying state to operate the intelligent aerorobot. Figure 3.6 shows an overview of the control panel for the intelligent aerorobot and a test operation by a first responder who visited a flight demonstration.

The intelligent aerorobot can be transported by van and requires only two operators for robot set-up and operations. The console panel equipped with a control and monitoring PC and wireless communication equipment is carried in the luggage compartment of the transport van. High mobility of the intelligent aerorobot system is a desirable functionality for practical operations in USAR.

Fig. 3.6 Easy operation of the intelligent aerorobot with GUI on a notebook PC

3.4.2 Autonomous Unmanned Helicopter (Small Vehicle)

The Chiba University group directed by K. Nonami has developed various aerial robot systems based on unmanned and small helicopters for hobby use.

The Chiba University group has developed an automatic control rule that realizes stable flight of various-scale helicopters and an autopilot unit applicable to various-scale helicopters.

One of the unmanned helicopters developed by this group has been applied to the inspection patrol of a power line in cooperation with an electric power company. Thus, aerial robot systems can be used effectively for many ordinary applications in industry and social services besides their use in USAR.

The Chiba University group has also developed important technology for the safe operation of helicopter-based aerial robots. If the engine of a helicopter fail in flight, the controller controls rotation of the main rotor so as to descend slowly and make a safe landing. This technology (autorotation landing) decreases the risk of a crash caused by fuel starvation or engine breakdown.

Small helicoptor-based aerial robots have several restrictions compared with medium-sized ones; for example, they have lower flying speed, continuous working time and payload. Further, they are more affected by bad weather conditions

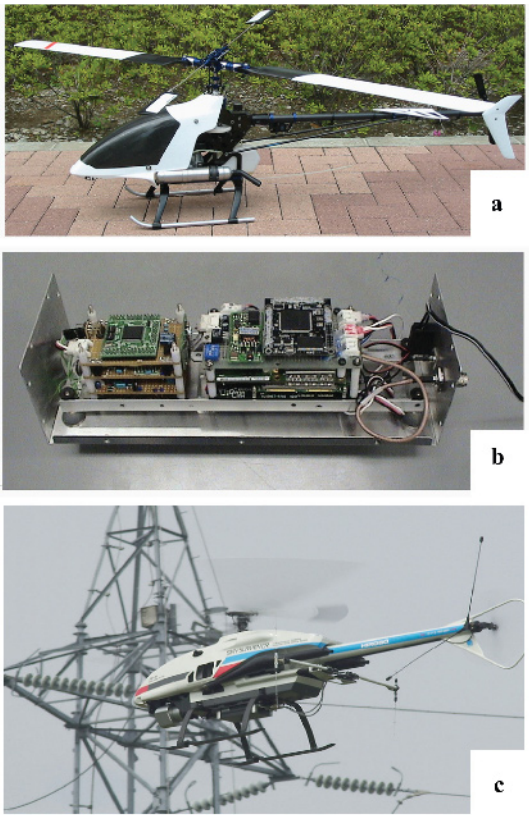


Fig. 3.7 Small-size autonomous unmanned helicopter developed by Chiba university. **a** SST-eagle2-EX (gross load 5 kg). **b** Autopilot unit (weight 0.5 kg). **c** Power-line inspection patrol helicopter (gross load 48 kg)

such as strong winds. However, they have the advantage of easy and low-cost operation. Thus, in USAR missions, it is necessary to select medium-sized or small aerial robots depending on the conditions.

3.4.3 Autonomous Blimp-Type Robot System

A joint research group from RIKEN and the University of Tokyo, directed by K. Kawabata, has developed an autonomous blimp-type robot system. This robot system flies slowly at low altitude over a disaster area, collecting any sign of victims under collapsed structures. The swept areas are decided in accordance with the disaster information collected by the unmanned helicopter systems.

This surveillance operation must be done silently, since noise from a surveillance robot may drown out a victim's calls. Helicopters and airplanes make loud continuous noises during flight and these air vehicles are unsuitable for surveillance listening for sounds. The blimp-type system can stop its thrusters and hover in the air while sensing signals from collapsed structures.

The basic specifications of this blimp-type robot system are as follows:

- fill gas: He, 24.9 m^3;
- size: length 6.5 m, width 3.0 m, height 4.1 m;
- propulsion: two electromotive thrusters, more than 8.0 N; and
- payload: 8.0 kg.

When the robot system is flying in a closed environment or in a light wind, it can be moved spatially by a computer control.

Small blimps like this robot system are usually uncontrollable in windy condition due to insufficient propulsive force to counter wind flows.

More powerful propulsion units increase the weight of the robot system and require a bigger helium gas chamber, which then causes more wind resistance. Further, large robot systems have less mobility and high cost. Therefore, the development of high-energy-density batteries and high-efficiency thrusters is necessary in order to solve this problem. One practical solution to the problem of blimp operation in windy conditions, is to use anchor ropes to hold the blimp at a downwind position. This concept is applied to the wire-driven balloon robot system explained in the next section.

Sweep tests using the blimp-type robot system were carried out in the rescue-robot test field at IRS's Kawasaki Laboratory, as shown in Fig. 3.8 (b) and (c). A Rescue Communicator (R-Comm) developed in the DDT project was loaded on the blimp-type robot system and received rescue request messages from other Rescue Communicators distributed across the test field. The robot system used a three-dimensional laser profiler to generate three-dimensional models of swept areas. (see Fig. 3.8 (d))

3.4.4 Cable-Driven Balloon Robot System

In addition to the blimp-type robot system described in the preceding section, a cable-driven balloon robot system has been developed as a collaborative work by IRS, Marine Technical College and Tohoku University, directed by F. Takemura, who is a former IRS researcher and now on the staff of Okinawa National Technical College. The cable-driven balloon robot is supported in the air by three extensible cables. At each corners of a big base triangle, a computer-controlled winder is fixed on the ground (Fig. 3.9 (a).) The winders are controlled from a mobile PC via wireless communication. By changing each cable length according to commands given by the control PC, the balloon body changes its 3D position in the air. Thus, the robot can sweep the ground area inside the base triangle of which corners have the

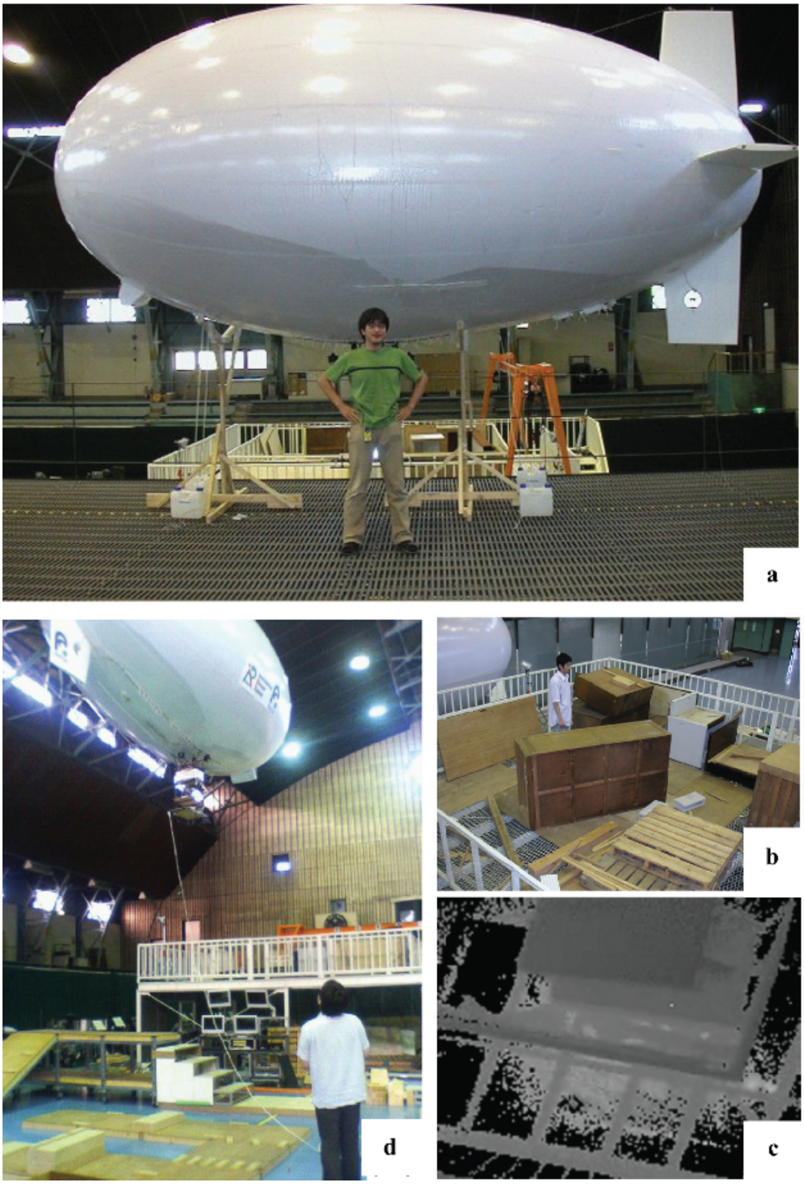


Fig. 3.8 Autonomous blimp-type robot system develped by RIKEN and the University of Tokyo. **a** Overview. **b** Sweeping an experimental section at Kawasaki Laboratory, IRS. **c** Collapsed house experiment facility. **d** Measuring image from a 3D profiler

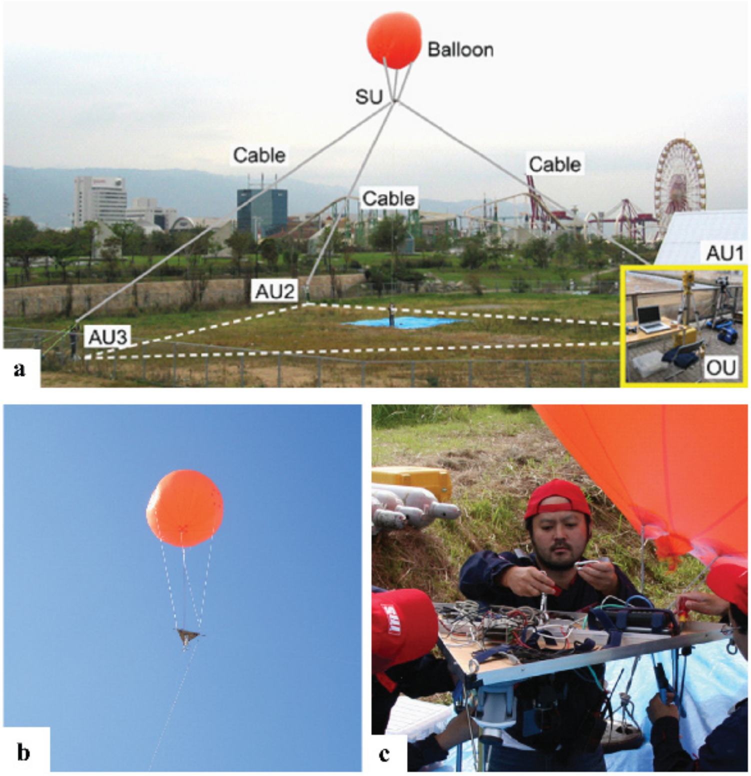


Fig. 3.9 Cable-driven balloon robot system. **a** Overview. **b** A balloon body lifting a triangle base. **c** Mounting mechanical elements on a machine base frame

winders. The balloon body filled with He gas supports a machine base frame on which is mounted a CCD camera, wireless communication devices, and measurement equipment to detect rescue request signs from collapsed structures (Fig. 3.9 (b) and (c).)

Compared with the blimp-type robot system, the cable-driven balloon robot system has a limited sweep area for each base triangle, but it has some advantages. The cable-driven balloon robot has high stability against winds and its 3D position in a working space is easily measured and controlled. The stability of the machine base frame provides a convenient platform for sensing devices. In addition, the cable-driven balloon robot system has a power supply line connecting to a power source on the ground. Thus, this robot system can be operated continuously for a long time.

3.4.5 Captive Balloon Robot System

Hokkaido University group directed by M. Onosato has developed a captive balloon robot system for long-term information gathering in a disaster area. The system is named InfoBalloon.

In the development of an aerial robot system using a helium gas balloon, the following problems should be solved for long-term and stable operation:

- Balloons made of PVC or latex sheet cannot hold He gas for a long time. Therefore, it is necessary to add or replace the gas in a balloon every few days.
- If a balloon bursts in the air, its sensor platform will fall at high speed and may cause a serious accident on the ground.
- Spherical balloons, commonly used as ad-balloons, have higher wind resistance than kytoon-type balloons.
- Balloons anchored with a single wire are easily swept away downwind and lose altitude.

To solve the problems of traditional balloons, a new type of balloon was designed with the following features:

- InfoBalloon's body has a double-layer structure, which consists of an outer envelope for mechanical strength and an inner film for the He gas. InfoBalloon can maintain its buoyancy for more than a month.
- Its double-layer structure gives less risk of puncture and subsequent fall to the ground.
- InfoBalloon adopts the form of a vertically depressed sphere (Fig. 3.10.) The height of InfoBalloon's body is 2.3 m and its radius is 4.0 m. This shape has less wind resistance and produces some lift force from a wing effect due to wind flow.
- It is supported with three parallel wires fixed to a tetrahedral frame with a pivot base. With this anchor method and balloon shape, InfoBalloon autonomously maintains its position in the air (Fig. 3.10 right part.)

A CCD camera with a pan-tilt-zoom(PTZ) control is carried by InfoBalloon and the video images are transmitted using wireless communication. In addition to the equipment for disaster information gathering, small equipments for communication relay and radio broadcast can be loaded into its chamber space. In experimental operations, InfoBalloon was successfully held at 100 m altitude, and continuous video images were sent by the PTZ camera via a wireless LAN connection.

As part of the InfoBalloon project, a simplified balloon system for one-time use has been developed. It is easy to make a balloon with a rounded tetrahedral shape because all seals of the gas barrier film are straight. The simple balloon, named InfoBalloon-TETRA, with a tele-operation digital camera, can take high-quality photographs from the sky. Figure 3.11 shows an overview of InfoBalloon-TETRA and a bird's-eye-view photograph.

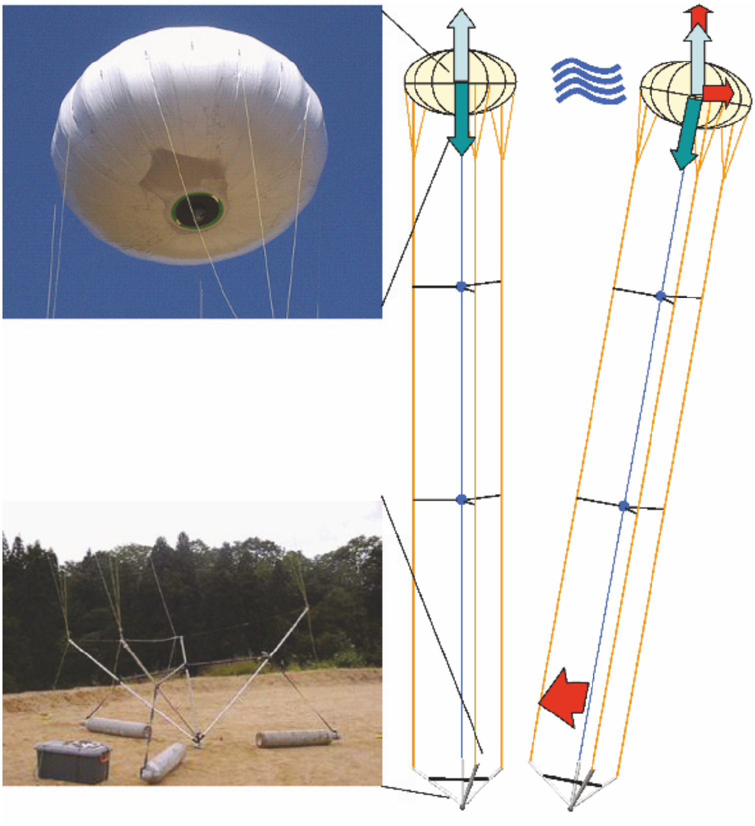


Fig. 3.10 Captive balloon robot system: InfoBalloon

3.4.6 Image Clearing for Field Camera Systems

The image-clearing method introduced in this subsection was developed not only for a particular robot system, but for every robot system used in disaster situation. Shizuoka University group directed by K. Miura has developed an image-clearing method for a field camera system.

The robots used for USAR usually operate in a dusty environment and the lenses and protection glass of camera systems mounted on these robots are frequently spotted with mud and water drops. Some camera systems are equipped with a cleaning wiper to remove such spots from their lenses and protection glass. Such equipment is expensive and heavy, whereas monitoring cameras loaded on aerial robots should be compact and lightweight.

The Shizuoka University group has proposed a new image-clearing method, named "virtual wiper," based on an image restoration technique. With this method, two more cameras are used to separate the dirty spots present on the lens or protec-

Fig. 3.11 InfoBalloon-TETRA and a bird's-eye-view photograph captured by it

tion glass from scene images. Figure 3.12 shows an example of clearing images for a stereo camera system. The concept of a virtual wiper will be widely used for field camera systems in USAR and other field activities.

3.5 Field Test of Aerial Robot Systems at Yamakoshi

The aerial robot systems developed by the AIR MU were tested at the Yamakoshi region in September, 2006. The Yamakoshi region, a part of Nagaoka City and Niigata Prefecture, was severely damaged by the Niigata-Chuetsu Earthquake in 2004. The Yamakoshi region is an area with many mountains and deep valleys. The earthquake caused a number of landslides and blocked most roads connecting to other neighboring towns. Thus, the Yamakoshi region was completely isolated in terms of both traffic and communications, and it was important for rescue activity to gather disaster information about this region from the air as quickly as possible. Figure 3.13 shows two photographs of a test site, the Takano firm, at the Yamakoshi region. At the time of the field test, the test field was specified as a restriced area for damage repair.

Some groups of the AIR MU brought the following systems to the Yamakoshi region for field tests:

- Intelligent Aerorobot (autonomous unmanned helicopter: medium size);
- cable-driven balloon robot system;
- InfoBalloon (captive balloon system);
- Rescue Communicators; and
- omnidirectional camera system.

The Shizuoka University group joined this test from a remote site in Hamamatsu and cleared the dirty images sent from the Yamakoshi site via the Internet using the virtual-wiper technique. A long-distance wireless communication facility was set up temporally for this field test.

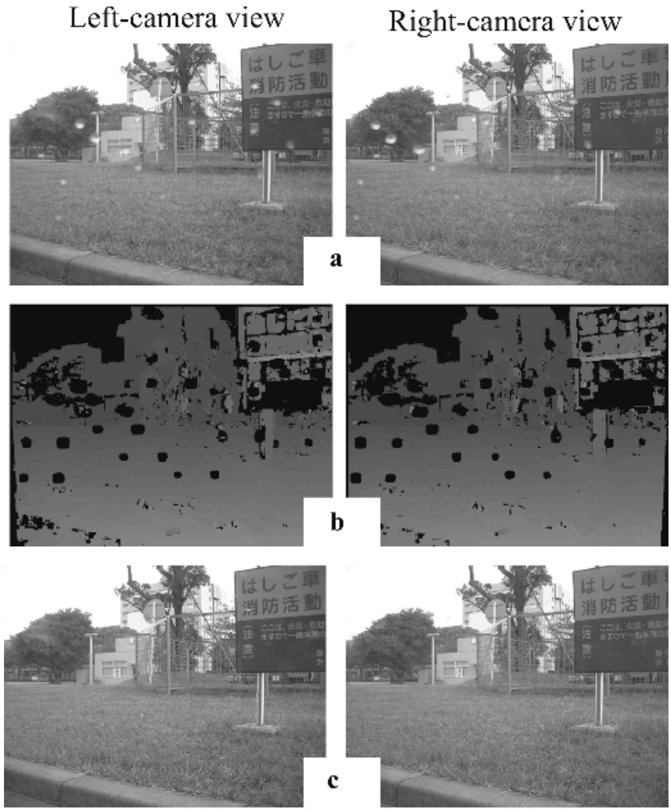


Fig. 3.12 Example of image restoration. **a** Original images. **b** Noise detection by disparity estimation. **c** Noise removal

The objectives of this field test of aerial robot systems were as follows:

- to test each robot system in a natural environment, including land conditions and weather conditions;
- to test collaborative operations by multiple robot systems;
- to test long-range wireless communication in mountaineous areas; and
- to demonstrat the availability of aerial robot systems for disaster-prevention organizations.

Most of these test items were successfully carried out. In addition to the high performance of the developed robot systems, the field test also demonstrated the ease of system setup operations. A small staff was sufficient for system preparation and operations. For example, the intelligent aerorobot was quickly prepared by two operators. Figures 3.14 and 3.15 show snapshots of the preparation of aerial robot systems.

Fig. 3.13 Overviews of the test site at Yamakoshi region

Fig. 3.14 Set-up of aerial robot systems at Yamakoshi test site

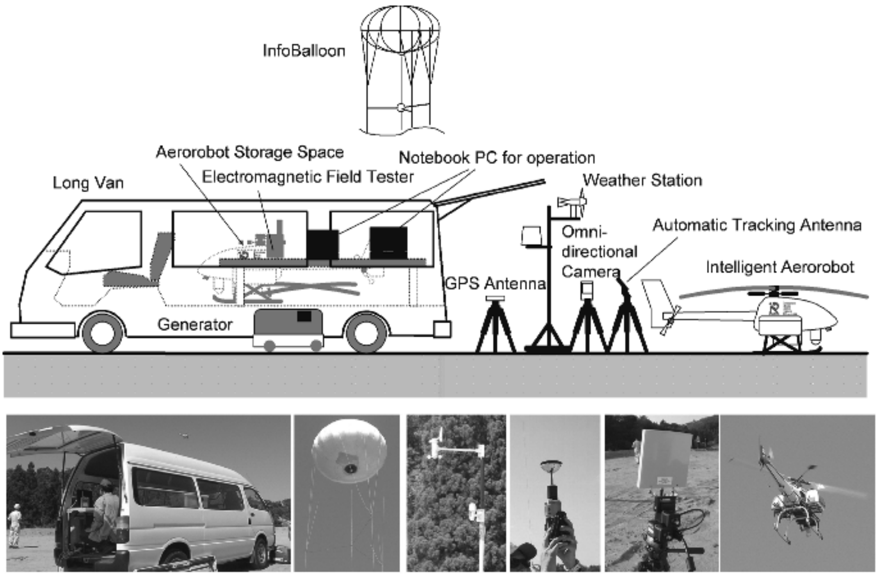


Fig. 3.15 Overviews of ground facility for aerial robot systems

The system configuration for the Yamakoshi field test is illustrated in Figure 3.16. Only the cable-driven balloon robot was tested at the Iketani area because the scheduled test place for the robot at Takano farm area was closed for disaster-relief work. Detailed explanations of the DaRuMa and R-Comm can be found in other MU reports.

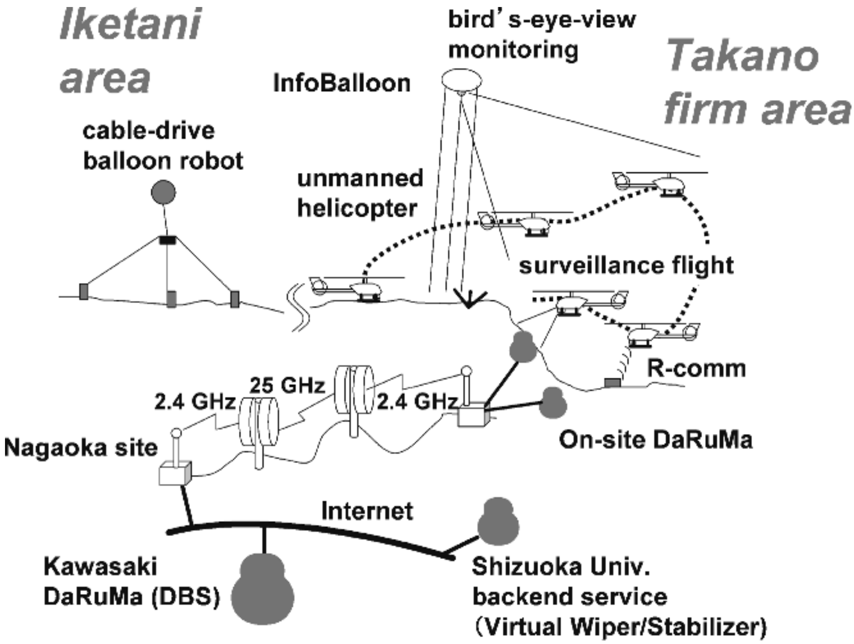


Fig. 3.16 Overview of robot system configuration for Yamakoshi test

3.6 Summary of R&D Results by the AIR MU

This report can only introduce a few of the R&D results obtained by the AIR MU among many other interesting and important results. Important R&D results obtained by the AIR MU are summarized below.

Unmanned Autonomous Helicopters

- Autonomous and stable flight by a intelligent control unit equipped with GPS and INS;

- GIS-based user interface for flight path planning and monitoring;
- automatic take-off and landing;
- automatic object tracking flight by camera image processing;
- soft landing by autorotation;
- digital terrain modeling with a 3D laser profiler;
- integrated GUI for monitoring and operation;
- automatic antenna control for aerial remote robot tracking based on GPS and INS data; and
- formation flight control method for autonomous helicopters.

Autonomous Blimp and Balloons

- Blimp's autonomous flight by model predictive control;
- moving-object-extraction method using range sensor mounted on a blimp;
- low-speed blimp flight for capturing messages from R-Comms in collapsed structures;
- balloon-sweeping method using three extensible cables;
- vertically depressed spherical shape for balloon body for wing effect;
- double-layer strucuture of balloon body for gas barrier properties and mechanical strength; and
- stable control method of captive balloon position with three parallel wires and a pivot base.

Field Image Processing and Disaster Information Archiving

- Image restoration by multiple camera images;
- remote image restoration service for field camera systems via Internet;
- real-time cancellation of image blurring using a graphic processing unit (GPU); and
- quick search of interest points from aerial video archive using GIS.

Some of these resutls have been published as papers shown in the reference list of this chapter and others will be presented or published by each member of the AIR MU in the future.

3.7 Conclusions

The AIR MU has been mainly concentrating its efforts on the initial stage just after the occurrence of an earthquake. It is important to start this information-gathering process automatically since it may take a long time for human operator start-up. In the first hour, aerial robots based on autonomous helicopters are expected to automatically survey the concerned area. When the disaster headquarters are organized at the local government, the collected data will be available for effective decision making.

The main R&D results of the mission unit should be examined in more practical fields, and the part of the the action scenario in which different rescue robots effectively collaborate must be demonstrated. The information services provided to other rescue robots and human teams working on the ground are also important roles of aerial robot sysytems. Such a collaborative scenario involving many agents must be tested in future for practical support of USAR.

The R&D project of the AIR MU has contributed to the technological advancement of aerial robots for USAR. Some aerial robots already have sufficient functionality to perform unmanned operations in a disaster situation, however, it is still difficult to carry out the action scenario using the aerial robots described in this paper. Aerial robots are not allowed to fly over people and constructions even in the disaster area due to the risk of aerial robot crash. Establishment of a community's consensus for aerial robot service at the time of a disaster is most important in order to realize the scenario of disaster information gathering.

Acknowledgements Most works in this report were financially supported by the DDT Project (Special Project for Earthquake Disaster Mitigation in Urban Areas, III-4 Development of Advanced Robots and Information Systems for Disaster Response) sponsored by the Ministry of Education, Culture, Sport, Science and Technology. In addition to the coauthors of this reports, many collaborators such as AIR MU's group students, IRS staff, Nagaoka city staff made great contributions to this project. The authors would like to thank them for their significant contributions.

References

1. Bando M, Nakanishi H (2006) A stable approach for modular learning and its application to autonomous aero-robot. J Robotics and Mechatronics 18-1:44–50
2. Hada Y, Kawabata K, Kaetsu H, Asama H (2005) Autonomous blimp system for aerial infrastructure. Proc URAmI'05, KRW057
3. Hazawa K, Shin J, Fujiwara D, Igarashi K, Fernando D, Nonami K (2003) Autonomous flight control of unmanned small hobby-class helicopter, Report 2: Modeling based on experimental identification and autonomous flight control experiments. J Robotics and Mechatronics 15-5:546–554
4. Noda I (2006) Information sharing and integration in rescue robots and simulation. Proc SRMED2006 30–35
5. Ollero A (2003) Control and perception techniques for aerial robotics. Prep. 7th IFAC Symposium on Robot Control 717–725
6. Onosato M (2006) Mission Unit: Information Acquisition from the Sky (Aero-robots). Prep. 4th International Symposium on Rescue Robots
7. Onosato M, Watasue T (2002) Two attempts at linking robots with disaster information: InfoBalloon and gareki engineering. Advanced Robotics 16-6:545–548

8. Tadokoro S (2005) Special project on development of advanced robots for disaster response (DDT Project). Proc IEEE Int Workshop on Advance Robotics and its Social Impacts (ARSO'05)
9. Takemura F, Enomoto M, Denou K, Erbatur K, Zwiers U, Tadokoro S (2005) A human body searching strategy using a cable-driven robot with an electromagnetic wave direction finder at major disasters. Advanced Robotics 19-3:331–347
10. Yamashita A, Harada T, Kaneko T, Miura KT (2005) Virtual wiper – Removal of adherent noises from images of dynamic scenes by using a pan-tilt camera – Advanced Robotics 19-3:295–310

Chapter 4
Information Infrastructure for Rescue Systems

Hajime Asama, Yasushi Hada, Kuniaki Kawabata, Itsuki Noda, Osamu Takizawa, Junichi Meguro, Kiichiro Ishikawa, Takumi Hashizume, Tomowo Ohga, Kensuke Takita, Michinori Hatayama, Fumitoshi Matsuno, and Satoshi Todokoro

Abstract In a disaster situation, it is important to quickly collect global information on the disaster area and victims buried in the debris awaiting rescue. In the DDT project (Special Project for Earthquake Disaster Mitigation in Urban Areas, III-4 Development of Advanced Robots and Information Systems for Disaster Response), research and development activities on rescue infrastructure for global information collection have been carried out. In infrastructure-related activities carried out by the mission unit, ubiquitous handy terminal devices and technology for forming ad-hoc wireless communication networks were developed. In addition, technology was developed to integrate the information collected, including communication protocol

Hajime Asama
University of Tokyo

Yasushi Hada and Osamu Takizawa
National Institute of Information and Communications Technology (NICT)

Kuniaki Kawabata
RIKEN (Institute of Physical and Chemical Research)

Itsuki Noda
National Institute of Advanced Industrial Science and Technology (AIST)

Junichi Meguro, Kiichiro Ishikawa and Takumi Hashizume
Waseda University

Tomowo Ohga
Asia Air Survey Co., Ltd.

Kensuke Takita
HiBot Corporation

Michinori Hatayama
Kyoto University

Fumitoshi Matsuno
University of Electro-Communications

Satoshi Tadokoro
Tohoku University

design, on a GIS system. In this paper, the current R&D activities of the mission unit with regard to infrastructure in the DDT project are overviewed, and some technologies developed thus far are introduced.

4.1 Introduction

In the disaster situation presented by an earthquake, it is important to collect various types of information on the disaster as soon as possible and provide it to the right people. Quick acquisition of information on the locations of the damaged area, nature of the damage, and locations of debris under which victims are possibly trapped is necessary for rescue strategy planning. At the same time, people affected by the disaster seek information on the locations of refuge and family. For collecting and providing such information, the infrastructure of information plays quite an important role. In a disaster situation, conventional information infrastructure such as the Internet and cellular phones could possibly be damaged and rendered useless. Therefore, it would be indispensable to develop an ad-hoc information infrastructure. In this paper, the recent R&D activities of the mission unit related to infrastructure for the DDT project [13] are overviewed, and some technologies developed thus far are introduced.

4.2 Rescue Infrastructure

4.2.1 Information Collection and Sharing in the DDT Project

In the Japanese project for the Development of Advanced Robots and Information Systems for Disaster Response in DDT (Special Project for Earthquake Disaster Mitigation in Urban Areas, III-4 Development of Advanced Robots and Information Systems for Disaster Response) [13], the infrastructure mission unit has been developing ubiquitous devices for collecting information on the disaster area with the construction of an ad-hoc network, and a system to integrate the information collected into a GIS (Geographic Information System). In the DDT project, various types of robots (on-rubble robots, in-rubble robots, and aerial robots) have been developed to search for victims, collecting information on the disaster area, etc. It is expected that the information infrastructure would collaborate with these robots. The information collected by the robots is transmitted by ubiquitous devices in the information infrastructure and integrated with a GIS. The robots can also utilize this information (e.g., map information and victim information) stored in a GIS to operate intelligently and effectively.

4.2.2 R&D Activity Overview in Infra-MU

This mission unit [1, 2] has conducted research and development in technology to integrate the information obtained from a large number of intelligent sensors distributed over a disaster-stricken area. Operating effectively as a system in real time, network household electric appliances, PDAs, and robots provide information, and an action plan can be developed for an area stricken by disaster. We have implemented trial production based on the research and development work carried out thus far, with emphasis on the following two developments:

1. developing a ubiquitous handy terminal device and technology for forming an ad-hoc wireless communication network; and
2. designing communication protocols and developing a technology to integrate the information collected in a GIS system.

Figure 4.1 depicts the final stage of the R&D activities of the mission unit with regard to rescue information infrastructure.

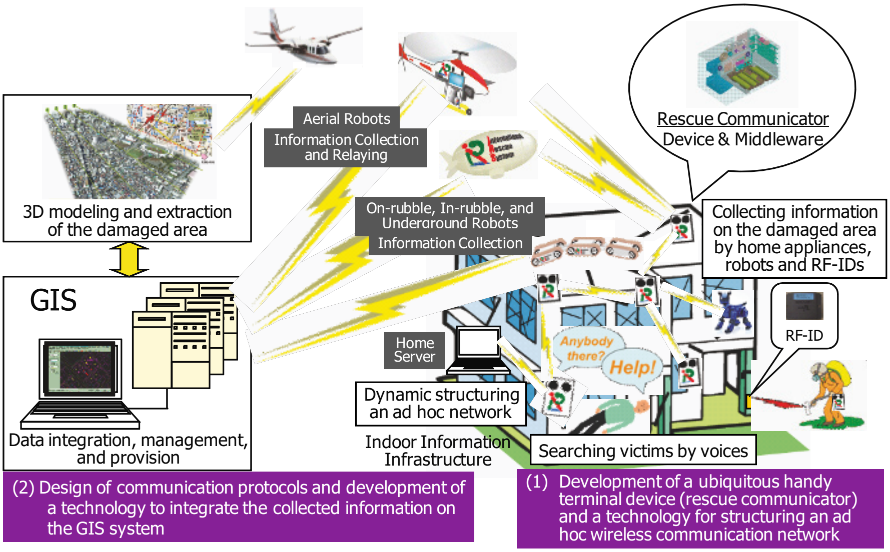


Fig. 4.1 Task force in rescue infrastructure

4.3 Development of Ubiquitous Devices for Collecting and Providing Information

4.3.1 Development of Rescue Communicator

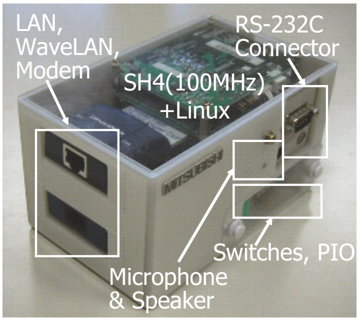
A new intelligent sensor node called the Rescue Communicator (R-Comm) has been developed for collecting and providing information as a ubiquitous device for a rescue information infrastructure platform. The main specifications of the R-Comm are listed in Table 4.1. The R-Comm comprises a microprocessor, a memory, three compact flash slots, a voice playback module including a speaker, a voice recording module including a microphone, a battery including a power control module, and two serial interfaces. One of the compact flash slots is equipped with a wireless or wired LAN model for wireless/wired communication. Linux is installed and used as the OS for the R-Comm. An RF-ID reader/writer and other peripheral devices can be connected to the serial interface. When the power plug is connected, the power control system charges the battery, and if the power supply is cut, the power control system switches the power source automatically to the battery. For intermittent use, the system can operate for 72 h, which is the critical time for humans to survive.

Two types of R-Comm were developed "long type and short type" depending on the inclusion or exclusion of the compact flash cards. Figure 4.2 shows the images of the two types of R-Comm.

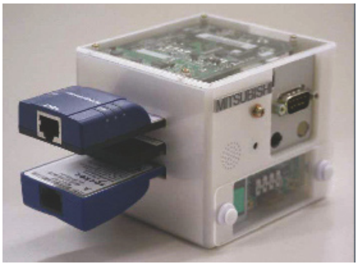
A function to form an ad-hoc network among multiple R-Comms was developed. Any data collected by the R-Comms can be sent not only by a one-to-one wired/wireless communication link, but also by hopping among multiple devices using the common protocol MISP via the ad-hoc network, which was also developed in this project. The details of the protocol are presented later.

Table 4.1 Specifications of R-Comm

Item	Specification
CPU	Renesas SH4 (100 MHz)
Memory	32 MB
Extension slot	Compact flash x3, RS-232C x2
Communication	Wireless LAN, InfraRed, RS-232C
Other interfaces	AD/DA/voice
Size	985 / 635 cc, 500g
Acting time	4 h (continuous), 72 h (intermittent)



a



b

Fig. 4.2 Images of R-Comm. **a** Long type. **b** Short type

4.3.2 Verbal Victim Search by R-Comms

A verbal victim search system was developed at RIKEN (The Institute of Physical and Chemical Research) and the University of Tokyo by utilizing the voice playback and recording function of the device [3, 7]. In an emergency situation, the device set in the living environment can be activated by signals sent from external systems or earthquakes detected by internal sensors (occurrence of vibration or voltage drop). The devices can then be operated automatically to call for victims by playing voice messages and by recording sounds for several seconds after a message, in which any voice reply by the victims must be included.

The device is supposed to set off fire alarms in houses/buildings, or serve as a wireless LAN router/access point for homes in advance. Figure 4.3 (a), (b), and (c) show the victim search procedure in the latter case.

In the normal situation, the R-Comm functions as a network router, as an access point, or as a bridge, and can provide home network services including information for home appliances, for nursing elderly people, or for security, as shown in Fig. 4.3 (a). However, if the R-Comm detects earthquakes, it changes its mode, broadcasts emergency information, calls for victims, collects information on victims, and sends the information to a disaster management center, as shown in Fig. 4.3 (b). If the global network is down, the R-Comm forms the ad-hoc network automatically with neighboring devices to send information, as shown in Fig. 4.3 (c).

A new version of the R-Comm is under development by the IRS (International Rescue System Institute); the new version has a TITech Wire I/F giving high expandability to add functions to control robots, such as A/D converters, D/A converters, counters, and motor drivers. PCMCIA card I/F and IEEE 1394 I/F modules are also under development for the new version.

To realize a distributed search environment, a miniature type R-Comm with reduced function is also under development. By using the miniature R-Comm, we can construct a hierarchical local network by one parent R-Comm and several miniature R-Comms, which can be deployed in each room. Figure 4.4 shows an experimen-

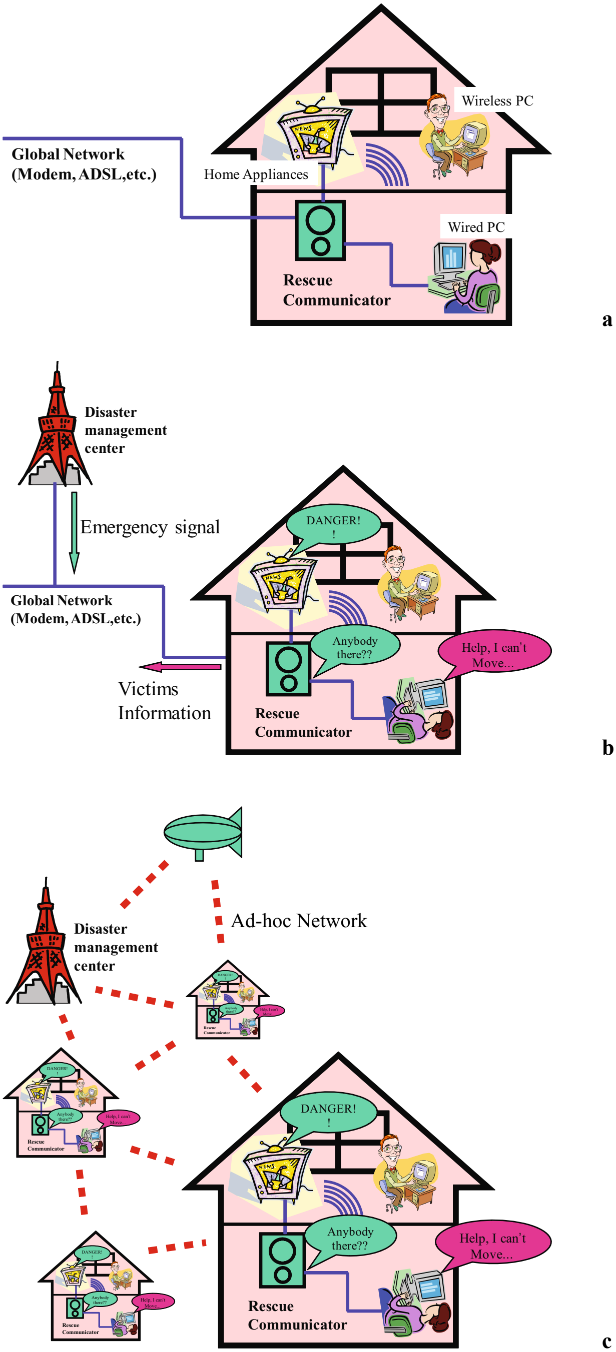


Fig. 4.3 Procedure of victim search depending on situation. **a** Normal situation. **b** Emergency situation (global network is alive). **c** Emergency situation (global network is down)

tal setup to construct such a local network using one parent R-Comm and three IDR-Rs (Intelligent Data Carriers for Rescue) representing the miniature R-Comm terminals.

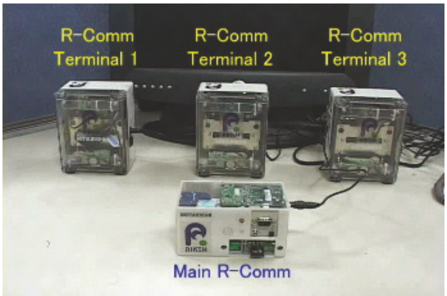


Fig. 4.4 Local network setup

UAV (unmanned aerial vehicle) is an effective means to collect sensory data stored in R-Comms using an ad-hoc network and to link them to record videos from the air. Field tests using an unmanned blimp developed by RIKEN [4, 5], a cable-driven balloon developed by the IRS [14], and an autonomous helicopter developed by Kyoto University [10] were carried out as shown in Figs. 4.5, 4.6, and 4.7, respectively. The communication between the R-Comm and UAVs was found to be reliable within 5 m, 40 m, and 20 m in the case of the blimp, balloon, and helicopter, respectively, while the stable communication range on ground without occlusion was 300 m.

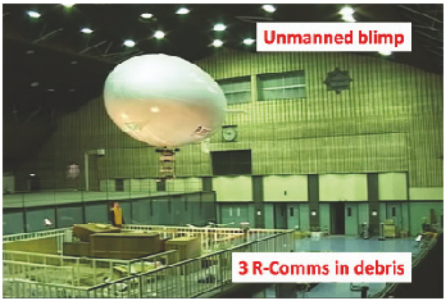


Fig. 4.5 Communication test between blimp and R-Comm in indoor environment

4.3.3 RF-ID-Based Emergency Information Collection and Delivery System

A disaster information collection system using an RF-ID transceiver and ad-hoc network was developed at the NICT (National Institute of Information and Commu-

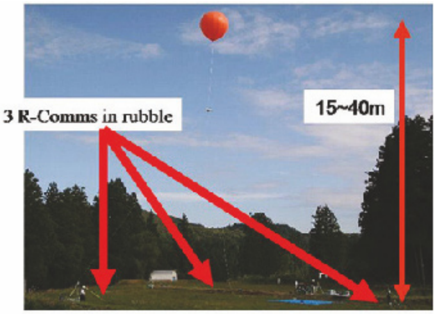


Fig. 4.6 Communication test between balloon and R-Comm

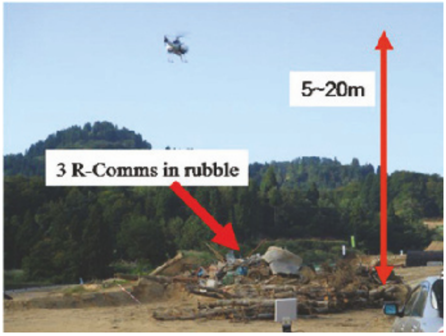


Fig. 4.7 Communication test between helicopter and R-Comm

nications Technology) [15, 16]. RF-ID is useful as a means to collect information on damage and the state of people with the help of intelligent devices and networks to determine strategies for rescue in disasters. A victim evacuated from a damaged house to a point of refuge can place an RF-ID tag at the entrance gate of his/her house and write into the tag a message indicating his/her safety and the place of refuge to any family member that may visit the house; here, the RF-ID tag works as an electrical signboard.

Another use of RF-ID tags is information storage on logs for victim search using rescue surveyors and corps. Any fire fighters, rescue surveyors, or corps searching the house can store the results of the search in the tag set at the entrance gate. This information can be shared by any other rescue surveyors or corps who visit the location with a reader device. The information can also be transmitted to a disaster information management center where all the information is collected, integrated, and utilized.

Figure 4.8 shows the handy terminal and RF-ID tag developed. A GPS antenna is equipped with the handy terminal. The rescue corps carrying the terminal can see a map of the damaged area with symbols over locations for which rescue information is stored; the information can be displayed using a GIS.

The rescue corps visiting a location where a tag is placed can read the message in the tag using a reader device, and can store the information together with the location information obtained by the GPS antenna in the GIS system. Alternatively,

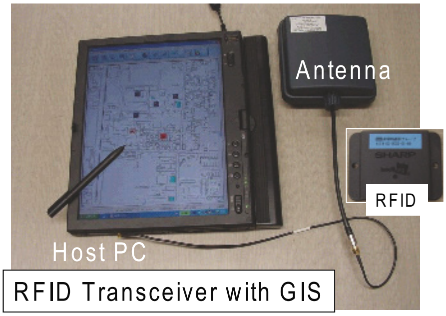


Fig. 4.8 Handy terminal and RF-ID tag

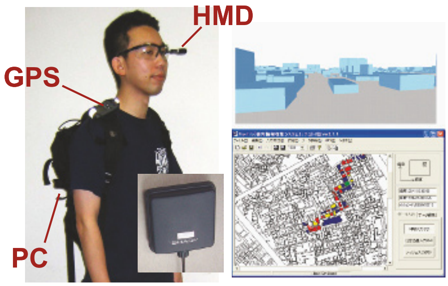


Fig. 4.9 Wearable system for rescue surveyor

they can send the information to a center by wireless communication. Figure 4.9 shows a wearable terminal prototype with which the rescue corps can see a 2D or 3D map with rescue information through an HMD (head-mounted display).

Field test experiments were carried out on the system, and it was verified that the information obtained by multiple rescue corps carrying the terminal device can be transmitted to a center by ad-hoc and multi-hop wireless networks, and that all the information collected can be integrated in the GIS database at the center.

4.4 Disaster Information Collection and Data Integration Using Dynamic Communication Networks

4.4.1 Protocols for Rescue Information Collection and Common-Use Database for Data Integration

In order to effectively utilize all the information collected by various agents, such as rescue surveyors, rescue corps, rescue robots, and sensor nodes (Rescue Communicators), a common protocol called the MISP (Mitigation Information Sharing Protocol) for rescue information exchange and sharing was designed by the AIST (National Institute of Advanced Industrial Science and Technology) [11]. All the data collected should be integrated in a database, referred to efficiently, and enable quick decision making on rescue team deployment to the right locations. A new common-use rescue information integrated database for unifying information using the MISP protocol and API, called RaRuMa (DAtabase for RescUe MAnagement), was developed by the AIST [11]. This integrated database accumulates the information that the rescue infrastructure and rescue robot collect in real time, and offers it in a reusable form. There are plans to combine this rescue-integrated database with integrated earthquake disaster simulation GIS systems called DiMSIS/DyLUPAs, which are currently being developed by the National Research Institute for Earth Science and Disaster Prevention (NIED) [6].

DaRuMa and MISP offer convenient functions for rescue information integration since they are extendable, fast, scalable, network-based, and compatible with various standards; in other words, they are platform independent. Some standard templates are provided for sensor data and coverage.

The details of MISP and DaRuMa are described in another chapter of this volume [12].

4.4.2 Experiments on Rescue Information Collection and Integration

Information sharing, based on spatial temporal GIS, between rescue robot systems and the disaster management system has been discussed at Kyoto University, University of Electro-Communications, and Waseda University [8, 9].

An autonomous mobile vehicle and an imaging system to extract objects different from the normal scene were also developed. The system employs omni-directional vision. It can be utilized for detecting objects that appear in a disaster, or damaged objects and buildings in the disaster area, by extracting the difference between the captured scene and the normal scene. The detected objects can be registered in the GIS in KIWI+ format.

The information exchange software was developed based on MISP, and it was applied to information sharing experiments in the Yomakoshi area, which was destroyed by a powerful earthquake in 2004. Figure 4.10 shows the system configuration of the experimental system for ground and aerial information collection with spatial temporal GIS. The system allows various ways of data collection, such as manual camera work by rescue surveyors using a PDA equipped with a GPS, image capture from the air by an unmanned aerial vehicle (UAV), and image capture by a ground vehicle equipped with a GPS gyro consisting of an RTK-GPS, a D-GPS and an inertia sensor, a high-resolution camera, and a laser range finder. All the data obtained by these means are sent to the DaRuMa database based on MISP, and they are also sent to the spatial temporal GIS (DiMSIS/DyLUPAs).

Figure 4.11 shows the result of the experiment. Each picture is saved on a DiMSIS/DyLUPAs synchronized with the position and time, and the data are indicated by a symbol on a map using a viewer system. The data contents, such as images, can be displayed by clicking the symbols. The integration of the data collected by various types of information sources on a GIS database was successfully executed, and easy lookup of all the collected data on the map was verified.

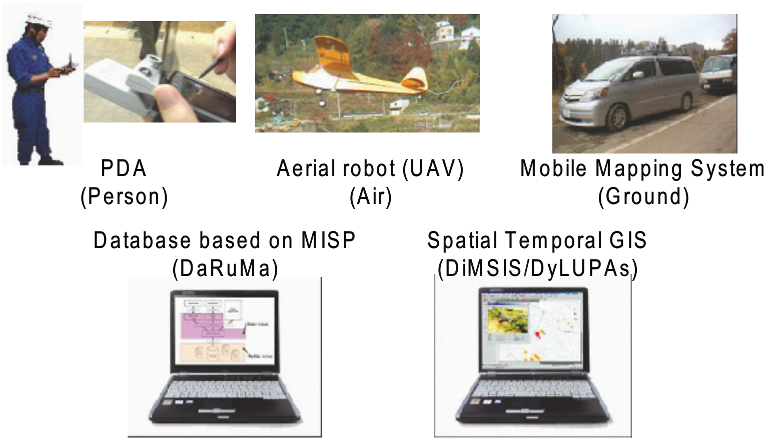


Fig. 4.10 Ground and aerial information collection system

Fig. 4.11 Experimental result for the disaster area

4.5 Conclusions

In this chapter, an overview of the R&D activities of the information infrastructure mission unit of the DDT project was provided. A ubiquitous device, called the Rescue Communicator (R-Comm), developed as part of the rescue infrastructure to collect, transmit, and provide information on the disaster situation was introduced and its application to victim search together with the utilization of RF-ID tags was discussed. The designed protocol, MISP, for communication between various types of data collection devices, including rescue robots, was introduced along with the GIS database, called DaRuMa, for disaster and rescue data integration. Some results of an experiment conducted in a real disaster area were also shown, in which a UAV, a ground vehicle, and rescue surveyors were used for data collection; the collected information was sent to and integrated in a GIS database.

The information infrastructure mission unit carried out some more tests together with other mission units on the transmission and integration of data collected by on-rubble robots, in-rubble robots, and aerial robots in test fields and in a real disaster area.

Acknowledgements The authors thank Mr Hiroshi Nakakomi and Mr Jun'ichi Takiguchi (Mitsubishi Electric Corp.) for the implementation of devices and the GIS registration system.

References

1. Asama H et al (2004) Introduction of Task Force for Rescue System Infrastructure in Special Project for Earthquake Disaster Mitigation in Urban Areas. Proc. IEEE Int Conf on Robotics and Biomimetics
2. Asama H et al (2006) Rescue infrastructure for global information collection. Proc SICE-ICASE Int Joint Conf 3443–3448
3. Asama H, Hada Y, Kawabata K (2005) Overview of information infrastructure and ubiquitous devices for victim search. Proc 2nd Int Conf on Ubiquitous Robots and Ambient Intelligence (URAmI'05) 158–161
4. Hada Y, Kawabata K, Kaetsu H, Asama H (2005) Autonomous blimp system for aerial infrastructure. Proc 2nd Int Conf on Ubiquitous Robots and Ambient Intelligence (URAmI'05) 162–165
5. Hada Y, Kawabata K, Koguchi H, Kaetsu H, Asama H (2006) Rescue Communicators for global victim search and local rescue planning. Proc 2006 IEEE/RSJ Int Conf on Intelligent Robots and Systems TP1-16
6. Hatayama M, Kakumoto S, Kameda H (2001) Development of dynamic management spatial-temporal information system and application for census data – Toward Asian spatial temporal GIS (ST-GIS)–. Proc Dynamic and Multi-Dimensional GIS, IAPRS 34-2-W2:123–127
7. Kawabata K, Hada Y, Kaetsu H, Asama H (2006) Ubiquitous victim search device: intelligent data carrier for rescue. Proc 2006 IEEE Int Conf on Robotics and Automation (ICRA2006) 4306–4308
8. Meguro J, Ishikawa K, Amano Y, Hashizume T, Takiguchi J, Kurosaki R, Hatayama M (2005) Creating spatial temporal database by autonomous mobile surveillance system (A study of mobile robot surveillance system using spatial temporal GIS Part1). Proc IEEE Int Workshop on Safety, Security and Rescue Robotics 143–150

9. Meguro J, Ishikawa K, Hashizume T, Takiguchi J, Noda I, Hatayama M (2006) Disaster information integration into geographic information system using rescue robots. Proc IEEE/RSJ Int Conf on Intelligent Robots and Systems (IROS2006)
10. Nakanishi H, Hashimoto H, Hosokawa N, Inoue K, Sato A (2003) Autonomous flight control system for intelligent aero-robot for disaster prevention. J Robotics and Mechatronics 15-5:489–497
11. Noda I (2005) Communication protocol and data format for GIS integration. Proc 2nd Int Conf on Ubiquitous Robots and Ambient Intelligence (URAmI'05) KRW-058
12. Noda I, Hada Y, Meguro J, Shimora H (2009) Information sharing and integration among rescue robots and information systems. In Tadokoro S (ed) Rescue robotics – DDT Project on robots and systems for urban search and rescue –. Springer
13. Tadokoro S (2005) DDT Project, an overview. Proc 2nd Int Conf on Ubiquitous Robots and Ambient Intelligence (URAmI'05)
14. Takemura F, Enomoto M, Tanaka T, Denou K, Kobayashi Y, Tadokoro S (2005) Development of the balloon-cable driven robot for information collection from sky and proposal of the search strategy at a major disaster. Proc IEEE/ASME Int Conf on Advanced Intelligent Mechatronics (AIM2005) 658–663
15. Takizawa O (2005) Ubiquitous communications technology for disaster mitigation. J National Institute of Information and Communications Technology 52-1-2:235–258
16. Takizawa O, Shibayama A, Hosokawa M, Takanashi K, Murakami M, Hisada Y, Hada Y, Kawabata K, Noda I, Asama H (2007) Hybrid radio frequency identification system for use in disaster relief,- as positioning source and emergency message boards. Int Workshop on Mobile Information Technology for Emergency Response, LNCS-4458: 85–94, Springer

Chapter 5
In-Rubble Robot System for USAR Under Debris

Koichi Osuka, Tomoharu Doi, Satoshi Tadokoro, Naoji Shiroma, Takashi Tsubouchi, Hideyuki Tsukagoshi, Shigeo Hirose, Fumitoshi Matsuno, Takumi Hashizume, Masamitsu Kurisu, Hiroyuki Kuwahara, Toshi Takamori, Yasuyoshi Yokokohji, Shugen Ma, Tatsuo Arai, and Koichi Suzumori

---

Koichi Osuka
Kobe University, and International Rescue System Institute (IRS)

Tomoharu Doi
Osaka Prefectural College of Technology

Satoshi Tadokoro
Tohoku University

Naoji Shiroma
Ibaraki University

Takashi Tsubouchi
University of Tsukuba

Hideyuki Tsukagoshi and Shigeo Hirose
Tokyo Institute of Technology

Fumitoshi Matsuno
University of Electro-Communications

Takumi Hashizume
Waseda University

Masamitsu Kurisu
Tokyo Denki University

Hiroyuki Kuwahara
Sustainable Robotics

Toshi Takamori
International Rescue System Institute (IRS)

Yasuyoshi Yokokohji
Kyoto University

Shugen Ma
Ritsumeikan University

Tatsuo Arai
Osaka University

Koichi Suzumori
Okayama University

Abstract This paper introduces the activities of the In-Rubble Robot System Mission Unit during the DDT project. The objective of the mission unit (MU) was to develop effective systems that can search for victims under debris. The main activities of the MU were as follows: (1) developing advanced search system based on IRS Souryu; (2) developing advanced tools such as jack robot, cutter robot, intelligent search cam, and KURUKURU-3; (3) developing a rescue system carrier named BENKEI-2.

5.1 Collection of Information Under Debris

Collecting information from under debris was the primary research theme of the "In-Rubble Robot System Mission Unit," and the purpose of the research was to develop a system to continuously search within rubble, from shallow areas to deep areas. Specifically, the following sections explain the "Advanced Tool Group," which was developed for shallow areas inside rubble; the "In-Rubble Search Robot System: Hyper Souryu IV," which was developed for deep areas inside rubble; and the "BENKEI-2," which is a vehicle for carrying the entire package to a disaster site.

To search for victims under debris, it is necessary to physically move search equipment inside rubble. For the initial search, it is useful to employ rescue suites that have a simple structure and are practical. However, to search areas deep inside rubble, a mobile in-rubble search system is needed. In some cases, these search processes are independent of each other; however, they are essentially sequential. In addition, a vehicle is necessary to carry various types of equipment to a disaster site.

Therefore, the MU considered the "Development of an In-Rubble Searching System" in order to design a complete search system that can cover both shallow and deep parts of rubble. Through this process, the MU aimed to create an effective in-rubble search system (Fig. 5.1). Furthermore, the MU aimed to study human interfaces to make it possible to operate different robots in a unified way to some extent. Then, the MU proposed a guided vehicle that could carry all equipment to a disaster site. Finally, the ultimate integration of the In-Rubble Robot System MU was realized.

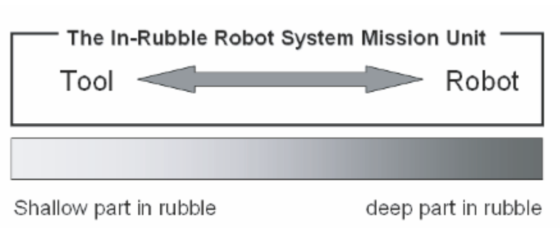


Fig. 5.1 Scope of In-Rubble Robot System MU

5.2 In-Rubble Search System

The focus of the MU was directed toward the development of three important systems: the Advanced In-Rubble Searching Tool, the In-Rubble Searching Robot System, and the Total Guided Vehicle. The three systems were considered as the factors controlling the In-Rubble Searching Robot System, and they are currently under development. In the following section, the overview of the research purpose for each system is explained (Fig. 5.2).

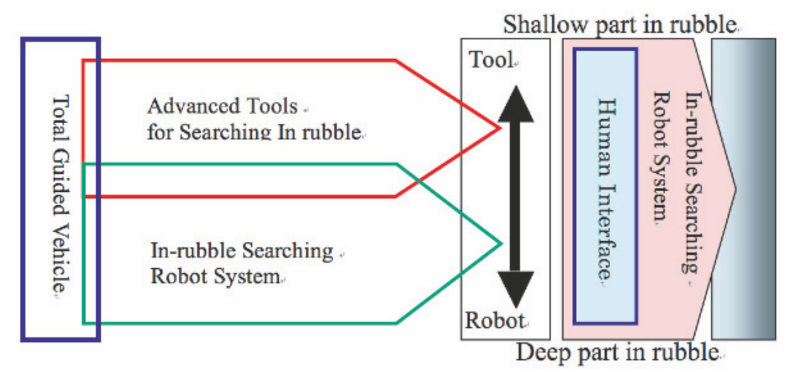


Fig. 5.2 Structure of In-Rubble Robot System MU

5.2.1 In-Rubble Search Robot System: Hyper Souryu IV

The goal of this study was to develop a search system that could be used when it is necessary to enter deeper parts of rubble where moving space is restricted. In this case, an in-rubble depth of approximately 5 to 30 m was assumed; hence, it is necessary to move into in-rubble areas with a powerful driving force. The specifications of the In-Rubble Searching Robot System are as follows:

1. **Size (two rescue workers can carry the entire system):**
   - Shape: An articulated connected crawler system was adopted.
   - Overall length: Less than 1.5 m.
   - Cross-section: Less than 0.2×0.2 m.
   - Weight: Less than 30 and 40 kg for the main body and control system, respectively.
2. **Operating system (two workers can operate the system: one worker controls and the other searches):**

- The system can be controlled remotely.
- To support controllability, a computer system could be installed.

3. **Performance while moving into and moving out of the rubble:**

- It is possible to move through a distance of approximately 30 m.
- It is possible to move at 0.15 m/s.
- It is easy to withdraw from inside the rubble.

4. **Equipment (a large volume of equipment can be installed):**

- Camera: Distributed and installed on the head, rear end, side, and other parts.
- Sensor: Ultrasound distance sensor, laser distance meter, and gas sensor are installed.
- Communication: A system that transmits the information collected to the control table is installed.
- Environmental responsiveness: Water proofing, dust prevention, and darkness readiness.

The MU produced various mobile robots experimentally. However, the MU eventually decided to develop a system based on the Souryu IV, which is the latest Souryu model.

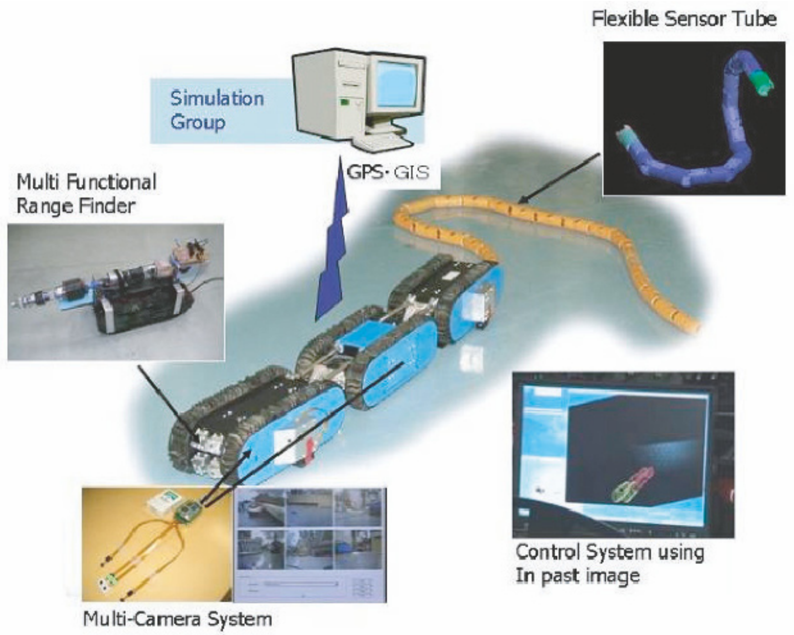


Fig. 5.3 Hyper Souryu IV

In this case, in order to design a Souryu IV not as a simple mobile robot but as a searching system, the MU examined and produced the following items on an experimental basis:

Hardware:	Section 5.3.1	main body and peripherals of the Souryu;
	Section 5.3.2	self-localization and development of 3D map; and
	Section 5.3.3	multi-camera system.
Software:	Section 5.3.4	controlling system; and
	Section 5.3.5	information-gathering system.

The goal of the MU for fiscal year 2006 was to enhance the maturity of these peripheral technologies and to integrate these technologies into the Souryu. Figure 5.3 shows the Integrated Searching System, the Hyper Souryu IV, which was developed by this MU.

5.2.2 Advanced In-Rubble Searching Tool

The objective of this team was to develop simple and practical rescue tools. The team has advanced research in this are to support rescue activities through the selection and use of appropriate tools from the configured rescue tool kit, which consists of various types of tools, according to the situation at a disaster site. These tools can be imaged as "Benkei's seven tools."

By fiscal year 2005, the team had already proceeded with research on the development and improvement of the tool group. The tool group can be further classified into the following three groups: the "searching tool," which investigates conditions under rubble or inside soil; the "working tool," which collects and cuts debris; and the "human power utilization tool," which generates power or high-pressure air utilizing human power at a disaster site (Fig. 5.4). In fiscal year 2006, based on the research results achieved in the previous fiscal year, the team conducted field tests, using results for the improvement of each tool. The team also clarified the role and utilization scenario of each tool in the advanced tool kit.

The main objective of this research was to determine how the advanced tools could be used in an organized manner and thus, to identify them as part of the rescue tool kit. The specifications of the advanced tool are provided below:

1. **Size:**
   - Shape: Shape varied with purpose.
   - Volume: The advanced tool can be accommodated in a carrier box such as a tool box.
   - Weight: Less than approximately 10 kg.
   - Productivity: Low-cost mass production is possible.
2. **Operatingsystem:**
   - The advanced tool can be remotely controlled and handled by one person.
   - To support controllability, a computer system could be installed.

3. **Performance while moving into and moving out of the rubble:**

   - It is possible for tools that move into rubble to move through a distance of approximately 0 to 2 m.
   - It is also easy to withdraw them from inside the rubble.

4. **Equipment:**

   - Camera: A camera is installed at the head.
   - Sensor: One or two sensors, selected from camera, ultrasound distance sensor, laser distance meter, and gas sensor, can be installed.
   - Environmental responsiveness: Water proofing, dust prevention, and darkness readiness.

Fig. 5.4 Concept of the advanced tool group

5.2.3 Carrier Vehicle for Rescue Materials and Equipment for Operation on Irregular Surfaces

A carrier vehicle for rescue materials and equipment for operation on irregular surfaces, "BENKEI-2," was developed. This carrier vehicle can consolidate and carry multiple types of equipment, which were developed as mentioned above, to a disaster site; the vehicle can also carry equipment in a situation where roads are damaged due to earthquake. An outline of the BENKEI-2 is provided below.

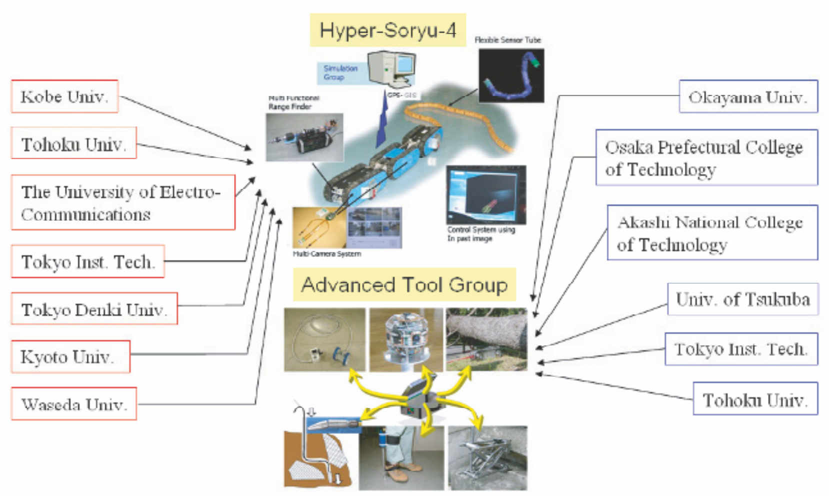


Fig. 5.5 Integration of In-Rubble Robot System MU

In addition to the transportation of equipment, the BENKEI-2 has a greater significance: it is symbolic of the fact that research by various organizations has been integrated, resulting the development of a unified search system (Figs. 5.4 and 5.5).

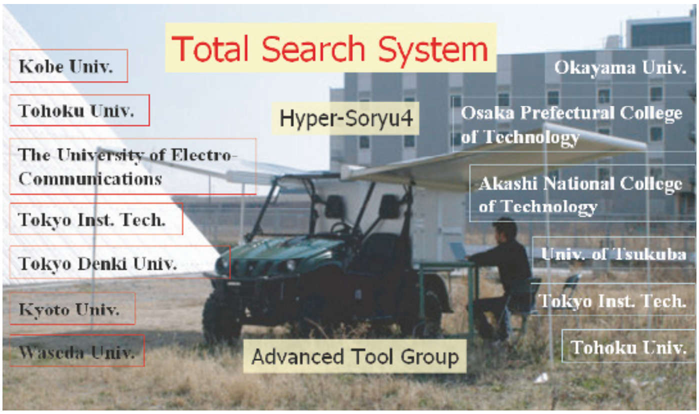


Fig. 5.6 BENKEI-2: Carrier vehicle for rescue materials and equipment

5.3 Components of In-Rubble Searching System

5.3.1 Development of In-Rubble Searching Serpentine Robot Souryu IV

The MU developed the Souryu IV, which is the fourth model in the Souryu series. The series is currently in the development phase and includes mobile robots with high capability to move through rubble. In particular, this MU intends to develop equipment with full operational capacity even under bad environmental conditions such as a post-disaster environment, and it aids and supports rescue team's activities. This MU also engaged in the following points and aimed to put them into practical use: (1) developing a robot equipped with protection mechanisms such as dust prevention and water proofing mechanism and with enhanced reliability at the disaster site; (2) improving operational performance, making it easier for rescue team members to handle the equipment; and (3) developing connection mechanisms between vehicles that prevent the robot from being caught in rubble when it is driving in and above rubble. Figure 5.7 shows the Souryu IV developed by this MU. Figure 5.8 shows the power system for the Souryu IV. To expand the distance between the Souryu IV and the control base, we adopted high-voltage DC power. Figure 5.9 shows the total system [2, 3].

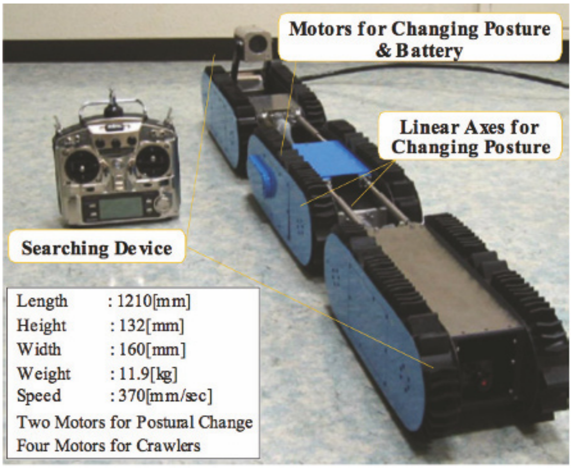


Fig. 5.7 Dimensions of Souryu IV

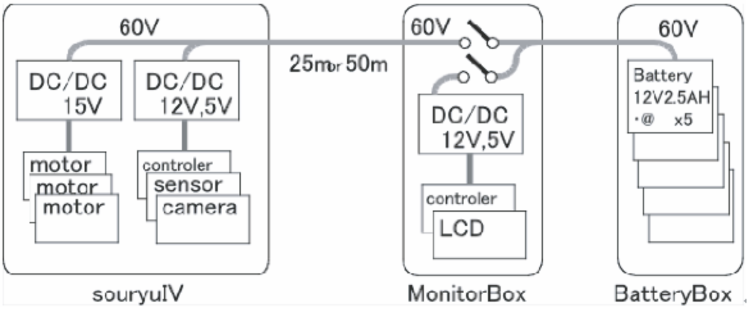


Fig. 5.8 Power lines of Souryu IV

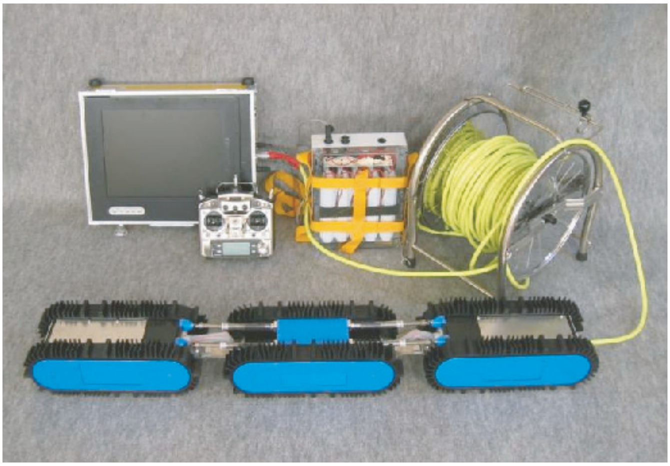


Fig. 5.9 Souryu IV system

5.3.2 Generation of Three-Dimensional Map of Rubble by Mobile Robot

It is desirable that a three-dimensional map be generated to achieve greater efficiency in searching for victims buried in rubble, so as to plan an optimal rescue route after victims are discovered and perform route navigation after they are rescued. However, for a robot to create a map while moving inside rubble, it is necessary to have not only a method to estimate the position and posture of the robot, but also to have compact measurement instruments that enable the robot to effectively measure areas above and alongside it. The objectives of this research are to develop a multi-range finder that can be installed into a compact mobile robot for measuring rubble and to develop a method to create a three-dimensional map of the entire rubble area from partial shape data of rubble that can be generated by the remotely controlled mobile robot driving inside the rubble [9, 10, 11].

Figure 5.10 shows the third compact multi-range finder prototype model, which utilizes an omni-directional camera and ring laser. Figure 5.11 shows the range finder embedded into the lead vehicle of the Souryu IV. As the figure shows, the range finder is normally placed inside the body, and a built-in mechanism exposes it to the outside when required.

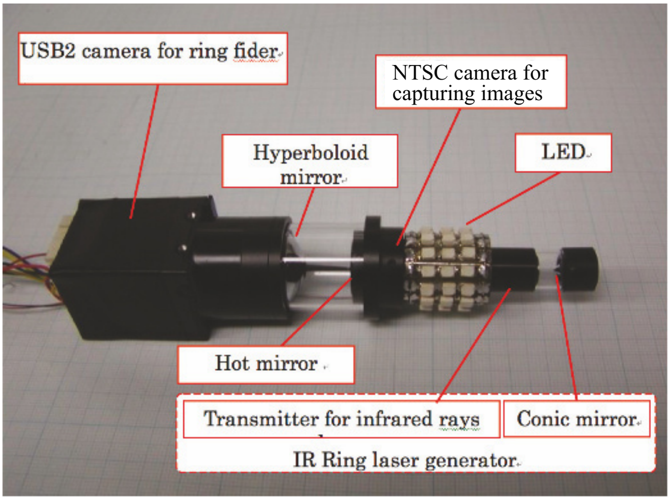


Fig. 5.10 Multi-range finder

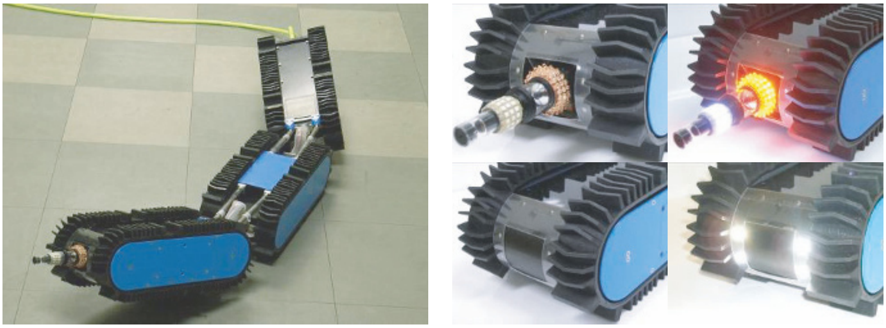


Fig. 5.11 Multi-range finder built in to Souryu IV

The upper left side of Fig. 5.12 shows an overview of the rubble model used in the experiment held in April 2006 at the Tachikawa Fire Training Center. The landmark could be photographed using the omni-directional camera embedded in the multi-range finder. Using this camera, the landmark was tracked.

The lower right side of Fig. 5.12 shows a three-dimensional rubble map generated from the range data in the experiment. However, due to failure to integrate

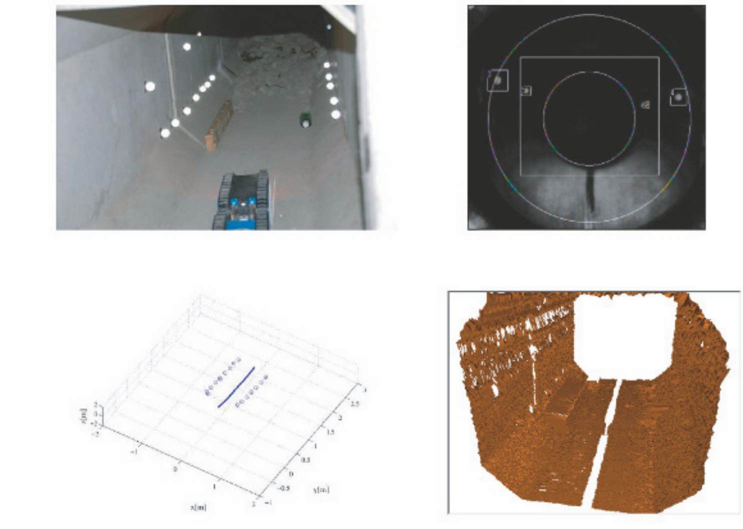


Fig. 5.12 Example of 3D rubble map generated from the multi-range finder

the map with the 3D-SLAM (see lower left side of Fig. 5.12), the position of the Souryu, shown on the left of the figure, was calculated based on the assumption that it proceeded straight ahead at constant speed. The figure shows that splinters of wood and other items in the rubble model were reproduced. Taking the result of self-location estimation into consideration, it is possible to generate a three-dimensional rubble map online by developing an integrated system of the 3D-SLAM and the multi-range finder.

5.3.3 Development of Built-In-Type Multiple Vision System

To search rubble by using rescue equipment and robots and to discover victims, it is essential to have a visual image with a wide view without any blind spots and a refined visual image that reveals details. Currently, rescue equipment or robots do not have the ability to understand a rubble environment based on image information. Thus, the following issues were acknowledged from the viewpoint of searching for human bodies and rubble recognition: (a) cameras are only installed to view along a particular direction, leading to a lack of image information; (b) no compact cameras exist that can project details of rubble; and (c) a search robot that emphasizes the ability to maneuver in rubble has little space for a sensor to be installed. Therefore, in this research, the aim was to develop a compact multiple vision camera system that can be installed in a robot to resolve the issues mentioned above by using multiple cameras; this setup would provide detailed images of all parts surrounding the robot with no blind spots. Figure 5.13 shows a conceptual image of the robot [20, 12].

Figures 5.14 and 5.15 show the configurations of the multi-camera system. Four CCD cameras can be connected to one board. Boards equipped with four CCD cameras are connected through a LAN. Figure 5.16 shows the Souryu IV equipped with these cameras. In the picture, multiple cameras are embedded on the sides, top, bottom, head, and rear ends. Figure 5.17 shows images photographed using these cameras. The images demonstrated that blind spots in the Souryu IV had been eliminated.

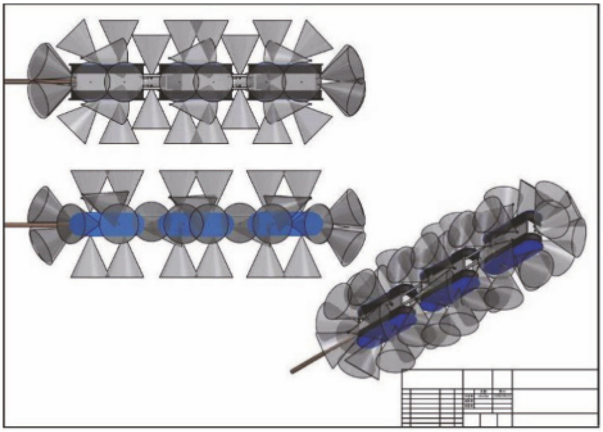


Fig. 5.13 Image of configuration of multi-camera system

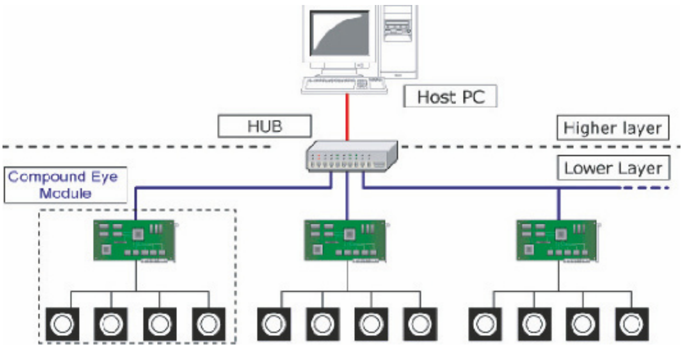


Fig. 5.14 System structure of multi-camera system

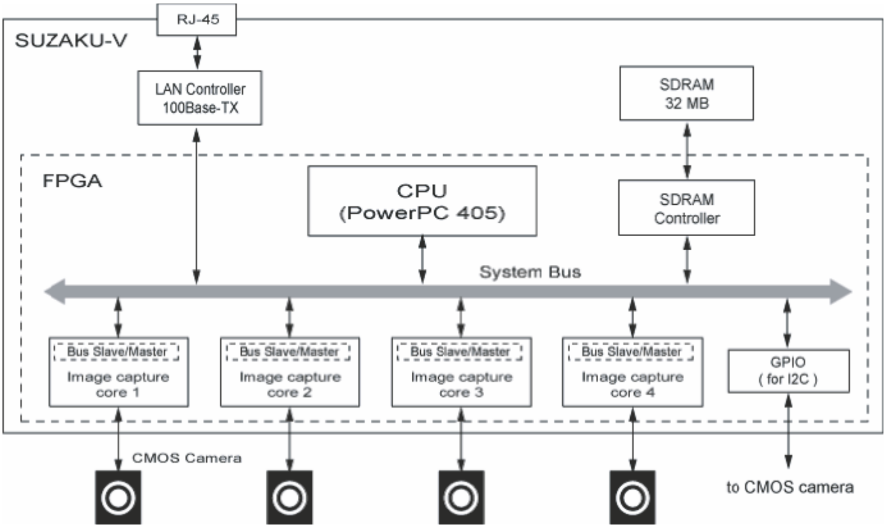


Fig. 5.15 System configuration of multi-camera system

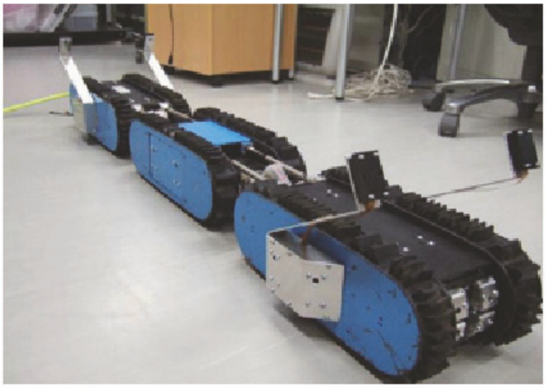


Fig. 5.16 Souryu IV with 32 cameras

5.3.4 Bird's-Eye-View Synthesis Control System

The In-Rubble MU aimed to develop a mobile robot system with unique models and functions to move inside rubble. In an actual environment, there are a large number of technological challenges for a robot to autonomously move and search. Hence, considering a rescue robot that works in an extreme environment, a model in which a robot is remotely controlled by a human has become a realistic solution. Therefore, the purpose of this research is to develop technologies that will achieve the enhancement of remote controllability, which is important for controlling a robot at a disaster site. Improvement of remote controllability of a robot allows the robot to

Fig. 5.17 Images photographed using multiple cameras

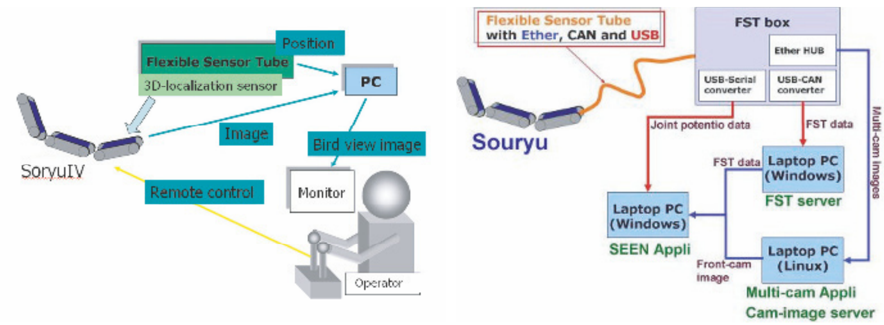


Fig. 5.18 Concept of bird's-eye-view synthesis system using past images

fully utilize its mobility performance, a feature that has not been effectively utilized so far. Thus, this is recognized as a very important issue [16, 17].

Figure 5.18 shows the configuration diagram and system structure of the bird's-eye-view synthesis system using past images that were developed in this research. The principle of this system is that the cameras installed in the robot accumulate images photographed at certain intervals, and the three-dimensional images (CG) being projected by the robot are superimposed on the static images. This enables

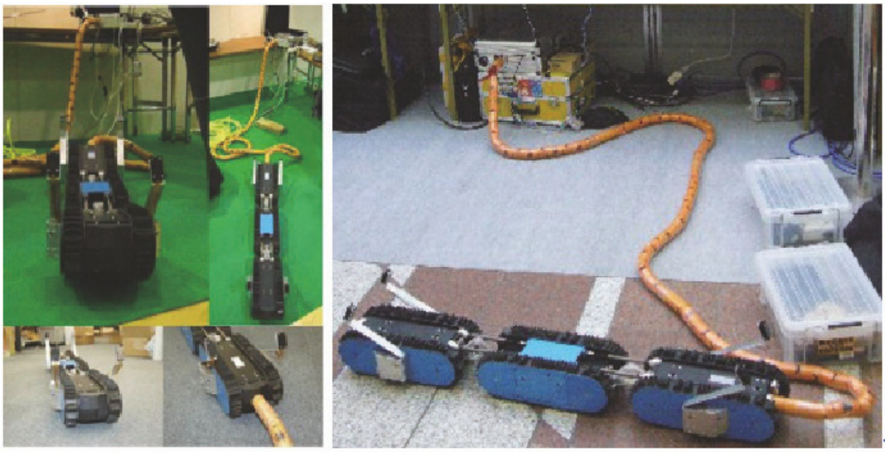


Fig. 5.19 Bird's-eye-view synthesis system using past images

Fig. 5.20 Computer systems for the operating system using past images

controllers to feel as if they are looking at a bird's-eye-view image; as a result, operating performance is improved significantly. However, to utilize this method, it is necessary to accurately identify the current location of the robot.

Figure 5.19 shows an example of the bird's-eye-view synthesis system using past images used for Hyper Souryu IV. In addition, the picture on the left in Fig. 5.20 shows the computer system used to realize the operation system using past images. The skeleton of the Hyper Souryu IV is presented in the captured background image, as seen on the right in Fig. 5.20.

5.3.5 Flexible Sensor Tube

In this research, Flexible Sensor Tube (FST) is proposed as a sensor that identifies the location of the in-rubble search robot inside rubble. So far, we have developed the FST as a self-localization sensor for in-rubble search robots MOIRA1 and MOIRA2 (Fig. 5.21). We produced the second prototype model to improve system versatility and then tried to install it in the Souryu IV [15].

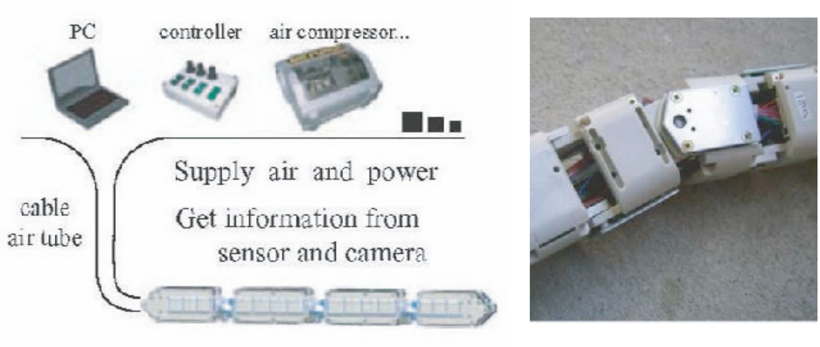


Fig. 5.21 MOIRA system and FST joint

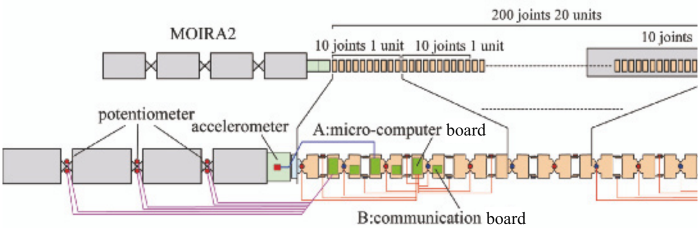


Fig. 5.22 Construction of FST system

Figure 5.21 shows that the MOIRA system is configured based on a wired operating system. An attempt is made to make cables between the MOIRA and the controller a shape sensor. Specifically, a multi-joint type tube that covers the cable is configured as shown in Fig. 5.22 (200 joints per 10 m) and an angle sensor is embedded at all the joints. This allows the relative position from the start point to the end point as well as angles to be calculated by tracking the angle.

The left image in Fig. 5.23 shows the FST2, which was produced experimentally to solve the issues raised by the first FST model. This system comprises a unit 1 m long, in which communication is performed through CAN. This enables each unit to be connected to create a tube of the necessary length. In addition, the external

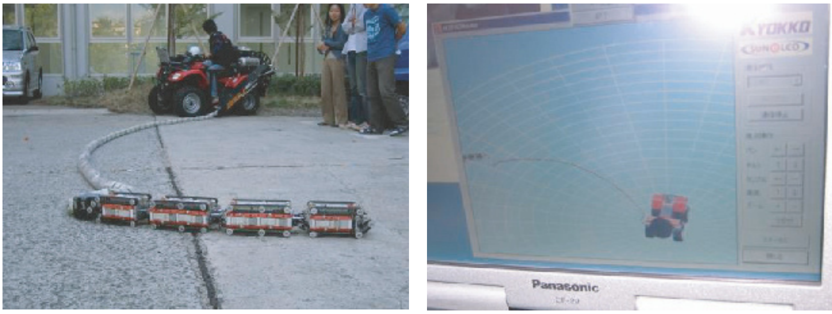


Fig. 5.23 FST system and the shape image built by the FST

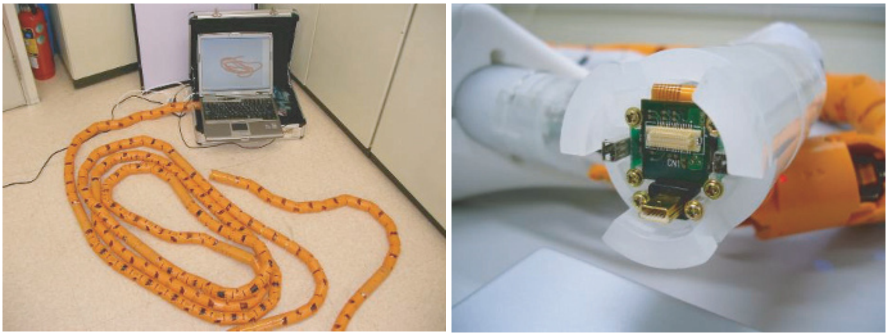


Fig. 5.24 Complete FST2 systm

diameter, which was originally 50 mm, was reduced to 38 mm. Inside the tube, a LAN cable, USB cable, power transmission line, and CAN cable are built-in, providing greater versatility. The right image in Fig. 5.23 shows the connector of each unit.

5.3.6 Hyper Souryu IV

The units described in Section 5.3.1 to Section 5.3.5 were integrated based on the Souryu IV. This integration completed the search system. We named the completed system Hyper Souryu IV, which is shown in Fig. 5.2. In addition, Figs. 5.14 and 5.15 demonstrate the operation of the Hyper Souryu IV. It is obvious that the Hyper Souryu IV is significant from the standpoint of the integration of basic technologies. However, it is also significant from the standpoint of organizational collaboration. In other words, as discussed, a large number of universities and organizations have been responsible for each component of the Hyper Souryu IV:

Section 5.3.1 Souryu IV: Tokyo Institute of Technology and IRS;
Section 5.3.2 multi-camera system: Tohoku University;

Section 5.3.3 three-dimensional map generation: Tokyo Denki University and Kyoto University;
Section 5.3.4 bird's-eye-view synthesis system utilizing past images: Ibaraki University and University of Electro-communications; and
Section 5.3.5 Flexible Sensor Tube: Kobe University.

These organizations have been collaborating based on the common theme of the Hyper Souryu IV.

The "collaboration of technologies and organizations" demonstrated through the Hyper Souryu IV is one of the achievements of the In-Rubble Robot System Mission Unit.

5.4 Advanced Tools

5.4.1 Human-Powered Moving Search Cam

This research aims at the development of simplified search equipment based on a human power generation system. We introduce herein a strong search cam, which was invented in the process of developing a simplified search equipment based on a human power generation system [4, 5, 6].

5.4.1.1 Strong Search Cam

Figure 5.25 shows the complete simplified search equipment (hereafter referred to as a Strong Search Cam), and Fig. 5.26 shows some parts of the Strong Search Cam. Table 5.1 lists its specifications.

Fig. 5.25 Strong Search Cam

This Strong Search Cam was designed to be simple and strong by combining a crowbar and a search cam. The apical end of the cam can be inserted into a space in rubble to open it using the action achieved by a crowbar. The cam can also be inserted further into the rubble to search deeper. Figure 5.27 shows a situation where the Strong Search Cam can be used.

Table 5.1 Specification of Strong Search Cam

Item	Basic specifications
Overall length	1,200 mm
Maximum width and height	150 × 150 mm
Weight	3.5 kg
Monitor	2.5 in, color
Battery	DC 12 V
Material	Aluminum

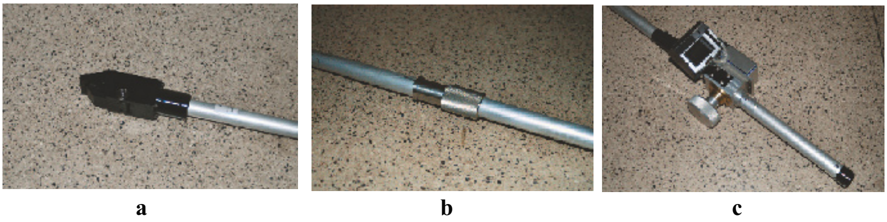


Fig. 5.26 Parts of Strong Search Cam. **a** Tip part. **b** Connection part. **c** Operating part

Fig. 5.27 Using the Strong Search Cam. **a** Pushing into narrow space. **b** Using like crowbar

5.4.1.2 Practical Model of Simplified Device for Searching Inside Rubble Based on Human Power Generation System

Figure 5.28 shows the external view of the simplified device for searching inside rubble based on the human power generation system (hereafter referred to as the fourth model). The fourth model emphasized searching for images and aimed at developing a compact search device and providing high illumination. In addition, the fourth model search device could perform oscillating movements in a horizontal manner within a range of approximately ±15° after a stick-like piece adopted in the third model was incorporated.

Figure 5.29 shows the experimental results. In this experiment, the third model was made to run through disconnected cylinders. The left picture in Fig. 5.29 provides an external view of the verification field. The right picture shows the search device that was separated at the entrance of the second cylinder after searching for the first cylinder. Through this experiment, we verified that it is possible to perform simplified searches covering the area from the opening to the interior at a depth of 6 m. Table 5.2 provides some basic data on the KURUKURU-4.

Fig. 5.28 External view of the fourth model KURUKURU-4

Fig. 5.29 Practical application verification experiment: running through disconnected cylinders

5.4.2 *Jack Robot, Compact Jack Robot, and Cutter Robot*

Here, the features of the rescue robots this research targets are mentioned. In Fig. 5.30, rescue robots and tools that can be currently considered are classified according to the power exerted and the space necessary for the robots and tools to move into the work site [18, 13, 14].

Table 5.2 Basic specification of KURUKURU-4

Part	Item	Dimensions
Search part		
	Size	W150 × D180 × H110 mm
	Wheel	ϕ 110 mm
	Material	Aluminum
	Motor	6 W, 24 V
	Equipments	Camera, light
	Weight	3.0 kg
Cable part		
	Length	20 m
	Diameter	10.2 mm
	Coat	Polyurethane elastomer
	Connector	D-sub9
	Weight	2.2 kg
Operating part		
	Size	W120 × D200×H90 mm
	Motor	TSUKASA(14.4 W)
	I/O	NTSC ×1, Power input-output (DC 12 V)
	Weight	1.4 kg
Pole part		
	Length	1.9–3.3 m
	Weight	1.5 kg
Whole system		
	Weight	7.6 kg
	Power source	Manual power generation

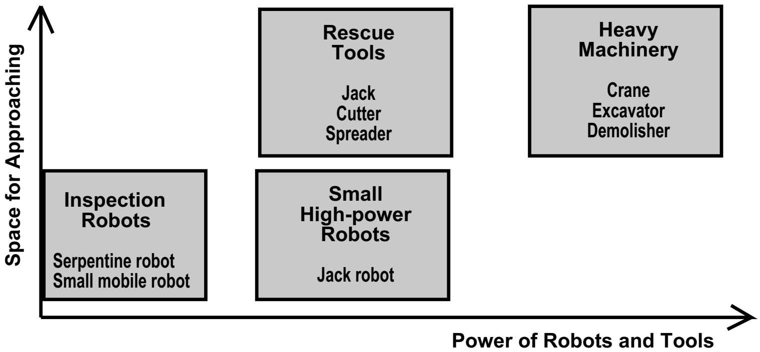


Fig. 5.30 Classification of rescue robots and tools

This research aims at the development of a compact high-power rescue robot shown in Fig. 5.31. In short, while it is difficult for the robot to exert as much output as construction equipment, we aim to realize a robot with the following features: it must have a mobility mechanism; it should be able to move into narrow areas inside rubble; and in the narrow areas, it should be able to exert power equivalent to or greater than that of current rescue tools.

Fig. 5.31 Cutter robot and jack robot

Fig. 5.32 Joint verification training with IRS-U

Figure 5.32 shows a verification experiment conducted by the IRS-U (volunteer organization made up of rescue teams).

5.4.3 Jack-Up Mobile Body (Bari-Bari-I and II)

Thus far, a large number of rescue robots have been developed that search for and rescues victims buried under buildings during disasters and terrorist attacks. However, most of these robots just attempt to move through an already existing space, and a method by which a robot can be moved forcibly through blocked space remains to be developed. The purpose of this research is to develop a mobile rescue support robot. The robot is expected to forcibly open blocked spaces narrower than its width to infiltrate the rubble, move within a narrow space, and jack up heavy rubble while moving. Thus, the robot would not only have search functions but also be able to reduce the weight of the burden imposed on victims.

We propose the jack-up promotion method (Fig. 5.33). In this method, a robot forcibly opens up blocked space narrower than its width to move into rubble, search for victims, and provide rescue support while alternating between “lifting” heavy rubble and “driving” through the narrow space. The driving mechanism to achieve these actions includes a system that performs lifting and driving motions using the same actuator. The first prototype model, “Bari-Bari” was developed to verify the validity of this system (left image in Fig. 5.34).

We also developed a second prototype model, “Bari-Bari-II” (right image in Fig. 5.26). In this prototype, while lifting of heavy rubble is driven by high-power hydraulic cylinders, driving through narrow space is performed by electric motors that have simple system configuration. Bari-Bari-II can forcibly open a 30 mm space and lift rubble to a height of 250 mm, which is the minimum height required to rescue victims. The range of this height is variable. We have verified the validity of this function. In addition, with regard to searching for victims, the Bari-Bari-II is equipped with a microphone, camera, speaker, and interfaces connecting them. The capability of Bari-Bari-II to move through rubble while employing these instruments was verified. Figure 5.35 shows how the jack-up method works.

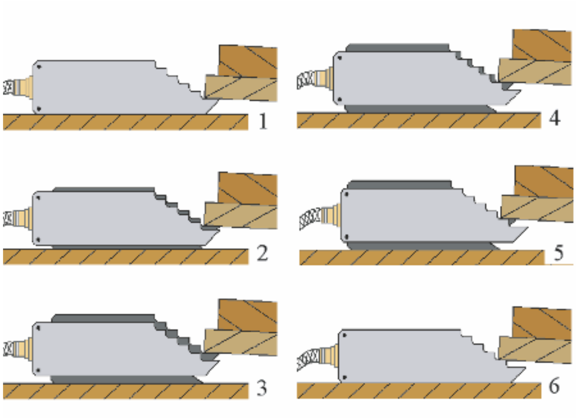


Fig. 5.33 Image of jack-up promotion method

5.4.4 Intelligent Search Cam

Traditionally, at a disaster site, a fiber scope or “search cam” equipment is used. However, this equipment only provides a single view. There is thus a lack of distance

Fig. 5.34 Bari-Bari-I (*left*) and Bari-Bari-II (*right*)

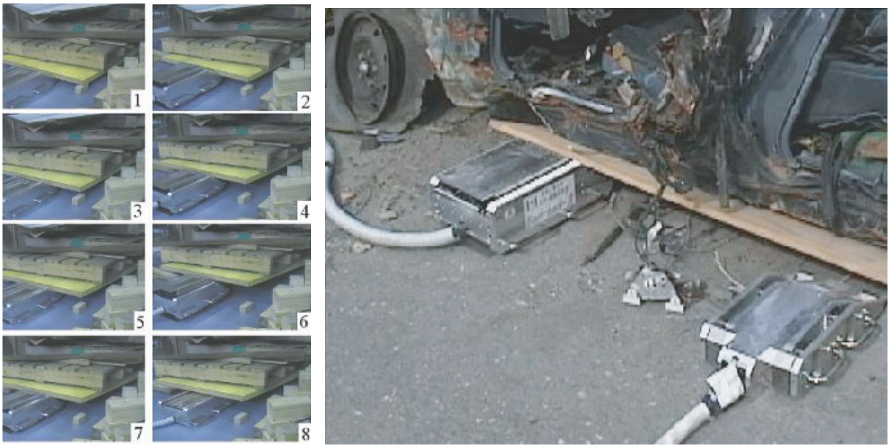


Fig. 5.35 Jack-up method in "Bari-Bari-II"

perspective and a sense of the three-dimensional appearance of the inside of rubble. It would be convenient if there were equipment that could check if there was sufficient space in the rubble into which rescue members could move. Through this research, we developed a sensor system that can obtain and provide three-dimensional images of the inside of narrow space [19].

Figure 5.36 shows images of the prototype of the sensor head produced. As observed in this figure, a laser range finder (LRF), board camera, and high-intensity LED as light source are integrated and placed in a chassis. Then, a servo motor is placed between this integrated setup and the bar so that the whole chassis can rotate. This rotational direction is set in such a way that the axis parallel to the LRF scanning surface works as a rotational axis. This makes the LRF scanning surface also rotate when the chassis is rotated along this axis. With this arrangement, it becomes possible for a sensor to scan the entire area within the range of movement using the chassis motor. Figure 5.37 shows the system structure and Fig. 5.38 shows the use of the search cam in scenario training.

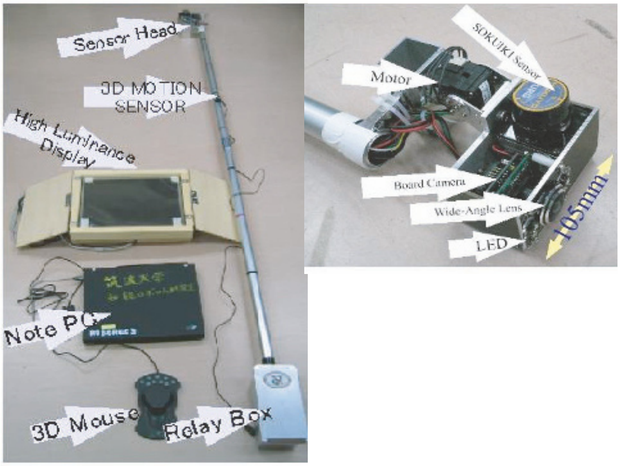


Fig. 5.36 Intelligent search cam

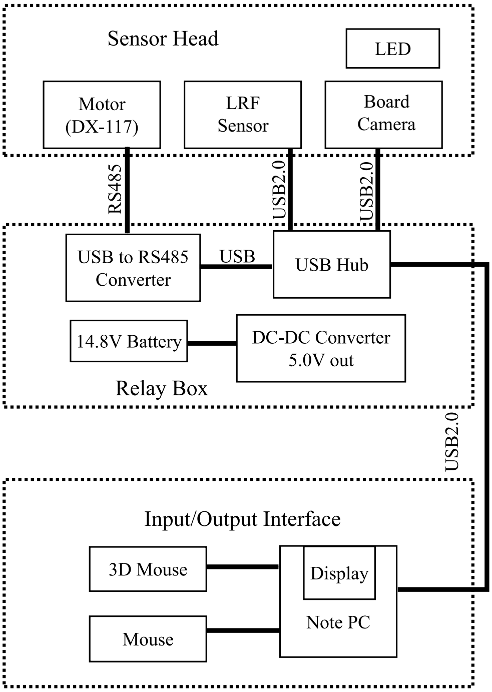


Fig. 5.37 System structure of the intelligent search cam

Fig. 5.38 Use of the intelligent search cam in scenario training

Fig. 5.39 Foot pump and the pneumatic jack

5.4.5 Pneumatic Jack

When large-scale and wide-area disasters occur, it becomes difficult to secure energy sources at the initial stage of the disaster due to severed power and transportation networks. Therefore, at the majority of such rescue sites, the main rescue activity is performed based on human power by people who have not acquired skills in sophisticated rescue technology [1].

This research aimed to develop a rescue system and equipment that can be operated by non-skilled persons; this enables effective use of human power.

Figure 5.39 shows a foot pump and an example of its use. Using the foot pump, it is possible to lift cars and other vehicles. The foot pump is currently being further improved. For a pneumatic jack, a fire hose was used, named Pneumatic Jack II. Work on its development, including the task of devising configuration, pipe arrangement, and other tasks, is now complete (Fig. 5.40).

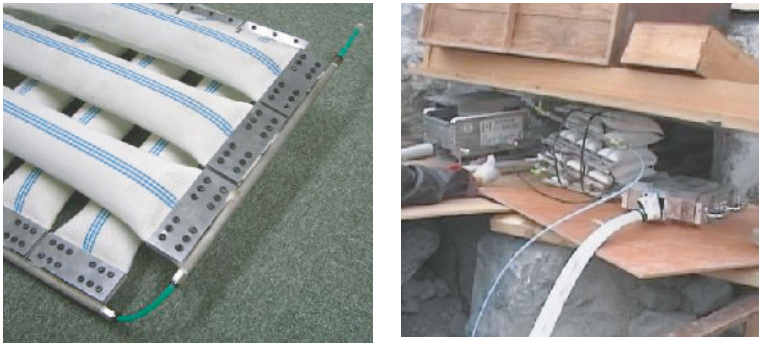


Fig. 5.40 Pneumatic Jack II

5.4.6 Active Scope Camera

We developed an Active Scope Camera by remodeling a fire video scope, as shown in Fig. 5.41. The objective of this Active Scope Camera is to search inside rubble with a small aperture diameter (approximately 3 cm). The actuator, based on the cilia vibration driving method, is placed on the cable surface. This enables the surface itself to have a forward driving force and move inside rubble. Hence, compared with the traditional method of pushing a camera from the back, such as using a video scope, the capability of movement in the deep and narrow space inside rubble is dramatically enhanced with the new scope camera. In addition, the simultaneous use of an oscillating mechanism has made it possible for the system to climb over a small step (less than 15 cm in height) and up a slope (less than 20°). Figure 5.42 shows the system structure of the Active Scope Camera [7, 8].

Fig. 5.41 Active Scope Camera

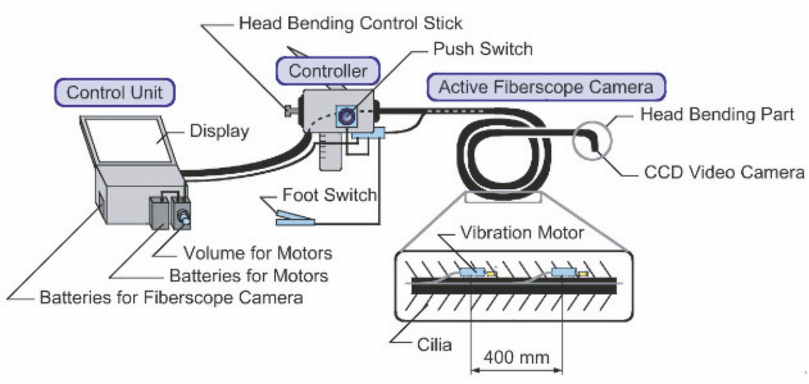


Fig. 5.42 System structure of Active Scope Camera

Fig. 5.43 BENKEI-2: carrier vehicle for rescue materials and equipment

5.5 BENKEI-2: Carrier Vehicle for Rescue Materials and Equipment for Operation on Irregular Ground Surfaces

As described above, the In-Rubble Robot System Mission Unit comprises various research institutions and research groups. The MU researches and develops rescue materials and equipment. To carry these materials and equipment to a disaster site, a conveyance system with high load capability is necessary. For this reason, a vehicle called BENKEI-2 that could be used to load various types of rescue tool groups and carry them to the work site was developed by the MU. This vehicle carries rescue materials and equipment for operation on irregular surfaces (Fig. 5.43 and Table 5.3).

Four boxes or containers can be placed in the rear area of the BENKEI-2 (Fig. 5.44), thus allowing tools and robots to be carried as needed.

In addition, tents are stored on both sides of the BENKEI-2 (Fig. 5.45), and as a result of this integration, the carrier vehicle can be utilized as a base at the work site

Fig. 5.44 Removing the storage container

Fig. 5.45 Base constructed by unfolding the tent

Fig. 5.46 Nighttime illumination equipment set up

Table 5.3 Specifications of BENKEI-2

Item	Value
Overall length, width, and height	3200, 1500, and 1800 mm
Weight and maximum load	520 and 120 kgf
Riding capacity	2 persons
Power source	DC 12 V
Power generator	1 unit of 900 W (AC 100 V-9 A)
Engine	Gasoline engine (660 cc)

in conjunction with the power generator and illuminating device (Fig. 5.46).

Furthermore, the BENKEI-2 has a system that obtains images of peripheral activities, namely, rescue activities performed along the perimeter, and consolidated images obtained by each type of system and equipment or rescue robot (hereafter referred to as the consolidation system). It is difficult for systems and equipment that are not sophisticated rescue robots to capture the location of an activity through GPS and distribute the images obtained to other equipment. Hence, the abovementioned system in the BENKEI-2 is equipped with an omni-directional camera (Fig. 5.47).

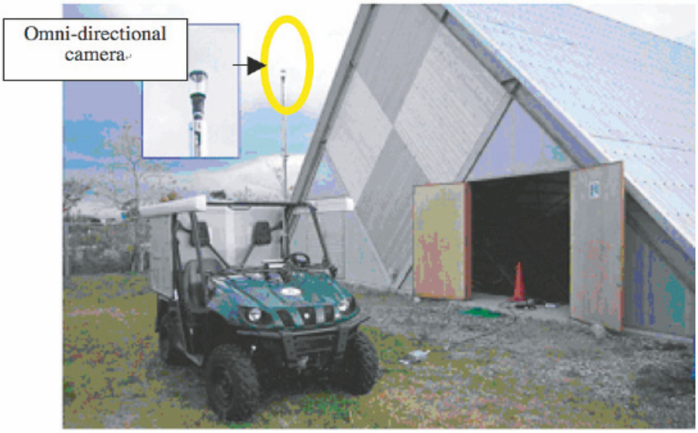


Fig. 5.47 BENKEI-2 equipped with omni-directional camera

Using the camera, rescue members engaged in rescue activities in surrounding areas are photographed. We have developed a system that consolidates four search images (up to three types) obtained by the robots and equipment used by rescue members (the image signal is in NTSC format) into one image through a media converter. The use of this system makes it possible to input consolidated NTSC signals into the mobile server installed in the BENKEI-2 (thereby achieving Infrastructure MU: Co-DaRuMa). The system also enables the addition of time and location information, which can then be uploaded to the main server (thereby achieving Infrastructure MU: DaRuMa). This allows the images of rescue members working in the surrounding areas and the images obtained by each type of system and equipment to be registered in the database developed by the Infrastructure MU. Figure 5.48 shows images of areas around the BENKEI-2 and consolidated camera images obtained by three simplified search cams.

Fig. 5.48 Example of consolidated images

Fig. 5.49 Joint verification training with IRS-U (April 2006)

5.6 Conclusions

The In-Rubble Robot System MU has developed integrated systems centering on the BENKEI-2 (Fig. 5.6). In the future, we will improve individual element technologies and also proactively carry out training with fire teams to obtain feedback for further development. Figure 5.49 depicts the verification training that was conducted in Tachikawa.

References

1. Aoki T, Hirose S (2008) Development of unified pneumatic pillars and pedal-pump for rescue operation. Proc 2008 JSME Conf on Robotics and Mechatronics 08-4 (in Japanese)
2. Arai M, Tanaka Y, Hirose S, Tsukui S, Kuwahara H (2006) Improved driving mechanism for connected crawler vehicle “Souryu-IV” for in-rubble searching operations. Proc 2006 IEEE Int Workshop on Safety, Security and Rescue Robotics (SSRR2006)
3. Arai M, Tanaka Y, Hirose S (2008) Development of “Souryu-VI” and “Souryu-V:” serially connected crawler vehicles for in-rubble searching operations. J Field Robotics 31–65
4. Doi T, Tamari, Kaneda, Umemoto, Yoshitani (2003) Development of simple search device by person’s power. J Robotics and Mechatronics 15-5:528–536
5. Doi T, Sasahara, Kaneda, Umemoto, Yoshitani (2005) Development of simple search device driven by a human-powered generator. J Robotics and Mechatronics 17-3:342–351
6. Doi T, Hino Y (2007) Development and evaluation of a practical use device with human power generation to search in debris. Proc JSME Robotics and Mechatronics Conference 2007 (ROBOMEC2007) 2P1-K08 (in Japanese)
7. Isaki K, Niitsuma A, Konyo M, Takemura F, Tadokoro S (2006) Development of an active flexible cable by ciliary vibration drive for scope camera. Proc IEEE/RSJ Int Conf on Intelligent Robots and Systems (IROS2006) 3946–3951
8. Konyo M, Isaki K, Hatazaki K, Tadokoro S, Takemura F (2008) A ciliary vibration drive mechanism for Active Scope Cameras. J Robotics and Mechatronics 20-3:490–499
9. Kurisu M, Yokokohji Y, Shiokawa Y, Samejima T (2005) Development of a laser range finder for 3D map-building in rubble. Advanced Robotics 19-3:273–294
10. Kurisu M, Yokokohji Y, Oosato Y (2005) Development of a laser range finder for 3D map-building in rubble — The 2nd report: development of the 2nd prototype — Proc 2005 IEEE Int Conf on Mechatronics and Automation (ICMA2005) 1842–1847
11. Kurisu M, Muroi H, Yokokohji Y, Kuwahara H (2007) Development of a laser range finder for 3D map-building in rubble — installation in a rescue robot — Proc 2007 IEEE Int Conf on Mechatronics and Automation (ICMA2007) 2054–2059
12. Midorikawa N, Ohno K, Kuwahara H, Tadokoro S (2007) Development of small-size multi camera system for snake-like robot, and display of wide view-angle image. Proc 2007 IEEE International Workshop on Safety, Security and Rescue Robotics (SSRR2007) T2
13. Mori M, Suzumori K, Tanaka J, Kanda T (2005) A mobile cutter robot for rescue operations. Proc SICE Annual Conference 2005 361–364
14. Mori M, Tanaka J, Suzumori K, Kanda T (2006) Field test for verifying the capability of two high-powered hydraulic small robots for rescue operations. 2006 IEEE/RSJ Int Conf on Intelligent Robots and Systems (IROS2006) 3492–3497
15. Osuka K, Haraguchi R, Masukawa J (2005) Mobile inspection robot for rescue activity MOIRA2 and it’s carrier BENKEI. Proc 36th Int Symp on Robotics (ISR2005)
16. Shiroma N, Sugimoto M, Kagotani G, Inami M, Matsuno F (2004) A novel teleoperation method for a mobile robot using real image data records. Proc IEEE Int Conf on Robotics and Biomimetics (ROBIO2004)

17. Shiroma N, Nagai H, Sugimoto M, Inami M, Matsuno F (2005) Synthesized scene recollection for robot teleoperation. Prep Int Conf on Field and Service Robotics (FSR2005)
18. Tanaka J, Suzumori K, Takata M, Kanda T, Mori M (2005) A mobile jack robot for rescue operation. Proc IEEE Int Workshop on Safety, Security and Rescue Robotics (SSRR2005) 99–104
19. Tsukagoshi H, Kitagawa A, Ito M, Ooe K, Kiryu I, Kochiya T (2008) Bari-Bari-II jack-up rescue robot with debris opening function. Proc 2008 IEEE Int Conf on Robotics and Automation (ICRA2008) ThB12.5
20. Yanco HA, Drury J (2004) "Where Am I" Acquiring situation awareness using a remote robot platform. Proc 2004 IEEE Conf on Systems, Man and Cybernetics (SMC2004) 2835–2840

Chapter 6
On-Rubble Robot Systems for the DDT Project

Fumitoshi Matsuno, Takashi Tsubouchi, Shigeo Hirose, Iwaki Akiyama, Takao Inoh, Michele Guarnieri, Kenji Kawashima, Takahiro Sasaki, Naoji Shiroma, Tetsushi Kamegawa, Kazunori Ohno, Satoshi Tadokoro, Noritaka Sato, Yoshikazu Inoue, Takahide Takeuchi, Hideyuki Tsukagoshi, Masashi Sasaki, Ato Kitagawa, Takahiro Tanaka, Yasuhiro Masutani, Haruo Soeda, Koichi Osuka, Masamitsu Kurisu, Tomoharu Doi, Tadahiro Kaneda, Xin-Zhi Zheng, Hiroshi Sugimoto, Noriyuki Matsuoka, Teruaki Azuma, and Masahiro Hatsuda

---

Fumitoshi Matsuno, Noritaka Sato, Yoshikazu Inoue, and Takahide Takeuchi
The University of Electro-Communications

Takashi Tsubouchi
University of Tsukuba

Shigeo Hirose, Hideyuki Tsukagoshi, Kenji Kawashima, Ato Kitagawa, Masashi Sasaki, Takahiro Tanaka, Michele Guarnieri, and Takahiro Sasaki
Tokyo Institute of Technology

Iwaki Akiyama
Shonan Institute of Technology

Takao Inoh
Hibot Co. Ltd.

Naoji Shiroma
Ibaraki University

Tetsushi Kamegawa
Okayama University

Kazunori Ohno, Satoshi Tadokoro
Tohoku University

Yasuhiro Masutani and Haruo Soeda
Osaka Electro-Communication University

Koichi Osuka
Kobe University

Masamitsu Kurisu
Tokyo Denki University

Tomoharu Doi and Tadahiro Kaneda
Osaka Prefectural College of Technology

Xin-Zhi Zheng
ASTEM

Hiroshi Sugimoto and Noriyuki Matsuoka
Kyoto Kagaku Co., Ltd.

Abstract Intelligent rescue systems with advanced information and robot technology have been expected to mitigate disaster damage, particularly in Japan after the 1995 Hanshin-Awaji Earthquake. It is important that the robots developed for search and rescue tasks can actually work at a real disaster site. Several robots were used for the search and detection operation in the collapsed World Trade Center building in September 2001. In 2002, the DDT Project (Special Project for Earthquake Disaster Mitigation in Urban Areas, III-4 Development of Advanced Robots and Information Systems for Disaster Response) was launched by MEXT (Ministry of Education, Culture, Sports, Science and Technology, Japan). It was a 5-year project for 2002–2007. It aimed at developing necessary technologies for mitigating the damage caused by large-scale earthquakes of the scale of the Great Hanshin-Awaji Earthquake, occurring in densely populated areas in big city regions such as the Tokyo metropolitan area and Keihanshin area. In this paper, we introduce the activities of the mission unit for the information collection by on-rubble mobile platforms.

6.1 Introduction

The purpose of the On-Rubble Robot System MU (Mission Unit on Information Collection using On-Rubble Robot System) is to develop efficient systems for local surveillance by moving on rubble piles to collect information about victims, the degree of structural damage, existence of gas and other hazardous materials, etc.

For information collection on rubble piles it is necessary to improve the locomotion capability of platforms over uneven terrain as well as the ability to cross over obstacles. It is also important to reduce the possibility of secondary collapse caused by the platforms.

For the target usage it is essential to consider the durability of platforms in disaster scenarios by incorporating waterproof, dustproof, and gasproof measures. It is also necessary to install sensing equipment on these platforms so that victims located under debris can be searched for from above the rubble. It is essential to improve the operator interface for the teleoperation of platforms and to develop a technology for creating a 3D map of the environment from the data gathered.

The following technologies are being developed by this MU:

- high-mobility platforms for rubble environments with consideration of secondary collapse;
- durable systems incorporating waterproof, dustproof, and gasproof measures;
- sensing systems for search for victims;
- technology to improve convenience and efficiency of remote operation of mobile platforms; and
- technology for generating 3D maps of the environment.

Teruaki Azuma and Masahiro Hatsuda
Nitta Corporation

The objective is to develop practical mobile platforms, which would incorporate the above mentioned technologies related to sensors, teleoperations, and mapping.

For comparative evaluation of the platforms they are tested at the test fields of Kawasaki Laboratory and Kobe Laboratory of International Rescue System Institute (IRS). For the evaluation of practicality of the user interface and the complete system, we ask firefighters to operate the platforms. Their comments constitute the feedback for making further improvements.

6.2 Development of HELIOS

In recent years the importance of robotic tools has been proved for search and rescue operations in disaster-struck areas. Although using robots it is difficult to physically rescue human beings, survivors can be detected and information can be gathered without risking the lives of rescuers.

HELIOS VII & VIII are tracked robot vehicles proposed for rescue operations. Their basic design consists of two tracks equipped with a manipulator. Due to their characteristics, HELIOS VII and VIII have very high terrain adaptability and several different motion capabilities [3, 4, 5].

6.2.1 HELIOS VII Concept

In order that the robots developed for search and rescue operations are practically usable and effective, they must first have high terrain adaptability. This is because of the unstructured environments in which robots might be deployed. For this main reason, during the development of HELIOS VII & VIII, we decided to introduce two main features:

- the use of an active arm, which is mainly used to assist vehicle motion by controlling the center of gravity, as a manipulator for some simple grasping operations; and
- the introduction of symmetry in the design of the vehicle; in fact in unstructured environments, when robots get stuck or turn upside down, the use of a symmetrical structure grants more usability.

Figure 6.1 shows the concept of HELIOS VII and the location of its unconventional actuators, while Fig. 6.2 shows the actual version. The two track units are connected to the main body by two actuators that make possible their independent and relative rotations. The body acts as a base for an arm with five degrees of freedom. By applying a differential motion with the actuators connected to the main body and by using the arm, the lateral and sideways stability can easily be controlled.

In the initial tests, HELIOS VII exhibited very high terrain adaptability and motion capabilities.

A new feature, compared with conventional tracked vehicles, is the capability to overcome high obstacles by utilizing the arm as a lever. Table 6.1 details the total weight and dimensions of HELIOS VII. With the second prototype, HELIOS VIII, we attempted to reduce the total weight and dimensions while maintaining the same vehicle capabilities.

From Table 6.2, it can be seen that HELIOS VIII is about 25% smaller and 50% lighter than its predecessor.

As described in Hirose et al. [6], tracked terrain adaptability can be significantly improved by utilizing two tracked vehicles connected by an arm. In the case of the HELIOS series of robots, the manipulator represents an active coupling [4] device. Therefore, two HELIOS units or a HELIOS vehicle and another conventional simple tracked system can be connected.

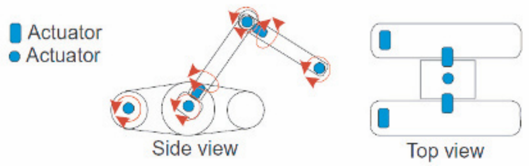


Fig. 6.1 Arrangement of actuators

Fig. 6.2 HELIOS VII

Table 6.1 Specification of HELIOS VII

Item	Value
Total Size [mm]	712 × 600 × 580
Weight (without batteries) [kg]	88

Table 6.2 Specification of HELIOS VIII

Item	Value
Total Size [mm]	570 × 520 × 548
Weight (without batteries) [kg]	45

6.2.2 Development of HELIOS VIII

In the first version of HELIOS VII, new powerful AC actuators were utilized for the entire vehicle [5]. With the need to improve the mobility of the proposed system and with the development of new light AC motors, the first version of HELIOS VIII was realized. It consists of DC motors installed in the track units and two AC motors for the arm. In the case of HELIOS VII, power was supplied externally, while in the new version a Ni-MH battery of 24 V was installed inside the main body. Therefore, sensing devices for detecting survivors and systems utilized to map an explored area will be installed on a carrier directly connected to HELIOS VIII. With this solution, as described above and illustrated in Fig. 6.3, high terrain adaptability is still ensured with simultaneous availability of sufficient space for the installation of eventual additional sensors, batteries, and other tools on the front carrier.

Fig. 6.3 HELIOS VIII

6.3 Development of HELIOS Carrier

6.3.1 HELIOS Carrier

The HELIOS Carrier has been developed as a mobile platform for carrying many sensors to a disaster site. The specification and a photograph of the HELIOS Carrier are shown in Table 6.3 and Fig. 6.4, respectively. It has two tracks, one on its right and the other on its left and has a flat plate on the top of the body. Various sensors for rescue task, such as a CCD camera, thermal camera, microphone, IR sensor, gas sensor, UWB sensor, LRF, and other devices such as a laptop, speakers, connecting mechanisms, and wireless devices will be set up/installed on this flat plane. Depending on the rescue task, the flat plate can be equipped with appropriate devices. The HELIOS Carrier has a battery (Ni-MH, 24 [V]) installed inside the main body and is controlled remotely by a wireless system. The track mechanism of the HELIOS Carrier is the same as that of HELIOS VIII, except that the HELIOS Carrier does not have a rotation axis passing through the body frame for rotation of its track mechanism. Therefore the HELIOS Carrier has a very simple mechanism (it has only two DOF, one for motion along a straight line and one for steering) and more load-carrying capacity than HELIOS VIII; on the other hand it has less mobility than HELIOS VIII.

To improve mobility, it is assumed that a HELIOS Carrier is used by connecting to another HELIOS Carrier or to HELIOS VIII. Fig. 6.5 shows two HELIOS Carriers connected by a 6-DOF arm with an elastic joint. This concept of connecting tracked vehicles is described as Gunryu [6]. Similar to Gunryu, it was experimentally demonstrated that the mobility of HELIOS Carrier is improved by connecting tracked vehicles. We adopt a steering method similar to 4WS to steer connected HELIOS Carriers. During steering of connected HELIOS Carriers, the elastic joint absorbs the small gap between the two HELIOS Carriers, and then the 4WS steering method works very well.

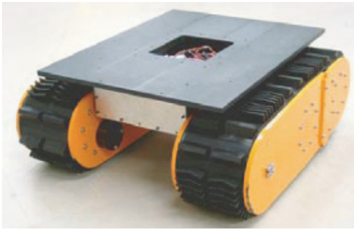


Fig. 6.4 HELIOS Carrier

Table 6.3 Specification of HELIOS Carrier

Item	Value
Total Size [mm]	570 × 520 × 285
Extent of upper plate [mm]	500 × 400
Weight (without batteries) [kg]	32

Fig. 6.5 Connected HELIOS Carriers

6.3.2 HELIOS Carriers Connected with an Arm Using Pneumatic Artificial Rubber Muscles

To improve the mobility, two HELIOS Carriers are connected to each other with an arm. Pneumatic artificial rubber muscles (PARMs) are used for connecting the arm because they are light in weight and have a high power-to-weight ratio.

Figure 6.6 shows two HELIOS Carriers connected with the arm. The arm has two degrees of freedom on each side of the part connected to the carrier, as shown in Fig. 6.7. Further, air grippers are attached as a brake for the rotating angle. The roll and pitch angles are 80° and 40°, respectively. The maximum speed at which the arm can rotate is 57°/s. The arm is driven with solenoid valves.

Figure 6.8 shows the procedure for climbing up stairs with help of the arm. First, the front carrier will be pulled up with the arm, as shown in Fig. 6.8 (a). Then, to maintain the grip of the tracks, the front arm will be pushed back (Fig. 6.8 (b)). The same procedure will also be applied to the back carrier when it comes to the stairs, as shown in Fig. 6.8 (c) and (d). Figure 6.9 shows pictures captured during an experiment. In this experiment, the climbing operation was manually controlled by an operator watching the carriers. We found that the carriers could successfully climb up the stairs in several minutes.

6.4 Development of Leg-in-Rotor-V

There is a requirement for robots that can efficiently find victims trapped under collapsed buildings. One of the design requirements common to these robots is to keep their size and weight to a necessary minimum, enabling them to move in narrow spaces where victims may be hidden, and making the robots easy to transport to the site. On the other hand, downsizing generally hinders traversing performance over debris. Therefore, highly innovative mobile methods have been sought that provide excellent traverse ability under severe ground conditions while satisfying the small-size requirement.

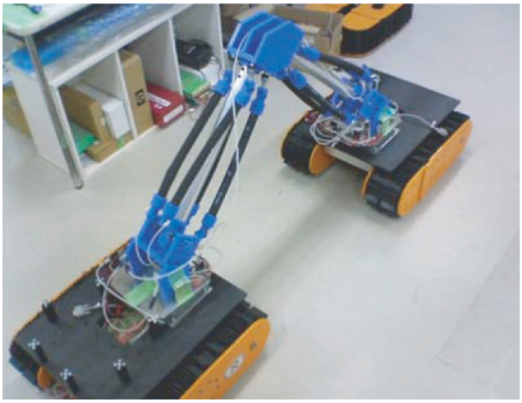


Fig. 6.6 HELIOS Carriers connected by the pneumatic arm

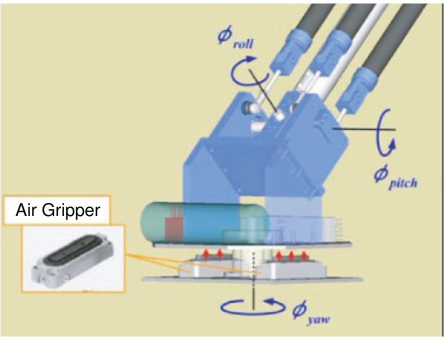


Fig. 6.7 Schematic view of part of the arm connected to the carrier

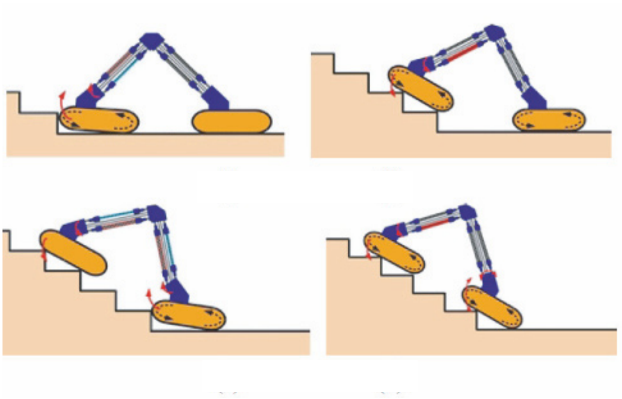


Fig. 6.8 Procedure for climbing stairs

Fig. 6.9 Pictures captured during experiment

A robot, named Leg-in-Rotor Jumping Inspector, is intended to traverse rugged terrain such as debris for the purpose of finding victims under collapsed buildings using the installed camera. The robot is expected to get over obstacles of 600 to 1000 mm in height, while its size is constrained to fit within a 300 mm^3 cube and the weight is constrained to be about 2 kg. These constraints are for ease in portability and ease in entering narrow spaces. In order to satisfy these severe design requirements, we introduced a structure consisting of two wheels and a cylinder, which enables the robot to roll on the flat efficiently and to jump over large obstacles, as shown in Fig. 6.10. This structure requires no complicated posture-stabilizing control when it lands, and it is possible to recover from the upside-down posture with its passively stored legs.

The mechanical model Leg-in-Rotor-V shown in Fig. 6.11 can jump higher than 1 m from the ground, as shown in Figs. 6.12 and 6.13.

The pneumatic circuit to drive the cylinder is composed of several components, as shown in Fig. 6.14. The air supplied from a pressure source is accumulated in the tank installed in the robot after it is decompressed to 0.7 [MPa abs]. The air accumulated in the tank is supplied to the pneumatic cylinder just after the solenoid valve is opened.

At an actual disaster site, a “dry-ice power cell” [7], which we proposed, is planned to be mounted on the robot as a portable power source. It generates carbon dioxide by milling the dry ice so that it evaporates quickly. The robot’s jumping performance was compared for carbon dioxide and air used as the working fluids; no noticeable difference in jumping heights was observed. Therefore, the knowledge gained in this study seems to be sufficient even if carbon dioxide is used as the working fluid.

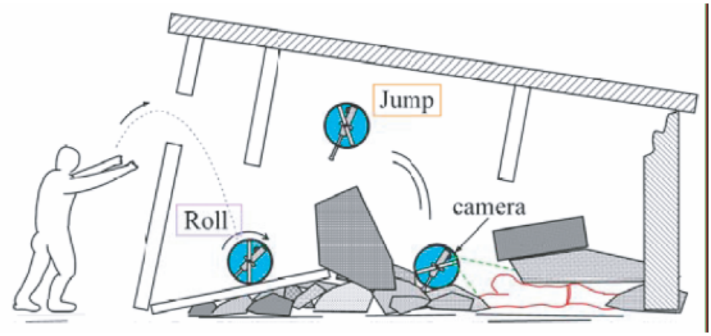


Fig. 6.10 Image of the jumping and rolling inspector to search for victims under debris

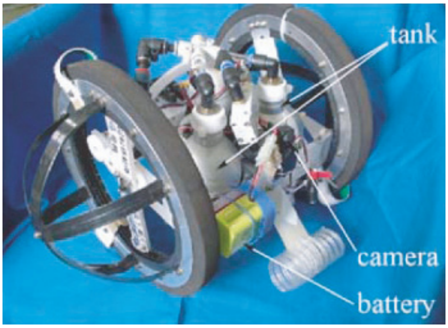


Fig. 6.11 Overview of the mechanical model developed

Fig. 6.12 Performance of Leg-in-Rotor-V, which can roll and jump on debris and can jump again after recovering its posture

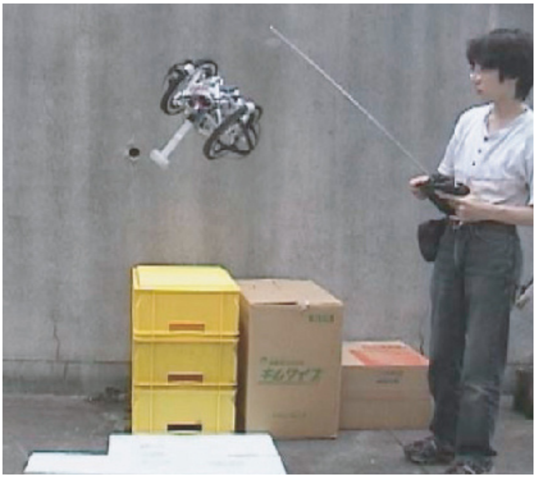


Fig. 6.13 Performance of Leg-in-Rotor-V, which can jump higher than 1 m from the ground using the elastic energy of the rod

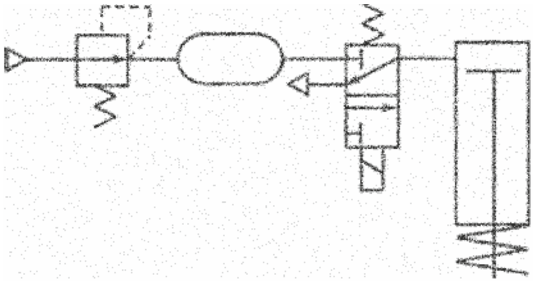


Fig. 6.14 Pneumatic components and their circuit for jumping operation

6.5 UWB Radar System

6.5.1 Equipments

We have developed an UWB (ultrawideband) radar system to search for survivors buried in rubble, from the top [2]. Figure 6.15 shows a photograph of the radar equipment with two horn antennas (manufactured by Lifesenser Co.) installed on a HELIOS Carrier. The specification of this radar system is provided in Table 6.4.

6.5.2 Experiments

We carried out experiments using the UWB radar system installed on a HELIOS Carrier while transmitting UWB pulses down toward a subject, as shown in Fig. 6.16. The UWB radar equipment moves straight from the head toward the feet, with 3 cm intervals of measurement. Each measurement is carried out for 20 s.

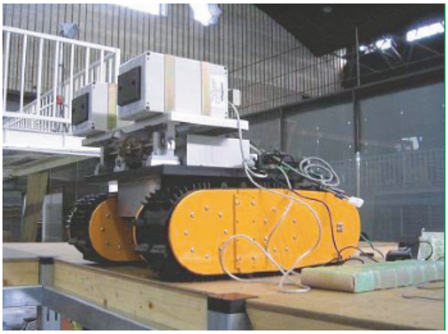


Fig. 6.15 UWB radar system on a HELIOS Carrier

Table 6.4 Specification for the radar system

Item	Value
Frequency bandwidth	3.1–10.6 GHz
Minimum range resolution	0.1% + 20 cm
Energy potential at S/N=1	140 dBz
Frequency bandwidth of digital filter	2, 10, 100 Hz and 2 kHz
Radiation beam angle	$< 30°$
Size of TEM horn antenna	$90 \times 120 \times 210$ mm
Weight of TEM horn antenna	0.7 kg
Total weight	3.25 kg
Electric power consumption	12V/0.85A

To visualize the location of survivors, we proposed fuzzy-based signal processing [1]. This method detects the respiratory motion of survivors in the received signals, which are reflected from a subject using the local average amplitude, standard deviation of fluctuation, and average frequency as fuzzy parameters. Figure 6.17 shows maps of survivor intensity in (a), rubble in (b), and noise in (c). The superposed image, as shown in (d), consists of the survivor intensity colored red, the degree of rubble colored green, and the noise intensity colored blue. The red-colored region, as shown in Fig. 6.17(d), indicates the location of the breast area of the subject because it moves with larger displacement than other areas.

Then, we carried out an experiment to confirm the feasibility of the radar system on the HELIOS Carrier at the rubble test field at the former Kawasaki Lab. The HELIOS Carrier moved on a wooden board with rubble on the second floor of the test field, as shown in Fig. 6.18(a). UWB pulsed waves were transmitted from the antenna down toward a subject lying on the first floor of the test field, as shown in Fig. 6.18(b).

Figure 6.19 shows the results of this experiment. The red-colored regions in (a) and (d) indicate the location of the subject lying on the first floor. This region is clearly observed 2 m below the antenna and 2 m from the starting point on the board, as shown in Fig. 6.19(a) and Fig. 6.19(d).

Fig. 6.16 Radar system on the HELIOS Carrier is moved to transmit UWB pulses down toward a subject

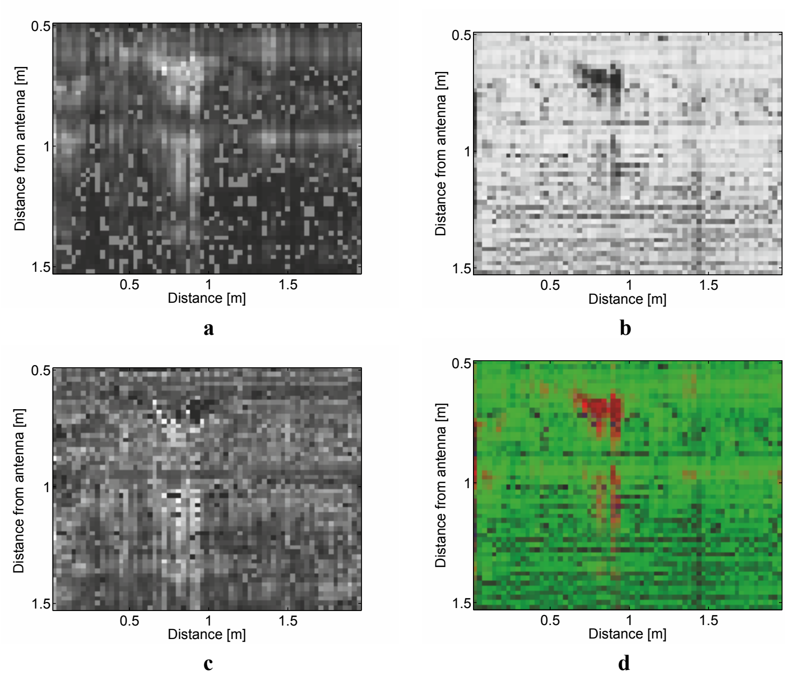


Fig. 6.17 Fuzzy maps obtained in experiment shown in Fig. 6.16. **a** Durvivor intensity. **b** Rubble intensity. **c** Noise intensity. **d** Superimposed image using RGB

a

b

Fig. 6.18 Feasibility experiments of the radar system on the HELIOS Carrier. **a** Radar system on the Helios carrier moves on a wooden board on the second floor of the test field. **b** Subject lying on the first floor of the test field

6.6 Rescue Dummy

Dummies (human models) currently used for training in the field of rescue simulate only the human shape, and are not suitable for quantitative and realistic experiments. Quantitative and real-time evaluation is also necessary for good motivation of a trainee. Therefore, we have been developing an advanced dummy that simulates a disaster victim for the purpose of evaluating rescue equipment (including robots) and the rescue skill of humans and robots [8]. Important results are as follows.

6.6.1 Development of Integrated Model

In this project we have developed models in which each component of a rescue dummy is integrated from the beginning. Although the functions and performance

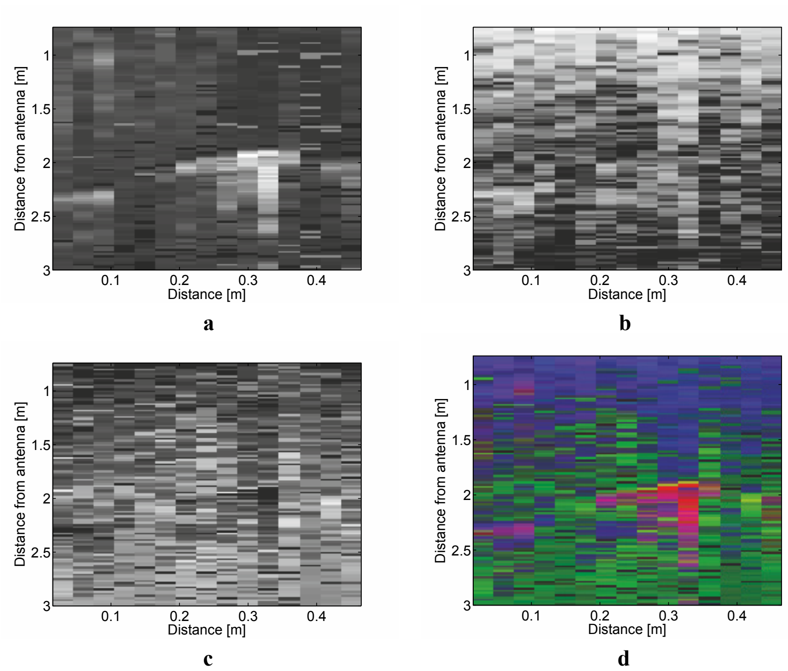


Fig. 6.19 Fuzzy maps obtained for the experiment shown in Fig. 6.18. **a** Durvivor intensity. **b** Rubble intensity. **c** Noise intensity. **d** Superimposed image using RGB

(for example, the number of sensors) of these integrated models are insufficient, it is important to clarify the requirements and technical subject of a dummy that should be developed. The 0th prototype (Fig. 6.20) was manufactured in 2002. It is a ready-made human-body model in which 8-channel sensors and a telemetric circuit using a microcomputer are embedded. The 1st prototype (Fig. 6.20) was manufactured in 2003 and 2004. It is the same human-body model as the 0th prototype, but with 40-channel sensors and a notebook PC with wireless LAN function. An improved version of the 1st prototype was manufactured in 2005 with enhanced durability.

On April 22 and 23, 2006, the improved version of the 1st prototype participated in "rescue robots; assumptions, training, and experiment" which were performed jointly with IRS-U at the training site of the Tokyo Fire Department, Tachikawa. It was used as a victim in assumption training (Fig. 6.21). In the experiment, correspondence between movies recorded with a video camera and from the sensor data recorded with outside PC through a wireless LAN was confirmed. Moreover, through discussions with IRS-U members, we found that they preferred displacement of each joint, which can be understood intuitively, as a monitor of a dummy's status, rather than force and pressure.

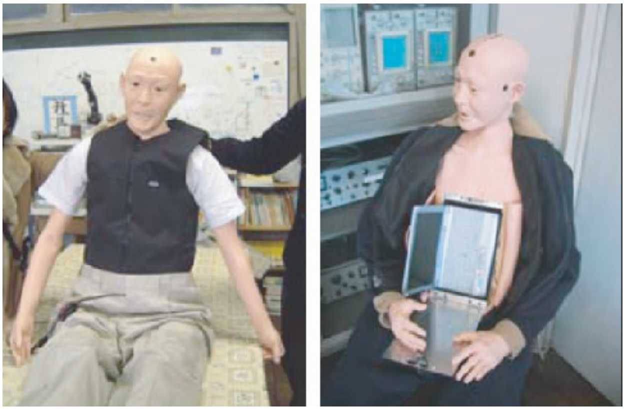


Fig. 6.20 Integrated model: the 0th (*left*) and 1st (*right*) prototypes

Fig. 6.21 Improved version of the 1st prototype before (*left*) and after (*right*) rescue

6.6.2 Whole-Body Tactile Force Sensor System

In the above mentioned integrated model, tactile sensors are mounted only on a part of the body surface. To overcome this restriction, we examined the methods of mounting a whole-body tactile sensor and manufactured a human-body model having a tactile sensor system on the entire surface of its body in 2004.

6.6.3 Simulation of Body Temperature Using MEPCM

Since the heat emitted from a human body is important information that serves as a key in human-body search, it is necessary to make a dummy simulate the human-body temperature. However, by the method of arranging an electric heater to the whole body, weight distribution of batteries and wiring become a problem. Therefore, we are studying a method of mixing micro-encapsulated phase change material (MEPCM) with dummy skin material in order to store heat in the whole body of the dummy. Confirming the effectiveness by using the arm part of the human-body model, we found that the duration for which the dummy simulates the human-body temperature is too short (about 30 min) in the current state.

6.6.4 Passive Musculoskeletal Model of Shoulder Complex

Often, when a victim needs to be carried without the help of adequate tools or through a narrow place, a rescuer puts his/her under arm the victim's armpit or carries the victim on their back. In order to evaluate the performance of such rescue operation performed using rescue dummies, a mechanical model that can naturally simulate the motion of the human shoulder is required. Therefore, considering the movement range of the acromion (top of the shoulder), a closed-link mechanism (Fig. 6.22) was designed and manufactured to realize almost the same movement range as that of the human shoulder. The mechanism is embedded in the human-body model (Fig. 6.23).

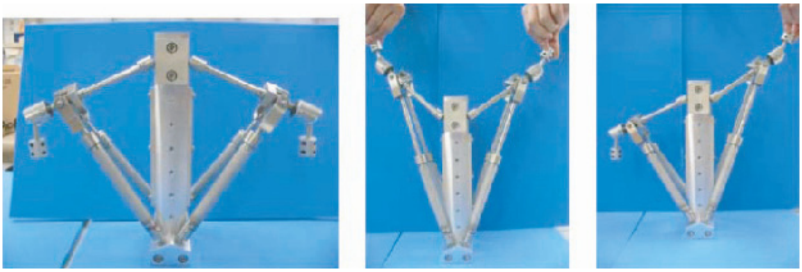


Fig. 6.22 Closed-link mechanism simulating human shoulder

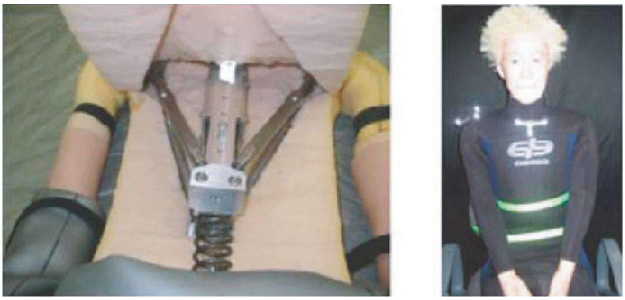


Fig. 6.23 Human model equipped with closed-link mechanism

6.6.5 Quantification of Pains by Pressure Stimulus

Although the dummy developed by us can measure the external force applied to each of its parts, it is unclear how much “pain” a human feels due to a pressure stimulus. Therefore, we are attempting to quantify pain for the purpose of showing the degree of pain based on tactile sensor values.

6.7 Human Interface

6.7.1 Robot Teleoperation

Since it is still difficult to develop fully autonomous robots to function well in real environments with current robot technologies, the system structure of a human operator remotely controlling a robot is one realistic solution that works well at real disaster sites during rescue robot operation. Most robot teleoperations are usually performed using the images captured by the camera mounted on the robot, controlled from a remote site. It is difficult to operate and control a robot using only a direct camera image mainly because it is difficult to understand the situation of the robot and its surroundings based on only the information of the captured images unless the teleoperator is well trained in robot operation.

We have investigated the effectiveness of different camera images for the teleoperation of mobile robots [10]. A reference view such as an image of a robot is positioned in the center of the camera view with a clear view of the surroundings and exhibited high efficiency in the remote control of a mobile robot. Figure 6.24 shows an example of a reference view used by us for controlling a robot. Such images can be obtained by placing a camera physically above a robot; however, one disadvantage is that it increases the robot height. We have developed an image synthesis method called synthesized scene recollection [11] that uses software and generates such reference views or bird’s-eye-views of the robot in an environment by using the position and orientation information of the robot, stored image history data captured by a camera mounted on the robot, and a model of the robot.

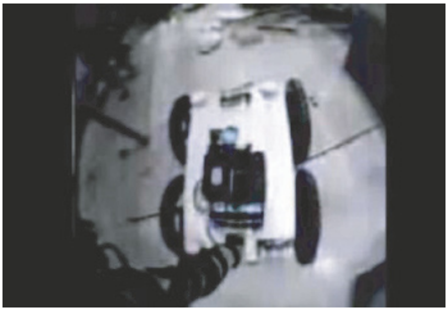


Fig. 6.24 Example of a reference view

6.7.2 Synthesis of Bird's-Eye-View Images to Improve Remote Controllability

In our work, the synthesis of bird's-eye-view images, which improves remote controllability, is carried out using the following technologies:

- estimation of the position and orientation of a robot; and
- image synthesis technique for bird's-eye-view images using estimated position and orientation information of the robot and spatial-temporal information, which are formerly captured real-image data records.

That is, we need to know the position and orientation of a robot and its stored real-image data records, which include formerly captured images associated with the position and orientation of the mounted camera where the image was captured. An overview of the bird's-eye-view synthesis is represented in Fig. 6.25. The upper left, center, and right pictures in Fig. 6.25 are the images currently captured by the camera, current position and orientation information of the robot, and the selected bird's-eye-view-like image of the robot from real-image data records, respectively. The bird's-eye-view of the robot in its unknown surroundings shown in the bottom picture of Fig. 6.25 is the image synthesized using the above information and the robot's CG model created in advance. An operator remotely controls the robot using the composite bird's-eye-view images, which are synthesized according to the process presented in Fig. 6.25 using real-image data records captured by the camera mounted on the robot and the position and orientation information of the robot measured by the sensors. The operator can easily understand the situation of the robot and its unknown surroundings for teleoperation using these composite images. Thus, the remote controllability of a robot is enhanced.

The following algorithm is used for synthesizing bird's-eye-view images:

Algorithm

1. Obtain position and orientation information of the robot during operation.
2. Store images associated with position and orientation information of the mounted camera when they are captured to the buffer while the robot is moving.
3. Select an appropriate image from the stored real-image data records according to the current position and orientation information of the robot and make the position and orientation of the selected image the viewing position of the bird's-eye-view image.
4. Render the model of the robot according to the current position and orientation information of the robot and the selected viewing position.
5. Superimpose the model of the robot viewed from the selected viewing position onto the selected image from the stored real-image data records (generation of the bird's-eye-view image).
6. Repeat this procedure continuously.

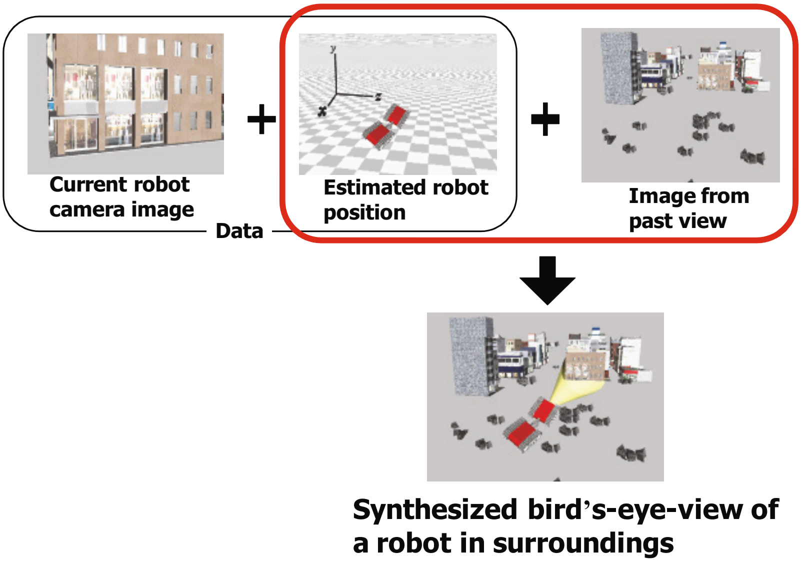


Fig. 6.25 Overview of the bird's-eye-view synthesis

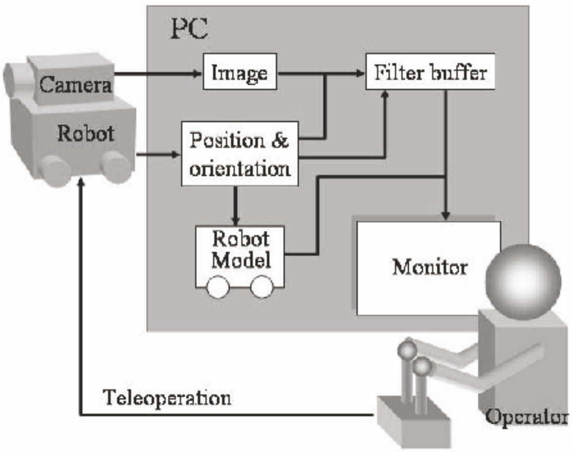


Fig. 6.26 System overview

Overview of this system is shown in Fig. 6.26. The images captured by the mounted camera are stored in the buffer as bitmap images along with the associated position and orientation information of the camera when they are captured. When the current position and orientation information of the robot is obtained from the sensors, the most appropriate image to view the robot at the present moment is selected from the stored real-image data records according to this information of the robot. Then, the model of the robot that is viewed from the selected image

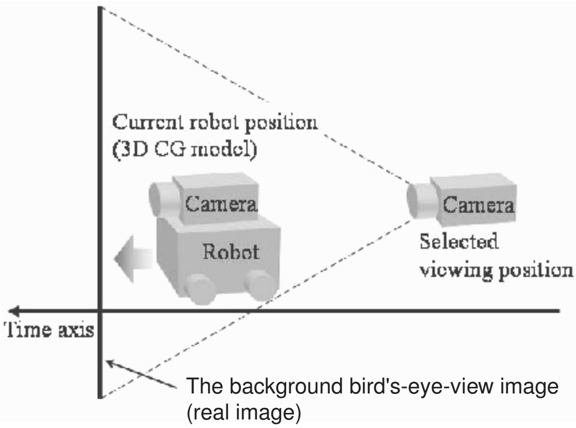


Fig. 6.27 Pseudo real-time view

position is superimposed onto the selected image. The selection of the most appropriate viewing position is according to the position and orientation information of the mounted camera, which is stored with the captured images in the buffer. As shown in Fig. 6.27, the selected image is used as the background image of the bird's-eye-view image. This background image is not a real-time one, but it is a pseudo-real-time image. Because of this system configuration, it can handle dynamically changing environments in a pseudo-real-time manner. Further, this system does not require the construction of a 3D environmental model since this is an image-based method, and it does not take much time to synthesize a bird's-eye-view image.

Figure 6.28 shows snapshots of robot teleoperation using the synthesized scene recollection. It can be said that the situation of the robot in the surroundings of a remote site can be understood with ease and this helps the operator to control the robot.

6.8 3D Map Building and 3D Virtual Bird's-Eye-View for Control Interface

The 3D map of a disaster area can correctly inform a rescue team about the condition of the disaster area. In addition, such 3D maps are useful for the teloperation of rescue robots.

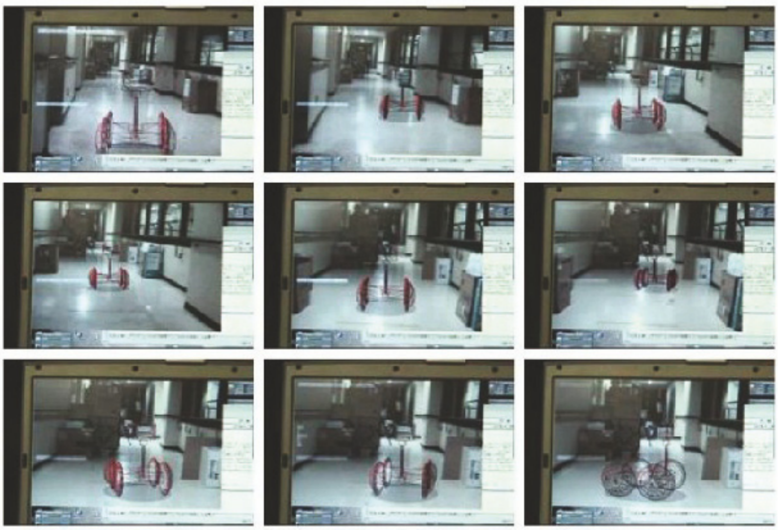


Fig. 6.28 Snapshots of teleoperation using the synthesized scene recollection

6.8.1 3D Scanner and 3D Map Building Method

Figure 6.29 illustrates a HELIOS Carrier equipped with a web camera and a 3D scanner at the front. This 3D scanner, which was developed by Tsukuba University and Tohoku University collaboratively [12], consists of a 2D laser range finder (LRF) and a servo motor. A 3D shape can be measured by rotating the 2D LRF through pitch angle with a servo motor. Snapshots of the scanner's movement are shown on the right side in Fig. 6.29. A 3D map was constructed by combining the 3D shapes measured from different view points. The tracked robot's motion between different view points was estimated by 2D scan matching. An ICP algorithm was used for these 2D and 3D scan matching methods.

Figure 6.30 shows an experimental result of 3D map building at IRS Kawasaki Lab. An operator controlled the robot using a camera image and a virtual bird's-eye-view image shown in the right-side row in Fig. 6.30. The 3D map was constructed during the exploration.

6.8.2 Virtual Bird's-Eye-View for Control Interface

It is well known that an operator at a remote place can easily control a robot by using a bird's-eye-view image. In this research, a 3D bird's-eye-view image was virtually constructed from a 3D map and a 3D robot wire-frame model (right row in

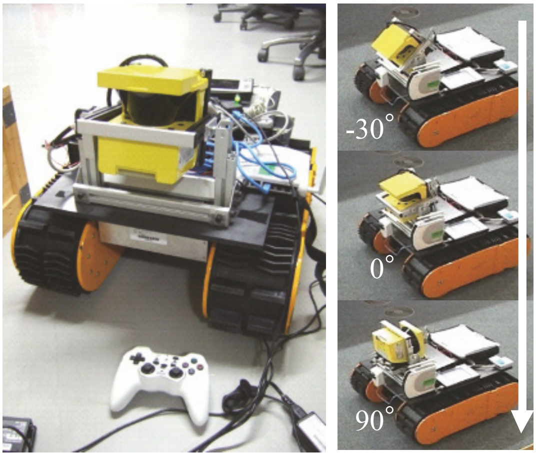


Fig. 6.29 HELIOS Carrier equipped with a 3D scanner (*left*) and snapshots of 3D scanner's movement (*right*)

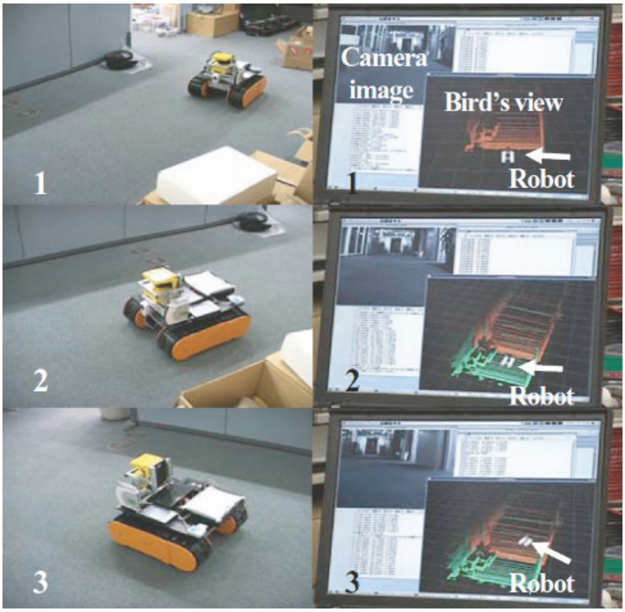


Fig. 6.30 Exploration in IRS Kawasaki Laboratory: real robot movement (*left row*); control interface (web camera image and virtual bird's-eye-view image) (*right row*)

Fig. 6.30). The robot model in the 3D map was moved according to the real robot movement in the real world.

In this exploration (Fig. 6.30), using the 3D virtual bird's-eye-view image in the control interface, the operator can avoid collision of the robot with an obstacle at a blind spot of the front-camera image. This interface was also useful to check collision between the robot and its environment when the robot passed through a narrow space.

6.8.3 Dense 3D Map Building and Its Coloring

For human intuitive recognition, a dense 3D shape and its texture information are necessary. A dense 3D map that has color information can be built by combining a 3D shape and its texture images. In our approach, these were achieved by using the voxel carving technique [9]. Figure 6.31 illustrates a reconstructed result. This reconstruction was an off-line process.

Fig. 6.31 Dense 3D shape reconstruction and its coloring

6.9 Concluding Remarks

In this paper, we have introduced the activities of the mission unit on information collection by on-rubble mobile platforms of the DDT Project in Japan. Demonstration experiments and training for rescue activities by firefighters have been carried out. Figure 6.32 shows training being conducted in the underground town of JR Kawasaki Station on November 5, 2006.

Fig. 6.32 Training with firefighters using robots in the underground town of JR Kawasaki Station on November 5, 2006

References

1. Akiyama I, Ohya A, Enokito M (2006) Development of an UWB rescue radar system: detection of survivors using fuzzy reasoning. Proc Int Conf on Information Processing and Management of Uncertainty in Knowledge-Based Systems 2119–2126
2. Araki Y, Akiyama I, Ohya A (2004) UWB radar for rescue of survivors. Proc SICE System Integration Division Annual Conf 38–39
3. Guarnieri M, Debenest, Inoh T, Fukushima E, Hirose S (2004) HELIOS VII a new vehicle for rescue and search operations. Proc. 2004 IEEE Int Workshop on Safety, Security and Rescue Robotics (SSRR2004)
4. Guarnieri M, Hirose S (2004) Research and development of rescue robots at Hirose and Yoneda Laboratory. IROS 2004 Workshop, 1
5. Guarnieri M, Debenest, Inoh T, Fukushima E, Hirose S (2004) Development of HELIOS VII: an arm-equipped tracked vehicle for search and rescue operations. Proc IEEE/RSJ Int Conf on Intelligent Robots and Systems (IROS2004) 39–45
6. Hirose S, Shirasu T, Fukushima E (1996) Proposal for cooperative robot “Gunryu” composed of autonomous segments. Robotics and Autonomous Systems 17:107–118
7. Kitagawa A, Tsukagoshi H, Wu H, Park S (2003) A novel pneumatic power source using solid-gas phase transition. Proc Autumn Conf of Japan Fluid Power System Society 123–126 (in Japanese)
8. Masutani Y et al (2003) Development of a standard robotic dummy for the purpose of evaluating rescue equipment and skill. Proc 2003 IEEE/RSJ Int Conf on Intelligent Robots and Systems (IROS2003) RPII-3-6
9. Ohno K, Tadokoro S (2005) Dense 3D map building based on LRF data and color image fusion. Proc 2005 IEEE/RSJ Int Conf on Intelligent Robots and System (IROS2005) 1774–1779
10. Shiroma N, Sato N, Chiu Y, Matsuno F (2005) Study on effective camera images for mobile robot teleoperation. Proc 13th IEEE Int Workshop on Robot and Human Interactive Communication
11. Sugimoto M, Kagotani G, Nii H, Shiroma N, Inami M, Matsuno F (2005) Time follower’s vision: A tele-operation interface with past images. The January/February 2005 issue of IEEE Computer Graphics and Applications 54–63
12. Tsubouchi T, Tanaka A, Ishioka A, Tomono M, Yuta S (2004) A SLAM based teleoperation and interface system for indoor environment reconnaissance in rescue activities. Proc 2004 IEEE/RSJ Int Conf on Intelligent Robots and System (IROS2004) 1096–1102

Chapter 7
Design Guidelines for Human Interface for Rescue Robots

Yasuyoshi Yokokohji, Takashi Tsubouchi, Akichika Tanaka, Tomoaki Yoshida, Eiji Koyanagi, Fumitoshi Matsuno, Shigeo Hirose, Hiroyuki Kuwahara, Fumiaki Takemura, Takao Ino, Kensuke Takita, Naoji Shiroma, Tetsushi Kamegawa, Yasushi Hada, Xin-Zhi Zheng, Koichi Osuka, Taro Watasue, Tetsuya Kimura, Hiroaki Nakanishi, Yukio Horiguchi, Satoshi Tadokoro, and Kazunori Ohno

---

Yasuyoshi Yokokohji
Kyoto University

Takashi Tsubouchi and Akichika Tanaka
University of Tsukuba

Tomoaki Yoshida and Eiji Koyanagi
Chiba Institute of Technology

Fumitoshi Matsuno
University of Electro-Communications

Shigeo Hirose
Tokyo Institute of Technology

Hiroyuki Kuwahara
Sustainable Robotics

Fumiaki Takemura
Okinawa National College of Technology

Kensuke Takita and Takao Inoh
HiBot

Naoji Shiroma
Ibaraki University

Tetsushi Kamegawa
Okayama University

Yasushi Hada
National Institute of Information and Communications Technology (NICT)

Xin-Zhi Zheng
ASTEM

Koichi Osuka and Taro Watasue
Kobe University

Tetsuya Kimura
Nagaoka Institute of Technology

Hiroaki Nakanishi and Yukio Horiguchi
Kyoto University

Abstract In this chapter, we summarize the findings and knowhow in the individual developments of rescue robots and attempt to establish design guidelines for the human interface for rescue robots. The guidelines for image display were established on the basis of some case studies in the DDT project and RoboCupRescue. Since the established guidelines are general and independent of the purpose of a robot, we decided to build a standardized image display prototype. After introducing some implementation examples based on our guidelines, the standardized image display prototype is presented. The established guidelines would be useful for the future development of rescue robots. Further, the prototype image display is a good example of a standardized interface testbed.

7.1 Introduction

In the DDT project (Special Project for Earthquake Disaster Mitigation in Urban Areas, III-4 Development of Advanced Robots and Information Systems for Disaster Response) sponsored by the Ministry of Education, Culture, Sport, Science and Technology, Japan, we have developed several rescue systems and robots. Although each of them has its own human interface based on its specific purpose, there might be some common insights and knowledge that would be helpful when designing a new interface. In order to consider such common insights and knowledge and establish the design guidelines for a human interface, we organized the Human-Interface Group in the DDT project.

Although this group is officially organized under the In-rubble Robot System MU (mission unit) for project management reason, any members of the DDT project could join this group and discuss any issues on a human interface that are beyond the bound of MUs.

In this paper, we summarize the findings and knowhow from some case studies discussed in the group and show the established guidelines for human-interface design for future developments. As the case studies, we investigated the robots developed in the DDT project and the RoboCupRescue. Although the guidelines should be as general as possible, we cannot consider all types of robots. In this paper, we limit our target to only teleoperated robots used for collecting information. We also assume that a robot is being operated far away from the control site or moving under collapsed buildings and the operator cannot see the robot directly, i.e., he/she has to teleoperate the robot through the on-board camera image.

The next goal of the Human-Interface Group was to propose a standardized interface for rescue robots. Although it is still an open question to what extent the human interface of rescue robots could be or should be standardized, a standardized interface is beneficial for robot designers and users. Since we found some generalities in the guidelines for image display, being independent of the purpose of a

Satoshi Tadokoro and Kazunori Ohno
Tohoku University

robot, we decided to build a standardized image display prototype as the first trial. Here, we show some implementation examples based on our guidelines for image display and introduce a standardized image display prototype combined with these implementation examples.

The guidelines established in this study would be useful for the future development of rescue robots. Further, the prototype image display could be a good example of a standardized interface testbed.

7.2 Guidelines for Display Design

In order to establish the guidelines, we discussed some case studies in the DDT project and the RoboCupRescue and picked up some common insights and knowhow that would be helpful when designing a new interface. Summarizing these common insights and knowhow, we established preliminary guidelines [9].

From the preliminary guidelines, we found some generalities in the guidelines related to an image display. In this section, we introduce the design guidelines for image displays. These guidelines could be the basis for designing a standardized interface for image displays.

7.2.1 Multiple Image Display

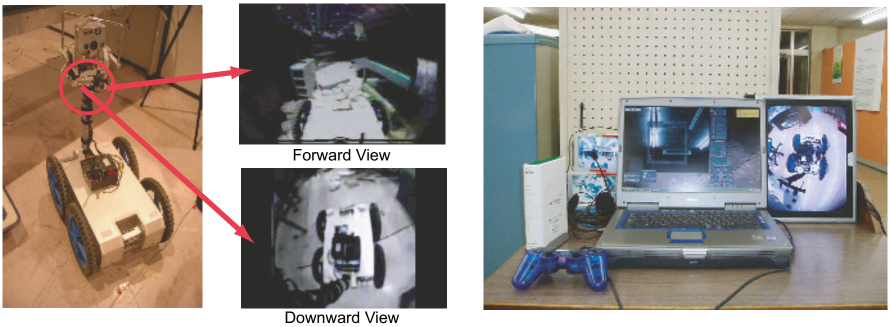
7.2.1.1 Global and Precise Views

An image display is one of the most important elements of a human interface, which displays the images captured by on-board cameras and/or an environmental map. It is effective to display multiple camera images from different viewpoints. A typical example is the combination of a global view and a precise view. Since it is difficult for the operator to understand the situation around a robot in a cluttered environment, a global view is effective for robot operation [5]. A bird's-eye-view including the image of the robot itself is a good implementation example.

However, a global view is insufficient for information gathering, such as searching for victims, which is the primary purpose of a rescue robot. Therefore, a precise image is necessary for information gathering. In summary, we need to display both a global view for robot operation and a precise view for information gathering.

Figure 7.1 shows such an example of multiple camera images. FUMA, a four-wheeled mobile robot developed by the group of Matsuno [1], has two fish-eye cameras at the top end of the mast, one covering the forward view and the other covering the downward view. With these two global views, a remote operator can easily understand what the current situation of the robot is and where the robot should go. Figure 7.1(a) shows two global-view cameras mounted on FUMA. FUMA has another camera with a narrower viewing angle but higher resolution for precise views at the top of the mast. Figure 7.1(b) shows an overview of the control interface for FUMA, where a precise view is displayed on the computer display in the middle while two global views are displayed on the small monitors on the left, and one of them is also displayed on the monitor on the right.

Figure 7.2 shows another example, the multiview display for Souryu III, a snake-like robot developed in the DDT project based on Souryu I and II [6]. The image from the frontal camera (precise view) is displayed on the primary (the largest) monitor. Three small monitors at the bottom display, from left to right, a global view from the fisheye camera mounted on the last section of Souryu, a thermography image, and the image of the gas sensor display mounted inside Souryu. The operator can change the image displayed on the primary monitor anytime by using a display switcher.



a **b**

Fig. 7.1 Four-wheeled mobile robot, FUMA (N. Shiroma, IRS and F. Matsuno, University of Electro-Communications). **a** Two global-view cameras on FUMA. **b** Control interface for FUMA

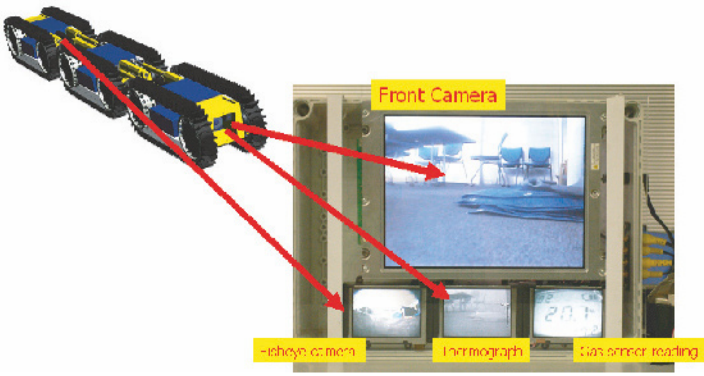


Fig. 7.2 Multiview display for IRS Souryu (H. Kuwahara, IRS)

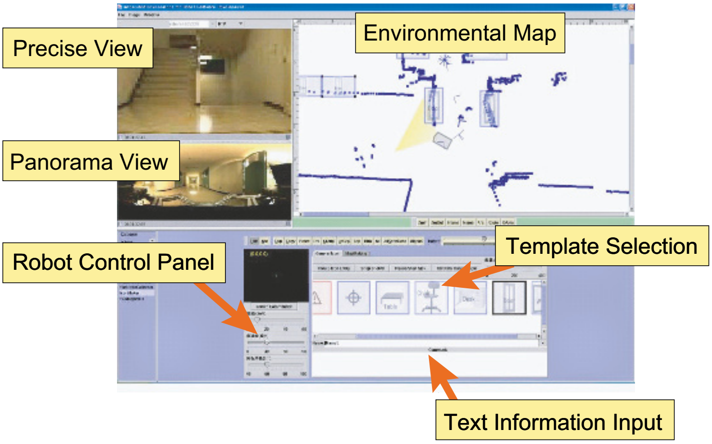


Fig. 7.3 User interface of the underground mall robot (T. Tsubouchi and A. Tanaka, University of Tsukuba)

One can also see examples having both precise and global views in Figs. 7.3 and 7.4. Figure 7.3 illustrates the user interface of the underground mall robot developed by the group of University of Tsukuba [7]. Figure 7.4 shows the user interface of a robot which participated in the RoboCupRescue, developed by the group of Toin University of Yokohama [4].

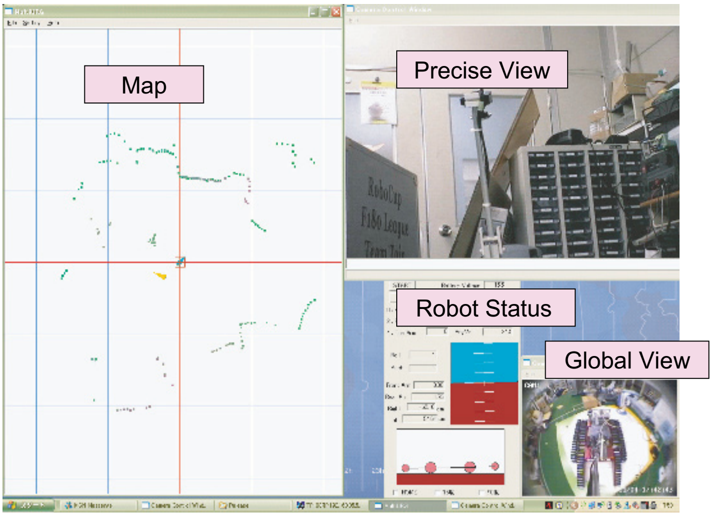


Fig. 7.4 User interface of the robot for RoboCupRescue (T. Yoshida and E. Koyanagi, Toin University of Yokohama)

7.2.1.2 Environmental Map

Needless to say, it is preferable to use an environmental map for effective search if the map is available in advance. If not, a map should be drawn in parallel with the search operation. An environmental map is useful for the operator to locate the current robot position and plan the future movement.

For the same reason as with camera images, two different maps, i.e., a global map and a local map, should be prepared, if possible. The global map is useful for grasping the entire situation. One can also display the current robot location on this map. The local map is useful for information input, such as passing information tags (representing, for example, rescued victims and dangerous materials, etc.). The orientation of the map must be selected such that the operator's burden of mental rotation is minimized. For this reason, the global map should be north-up in most cases and the local map should be consistent with the camera view (heading-up) for intuitive information input by the operator.

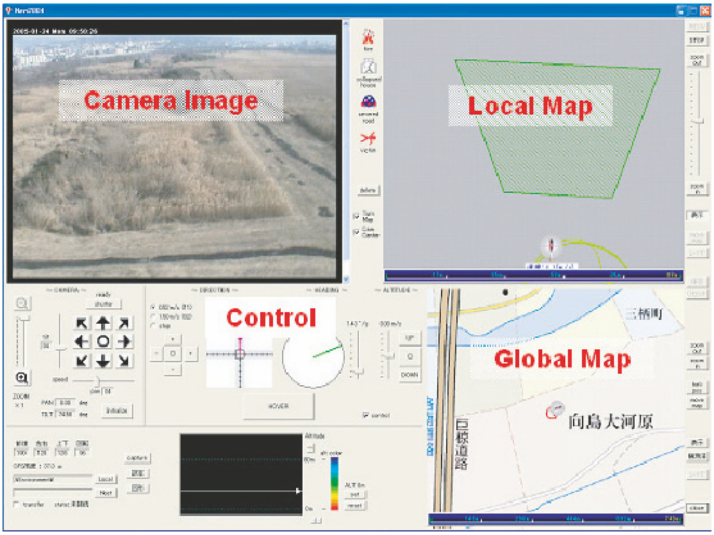


Fig. 7.5 User interface of the unmanned helicopter (H. Nakanishi, Kyoto University)

Figure 7.5 shows an example in which there are two different maps in the user interface of an unmanned helicopter [3]: a global map (bottom-right) and a local map (top-right). The orientation of the global map is north-up, consistent with the arrow buttons in the control panel, which are used to command the move direction of the helicopter. The orientation of the local map is heading-up, consistent with the camera image so that the operator can intuitively mark some information found from the camera image on this local map. One can also see environmental maps in Figs. 7.3 and 7.4.

In summary, we often need to display multiple camera images as well as multiple environmental maps. Such a multiple image display can be realized either by hardware (i.e., preparing multiple monitors) or software (i.e., multiwindow). Obviously, the software approach is simpler and more flexible than the hardware approach. The operator can arrange the size and location of each window depending on the situation. However, such flexibility may cause another problem. We will discuss this point in the next subsection.

7.2.2 Situational Arrangement of Windows

Depending on the situation, the importance of information may change. If we have multiple monitors as shown in Fig. 7.2, we can display the most important image on the primary display. In the case of multiple windows, we have to arrange the size and location of each window depending on the situation.

Figure 7.6 illustrates an example of rearranging window size and location during the robot operation. Initially, the operator arranged the windows in such a way that the left half of the display is occupied by a map, the top right by a precise view, and the bottom right is shared by a robot-status panel and a global-view window. In the case of an undesirable event, the operator might want to enlarge the global-view window to find out what exactly happened to the robot. Since the display area is limited, he/she has to reduce the size of other windows or relocate them. In the example of Fig. 7.6, the operator temporarily moved the robot-status panel to the top-left corner.

Regarding this situational arrangement of windows, we face the following two problems:

1. **Time to rearrange the windows:** It is time-consuming and a burden for the operator to rearrange the windows using, for example, a mouse, particularly in urgent situations, such as a robot getting stuck.
2. **Window overlapping:** Every window should stay visible in any situations. That is, we should avoid window overlapping, where some windows hide other windows.

In the sense of the second point above, the window rearrangement shown in Fig. 7.6 is not a good example, because the environmental map is partially occluded by the robot-status panel. In order to avoid window overlapping, we need more time to adjust the size and location of each window. Therefore, the above two problems are not independent but coupled.

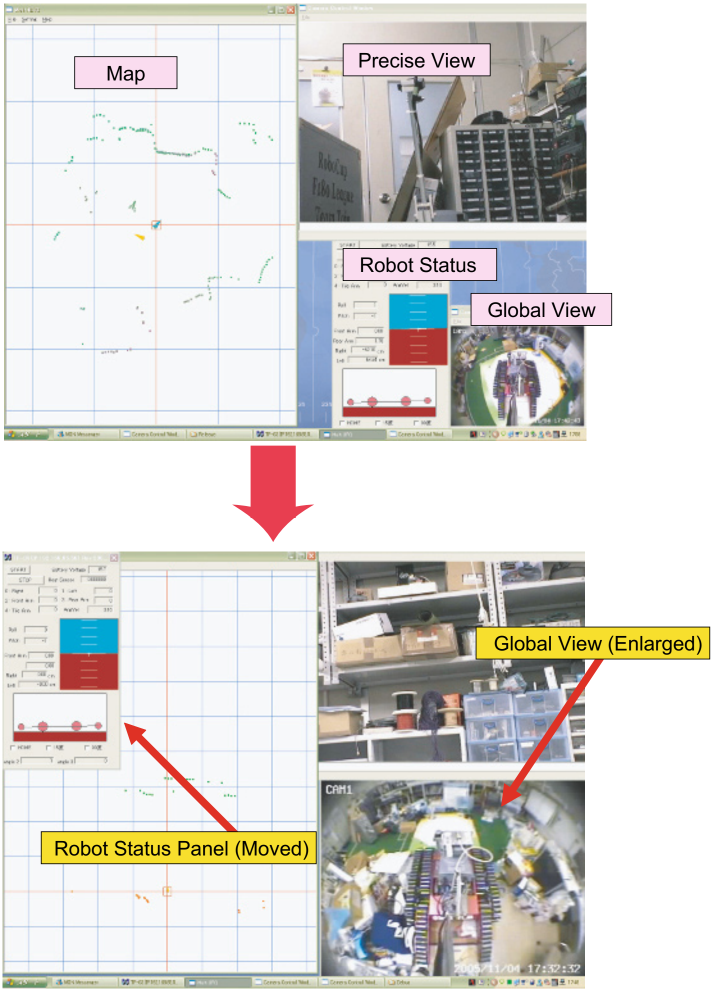


Fig. 7.6 An example of rearranging window size and location during robot operation (T. Yoshida and E. Koyanagi, Toin University of Yokohama)

7.2.3 Visibility of Display Devices

In the previous subsection, we discussed how the images should be displayed on a monitor. Another important issue is the visibility of the display.

Image displays must be visible any time, day or night. However, most liquid crystal displays (LCDs) become almost invisible under strong sunshine, even if we install a display hood as shown in Fig. 7.7. A reflective LCD shown in Fig. 7.8 would be one solution to make the display visible even under such strong sunshine. However, the visibility of this type of LCDs becomes worse than the conventional transmissive LCD in a dark environment. Therefore, a semi-transparent-type LCD would be a compromise choice for both daylight and dark conditions.

7.2.4 Pointing Device and Dust/Water Proofing

It is obvious that a mouse is unsuitable as the pointing device for a rescue robot interface. We usually use a touch screen as the pointing device for outdoor use. Therefore, we assume that a touch screen is used as the pointing device for the situational arrangement of windows discussed in Section 7.2.2. There are several types of touch screens, such as resistive type, capacitance type, electromagnetic induction type, and optical type.

Dust and water proofing of displays is necessary for outdoor use. We must ensure that such dust and water proofing does not degrade the usability of a touch screen for rescue workers who wear gloves. Therefore, resistive-type or optical-type touch screens would be suitable for rescue systems.

Fig. 7.7 Display hood in daylight condition (H. Kuwahara, IRS)

Fig. 7.8 Reflective LCD (K. Takita, IRS)

7.3 Standardized Interface

The guidelines for image display design discussed in Section 7.2 have some generalities, being independent of the purpose of the robot. Therefore, we decided to prototype a standardized image display based on these guidelines. In this section, we first introduce some actual implementation examples that match the guidelines and then show a standardized interface prototype.

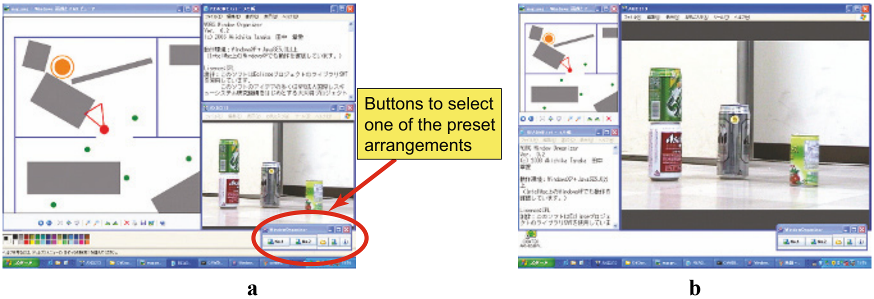


Fig. 7.9 Implementation example of WORG (Window Organizer) (A. Tanaka, University of Tsukuba). **a** Preset #1. **b** Preset #2

7.3.1 Window Arrangement Utility

The window manager of conventional operating systems enables the operator to arrange the window size and location as desired by using a pointing device such as a mouse. However, rescue-robot operators do not need such flexibility of window arrangement because they do not have time to adjust the window size and location during a critical situation. After discussion in the group, it was found that it is sufficient to let them select an appropriate window arrangement from some preset ones. Instead of rearranging the windows on site, one can prepare several window arrangements beforehand considering some expected situations. Then, the on-site operator can simply select one of the preset arrangements by, for example, pushing a button on the screen. Thus, the window-overlapping problem can also be solved because one can carefully preset the window arrangements so that there is no window overlapping.

On the basis of this conclusion, an original window arrangement utility named WORG (Window Organizer) was developed. Figure 7.9 illustrates a demonstration of WORG. Two window arrangements shown in Fig. 7.9 were preset beforehand. The user can choose one of these presets by simply pressing the button on the screen (located at the bottom-left corner of the screen). We assumed that we have three windows, an environmental map (which is dummy in this example), text (also dummy), and camera image. We assume that the text window is showing sensor readings or system log, etc.

WORG has the capability to capture the current window arrangement and register it as a preset arrangement. Preset #1 was arranged in such a way that the environmental map is displayed with a large window as shown in Fig. 7.9(a). In Preset #2, the camera image window was enlarged, the size of the map window was reduced, and the text window was relocated, as shown in Fig. 7.9(b). Once the arrangements are preset, the operator can choose one of them by pushing the corresponding select button in the bottom window. It is clear that WORG realizes the window rearrangement much more easily than the case shown in Fig. 7.6.

7.3.2 High-Intensity Display

One way to solve the visibility problem of a display would be to introduce a high-intensity LCD. For example, a high-intensity LCD made by HIKOM Co. Ltd. (HLC-1501) [2] has 1600 cd/m^2 intensity using a high-intensity backlight unit, providing sufficient visibility even under daylight conditions. One serious drawback of this display is high power consumption. Probably, we need a stable power source (e.g., a generator) at the rescue site to use such displays.

7.3.3 Optical Touch Screen

As discussed in Section 7.2.4, an optical touch screen would be appropriate for rescue systems where dust/water proofing is necessary. We selected an optical touch screen made by Xiroku, Inc. [8]. A small CMOS image sensor is installed at the two top corners of this touch screen. The location of a finger can be measured by triangulation. Since retroreflective material is attached to the inside of the panel-frame, which becomes the background image for the image sensor, the finger location can be obtained robustly. Any dust/water proofing on the screen does not affect the measurement performance. The location of a gloved finger can also be measured without any problem.

7.3.4 Standardized Interface Prototype

Combining the window arrangement utility, a high-intensity LCD, and an optical touch panel, we built a standardized interface prototype shown in Fig. 7.10.

To make the interface unit portable, all components are arranged inside a carry case. The case is 480 mm in width × 420 mm in depth × 300 mm in height. The total weight is approximately 14.0 kgf. On the lid side of the case, the high-intensity

Fig. 7.10 Overview of the standardized interface prototype

LCD (HIKOM) and the optical touch panel (Xiroku, Inc.) are installed. A notebook PC (Panasonic Toughbook CF-18DW1AXS) is installed at the bottom of the main body of the case and the high-intensity LCD is used as an external monitor of this PC.

Figure 7.11 shows the snapshots of the operation of this prototype. Note that the user in Figure 7.11 is wearing a glove. Since the touch panel is optical, the operator with the gloved hand can use the touch panel without any problem.

Figure 7.12 shows a comparison of intensity between the prototype using the high-intensity LCD and a conventional LCD monitor for a PC. One can see that the display of the prototype is much brighter than the conventional LCD monitor.

Fig. 7.11 Snapshots of operation

Fig. 7.12 Intensity comparison with a conventional LCD

7.4 Conclusions

In this paper, we summarized the findings and knowhow from some case studies discussed in the human-interface group of the DDT project and established the design guidelines for image displays.

The guidelines can be summarized as follows:

- We need multidisplay (hardware) or multiwindow (software) for multiple camera images, a global view for robot operation and a precise view for information gathering.
- An environmental map is useful for the operator to locate the current robot position and plan future movement. If possible, we can display two types of maps, a global map for robot operation and a local map in which the information obtained is input.
- Situational arrangement of the windows or switching the image on the primary (the largest) display is necessary. Windows should be rearranged easily and quickly without window overlapping.
- Image displays must be visible in any lighting conditions including strong sunshine.
- Dust and water proofing of displays is necessary for outdoor use, ensuring that it does not degrade the usability of the pointing device for gloved fingers.

On the basis of the guidelines for image displays, we built a standardized image display prototype as the first trial. Through discussions in the group, we ended up with a very simple conclusion, i.e., it is sufficient to let the operator choose an appropriate window arrangement from some preset ones, which were carefully arranged beforehand considering some expected situations. We built a window arrangement utility called WORG that enables us to preset multiple window arrangements and select one of them by simply pressing the button on the screen. Combining this window arrangement utility, a high-intensity LCD, and an optical touch screen, we built a standardized image display prototype.

Although the guidelines presented in this paper are not perfect, we hope that they would be useful for the future development of rescue robots. The prototype image display could be a good example of a standardized interface testbed.

Acknowledgements The study presented in this paper was financially supported by the DDT project (Special Project for Earthquake Disaster Mitigation in Urban Areas, III-4 Development of Advanced Robots and Information Systems for Disaster Response) sponsored by the Ministry of Education, Culture, Sport, Science and Technology. This is a joint project carried out by the human-interface group of the DDT project. The results presented in this paper represent the contribution of not only the coauthors of the paper but also other members of the group. We acknowledge their efforts and the information provided by them.

References

1. Chiu YH, Shiroma N, Igarashi H, Sato N, Inami M, Matsuno F (2005) FUMA: Environment information gathering wheeled rescue robot with one-DOF arm. Proc 2005 IEEE Int Workshop on Safety, Security and Rescue Robotics (SSRR2005)
2. HIKOM. http://www.hikom.co.jp/e_index.html
3. Nakanishi H, Hashimoto H, Hosokawa N, Inoue K, Sato S (2003) Autonomous flight control system for intelligent aero-robot for disaster prevention. J Robotics and Mechatronics 15-5:489–497
4. Oba Y, Hayashibara Y, Yoshida T, Koyanagi E (2005) Development of shape changeable type six crawler system with high-speed movement mechanism. SICE System Integration Division Annual Conference 3H4-2 (in Japanese)
5. Shiroma N, Sato N, Chiu YH, Matsuno F (2004) Study on effective camera images for mobile robot teleoperation. Proc 13th IEEE Int Workshop on Robot and Human Interactive Communication
6. Takayama T, Hirose S (2003) Development of "Souryu I & II" -connected crawler vehicle for inspection of narrow and winding space. J of Robotics and Mechatronics 15-1:61–69
7. Tsubouchi T, Tanaka A, Ishioka A, Tomono M, Yuta S (2004) A SLAM based teleoperation and interface system for indoor environment reconnaissance in rescue activities. Proc 2004 IEEE/RSJ Int Conf on Intelligent Robots and Systems (IROS2004) 1096–1102
8. Xiroku. http://www.xiroku.com/
9. Yokokohji Y, Tsubouchi T, Tanaka A, Yoshida T, Koyanagi E, Matsuno F, Hirose S, Kuwahara H, Takemura F, Ino T, Takita K, Shiroma N, Kamegawa T, Hada Y, Osuka K, Watasue T, Kimura T, Nakanishi H, Horiguchi Y, Tadokoro S, Ohno K (2006) Guidelines for human interface design of rescue robots. Proc SICE-ICASE Int Joint Conf 2006 3455–3460

Chapter 8
Information Sharing and Integration Framework Among Rescue Robots/Information Systems

Itsuki Noda, Yasushi Hada, Jun-ichi Meguro, and Hiroki Shimora

Abstract A framework for information sharing among robots/information systems for disaster mitigation is proposed. Gathering and sharing disaster information about damaged areas is the top-priority mission to support decision making in rescue processes. We are designing a standard protocol (MISP) and implementing a simple database system (DaRuMa) for this purpose. In order to utilize these facilities, we are also designing a standard format of sensed data collected by rescue robots and time representation to denote uncertain/ambiguous time periods, both of which form the essential core of rescue information sharing. We show the flexibilities and openness of the proposed framework and representation by several integration experiments with robotics, information, and communication technologies.

8.1 Motivation

"Information gathering and sharing" is the top-priority mission for managing rescue operation against disasters. When a huge disaster occurs, the headquarters of rescue organizations (local governments, fire departments, police offices, and so on) need to obtain information about damage as soon as possible in order to make decisions about rescue operations. However, it is quite difficult to gather the required information because we need to sense and monitor unusual places such as under debris, mudslides, underground, and so on. In addition, the disaster may damage normal information infrastructures; therefore, we cannot expect to be able to use rich platforms for information transfer/sharing. Without accurate information, the

Itsuki Noda and Hiroki Shimora
National Institute of Advanced Industrial Science and Technology (AIST)

Yasushi Hada
National Institute of Information and Communications Technology (NICT)

Jun-ichi Meguro
Toyota Central Research Institute

headquarters of rescue organizations cannot do anything even if they have enough rescue facilities. They need to allocate manpower to information-gathering tasks even if the manpower is special to actual rescue operations such as firefighting.

The DDT Project (Special Project for Earthquake Disaster Mitigation in Urban Areas) was launched by the Japanese Government in order to promote research on the mitigation of damage caused by huge disasters by helping information gathering using advanced technologies that include ICT, robotics [9, 2, 1] and computer simulation [4, 10, 6]. One of the goals is to provide an effective framework for the information and communication infrastructure for rescue systems. In order to achieve this goal, we have been designing a common framework of robust networking and flexible information-sharing, which help to gather sensed data about damage and to control search-and-rescue devices such as robots, sensor networks, and PDAs.

In this project, we have been designing and implementing a common protocol and database for information sharing among various rescue robots and rescue information systems. We are also designing a common and flexible representation to share sensing and time information that are acquired by robots. The rest of this article is organized as follows: in Section 8.2 we explain the information system that we are developing; in Section 8.3 we propose some standard representations for flexible rescue information systems. In Section 8.4 we present the results of some experiments on system integration achieved using the proposed protocol and database.

8.2 Information System in the DDT Project

8.2.1 Requirements for the Rescue Information System

The primary role of robots and devices developed in the DDT Project is to gather disaster information in order to support effective rescue activities. Because such robots and devices provide only fragments of information, we need a database system to store and integrate them. When we design such a database, we need to pay attention to the following three points.

The first point is that disaster information is *location-related* and *time-sensitive*. This implies that the database to integrate various pieces of information should be a type of geographical information system (GIS), which is designed so that it can represent geographical objects, retrieve objects using their location as a key, link information to a certain point, and store the information about the existence and changes in objects on a map. The GIS is also a key module to integrate rescue robots and other information systems for rescue activities. Figure 8.1 shows an overview of the design of the complete integrated information system for rescue. Here, information is transfered among subsystems via a database using a common protocol.

The second point is *on-the-fly* capability and *real-time* response. Generally, disasters may damage rescue information systems. Therefore, we need to replace some modules or counterparts of the systems on-the-fly. Further, because disaster and

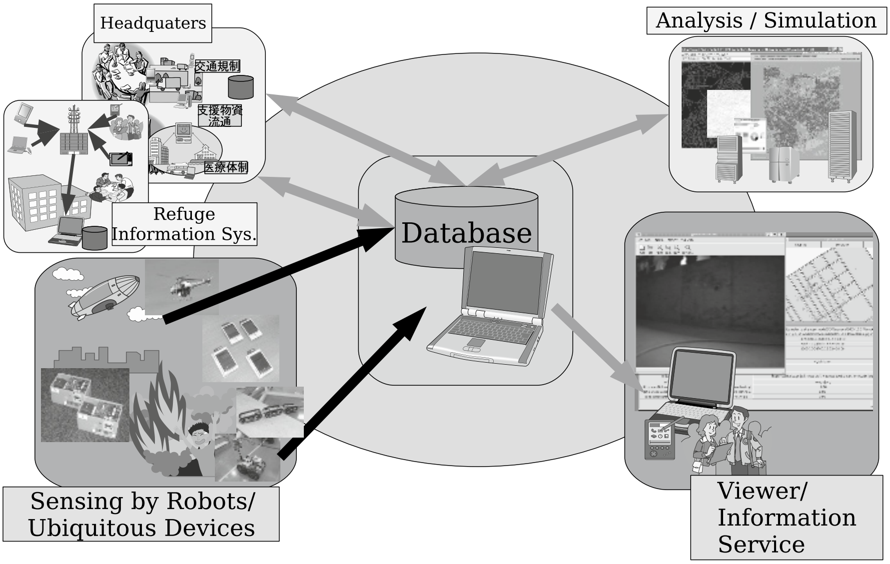


Fig. 8.1 Rescue systems integrated via geographic information database

rescue are dynamic phenomena, we need to keep the database running robustly in order to respond to real-time requests. This does not imply that the system should be a ‘super-dreadnought’ one, which may cause one-point-of-failure and difficulty of maintenance. Instead, we need just a simple, flexible, and light-weight system that is easy to operate and maintain.

The third point is the concept of *dual use*. This concept provides the following merits for rescue systems:

- It is easy and costs less to update a common platform. While the progress of ICT is fast, a huge disaster occurs once in a long while. Therefore, the cost of maintenance and update of the protocols and devices should be an important consideration while incorporating them in a rescue system. Protocols and devices that are used ordinarily, particularly by consumers, generally have low cost and are up-to-date in the ICT domain.
- It is easy to find spares when some modules have troubles. Because disasters such as earthquakes can occur anywhere, it is difficult to stock sufficient number of spare modules or devices for all cases. If the modules or devices are compatible with ordinary ones that are used by many people at home or office, the rescue team need not carry huge stocks of spare modules.

When we think about the dual use, openness and flexibility are key issues. Because ICT’s progress is so called dog-year, we need to choose technologies carefully from the viewpoint of the life cycle of developments. Openness and flexibility are the two major factors influencing the life cycle.

8.2.2 Mitigation Information Sharing Protocol

We have been designing a protocol for information sharing for rescue called MISP (Mitigation Information Sharing Protocol). MISP provides functions to access and to maintain geographical information databases over networks. We suppose that a complete system using MISP forms a client–server architecture, in which the server hosts a database and the clients provide or request data. The protocol consists of a pure and simple XML representation so that it is easy to develop systems to handle this protocol.

In MISP, geographical properties should be represented by geographical primitive types of GML [8]. Most of the existing GISs use SHAPE format for the geographical information. This format is originally designed to describe objects on maps. Therefore, a unit of information in this format is optimized to represent geographical simple features whose structure is restricted to be a geographical value and its associated nongeographical data. On the other hand, GML does not specify top-level structures of the information unit, but provides only a primitive expression of geographical values in XML. Because XML can flexibly represent various structures, we can handle complex information for disaster mitigation as it is.

While GML provides widely varied expressions for geographical primitives, we currently use only points, line-strings, polygons, and geometry collections. This set of primitives is sufficiently rich to construct GIS for rescue purpose and can be handled effectively using spatial indexing techniques such as R-tree.

As a database protocol, we take WFS (Web Feature Service) [7] with SOAP envelope as a base. WFS is a simple protocol to access a geographical XML database. It has been standardized by OGC (Open Geospatial Consortium) as part of a family of geographical web service protocols with WCS (Web Coverage Service) and WMS (Web Map Service).

Currently, the following protocols of WFS are available in MISP:

- `GetFeature`: Query data in the database.
- `Transaction`: Manipulate data in the database.
  - `Insert`: Add new data into the database.
  - `Update`: Modify a part of existing data in the database.
  - `Delete`: Remove existing data from the database.
- `GetCapabilities`: Ask for information about the functions provided by the database.
- `DescribeFeatureType`: Request information about an XML structure of a certain type of data that the database can handle.

In addition to these WFS protocols, MISP also has an additional protocol, `RegisterFeatureType`, to define a new type and its XML structure by XML schemes. Using this protocol, a user can add a new type of data without stopping and redesigning the entire systems. Such flexibility is important for a rescue system because it is difficult to define everything before a disaster. The additional protocol, `RegisterFeatureType`, enables one to connect new systems and to handle new types of information under emergency situations.

8.2.3 DaRuMa

DaRuMa (DAtabase for Rescue Utility MAnagement) is a reference system that is compliant with MISP. DaRuMa consists of a MySQL server and middleware written in Ruby/Java. The middleware translates between MISP and SQL. Figure 8.2 shows an overview of the DaRuMa system.

In order to utilize the effectiveness of MySQL as an RDBS, DaRuMa's middleware flattens an XML structure into an SQL table as much as possible. In addition, DaRuMa makes indexes of geographical properties in the XML structure, because most queries in a rescue situation are related to the locations of data.

Because MySQL, Ruby, and Java support a wide variety of platforms, we can run and port DaRuMa on various OS and hardware.

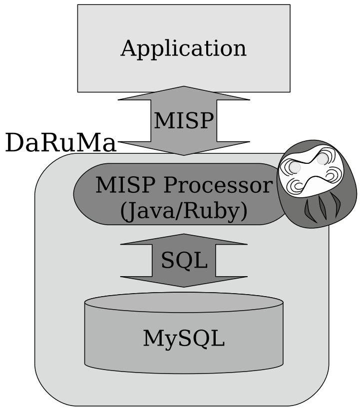


Fig. 8.2 System overview of DaRuMa

8.2.4 Advantage of DaRuMa/MISP

As described in Section 8.2.2, the MISP design is based on WFS. Further, we added several original features to this specification. In the rest of this section, we explain two of the features, `RegisterFeatureType` protocol and symbolic timestamp representation and show their advantages.

8.2.4.1 Utility of RegisterFeatureType

The original specification of WFS does not include a protocol to declare the structures of information that the database can deal with, while SQL can do it by "`CREATE TABLE`" protocol. This implies that WFS assumes that information structures are defined before the database runs. While this assumption is reasonable in normal usages of GIS, it is too rigid for the rescue purpose. As described in Section 8.2.1, we may switch some modules on-the-fly because of damage and/or situations of the systems. Hence, we need to redesign the information structure or add a new structure while running the database. The `RegisterFeatureType` protocol provides this flexibility.

The utility of this flexibility was shown when we attempted to integrate ten existing rescue information systems developed by different institutes, via DaRuMa/MISP. It required only three days to integrate all the systems from scratch without prior experience. During the integration, many information structures were repeatedly redesigned in order to achieve a consensus among institutes. The redesign process was very smooth because we did not have to stop DaRuMa; stopping DaRuMa wold have interfered with the operation of other institutes' systems. This is an episode of developing and debugging a system. However, we should suppose that the disaster situation is similar to debugging process because we may need to add and replace modules of the system. In such a situation, the utility of the `RegisterFeatureType` protocol will be effective in establishing the information infrastructure for disaster mitigation.

8.2.4.2 Symbolic Timestamp of Transaction

Because information is simultaneously collected and used in a disaster and the subsequent rescue operation, DaRuMa/MISP should respond to multiple requests in parallel. Therefore, a well-formed timestamp is necessary for DaRuMa/MISP. In particular, when a client of DaRuMa/MISP wants incrementally to process a large amount of information, a fine-grained timestamp is important.

In order to realize such a facility, we introduce a symbolic timestamp of the transaction, called '`transactionID`'. DaRuMa/MISP assigns each transaction operation a `transactionID`, which is a symbol (UUID string). The whole set of `transactionID`s in DaRuMa is totally ordered. That is, all transactions are serialized in a DaRuMa. Each data entry records its create and update timestamps by `transactionID`s. In addition, each MISP response also includes a `transactionID` that indicates the timestamp of the most recent transaction. Using this information, clients can incrementally process the dynamic information stored in DaRuMa.

In general, a timestamp is represented by a time value or a serial integer number instead of using a symbolic representation. However, we used a symbolic representation for the following reasons:

- Time value representation of a timestamp cannot provide sufficient granularity to serialize all transactions. If we use time values, we cannot escape the limit of the smallest time-tic of computer systems. While databases and operating systems have a fixed time-tic such as 1 second, 1 millisecond, or 1 nanosecond, the processing speed of CPUs is increasing day by day. Moreover, recently, multi-CPU and multicore technologies have become common. This implies that it will soon be possible to complete in a single time-tic.
- Serial integer numbers cannot handle distributed processing of multiple databases. While serial integer numbers can serialize the transactions in a single database, they cannot represent the order of transactions belonging to multiple databases. In future, the rescue information database will form a GRID to provide robustness and performance. In other words, timestamp representation should have a capacity to represent the complicated order among the transactions belonging to different databases. Integer representation is inadequate to serve this purpose, because we cannot guarantee that every timestamp is unique. On the other hand, UUIDs guarantee that every ID is unique by its definition.

8.3 Flexible Representation for Disaster Information

8.3.1 Representation for Sensed Data

MISP and DaRuMa provide a quite general framework to share information, but do not specify how to represent the actual data in an XML format. Such unrestricted specification enables DaRuMa (and other MISP-compliant systems) to connect to existing systems. However, for newly developing systems, we also need some guideline to represent information sharing in order to enable effective cooperation among systems.

As the first step to formulate such guidelines, we are designing the representation for the data from sensors and robot networks based on `directedObservation` of GML. The features of the representation are:

- The entity of sensed data (`ddt:sensedDataEntity`) and their metadata (`ddt:sensedDataInfo`) are separately represented. Because sensed data such as images and movies are generally large, the size of the query results may be huge even if the most of them may not be used. The separation of actual data and metadata enables the system to filter data using metadata information that is generally smaller than actual data.
- Each property can include noise element, which indicate noise and ambiguity levels. Because it is difficult to uniformly scan the entire area in a disaster, such information will be required in order to integrate the data received from different types of sensing devices.

Figures 8.3 and 8.4 show the conceptual framework and an XML example of the sensed data representation, respectively.

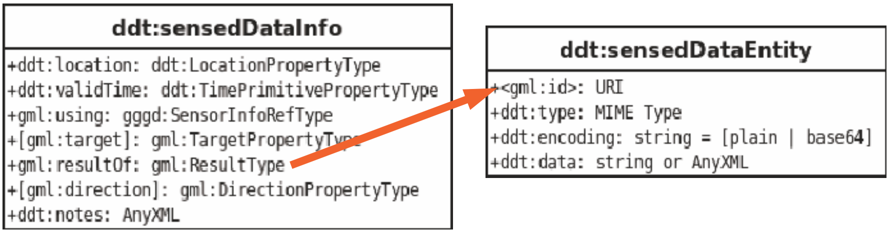


Fig. 8.3 Structure of sensed data information

8.3.2 Flexible Time Representation

Another problem with sensed information is noisy and ambiguous data. In particular, the ambiguities of location and time are not avoidable in robotic sensing. Therefore, information representation should have the capacity to permit and express such uncertainty. Currently, we have been designing the representation of ambiguous time.

In general, it is difficult to know the exact time or period of an event in a disaster and rescue situation. Instead, we can only know that the event “has not occurred”, “is occurring” or “has occurred” at a certain time or period. For example, we can observe a change in terrain caused by a landslide that occurred during a certain period from the photos taken by airplanes, but cannot know the exact time when the landslide occurred.

In order to represent such uncertain time information, KIWI+ [3] introduced four time positions, that are “begin-time of occurrence”, “definite time of occurrence”, “begin-time of vanishing”, and “definite time of vanishing”, in order to represent the time of an event. We formalize these four time positions as two time periods, *certain* time period and *possible* time period, based on fuzzy logic or certainty/possibility theory. Figure 8.5 shows the conceptual overview of the time representation. In this figure, a *certain* time period (`gml:TimePeriod`) shows the time period in which the event is certainly observed. On the other hand, the *possible* time period (`ddt:possibleTime`) indicates the period when the event might be appearing. In other words, outside of the possible time period, the event is definitely not occurring.

Using this definition of the meaning of time representation, we can derive the following inference rules for information integration:

- The possible time period must include the certain valid time period.
- When the certain valid time period is changed, it can be extended but not shrunk. If we need to shrink the period, we must reject some evidence used in a previous inference.
- When the possible valid time period is changed, it can be shrunk but not extended. If we need to extend the period, we must reject some evidence used in a previous inference.

```xml
<ddt:sensedDataInfo>
 <ddt:location>
  <gml:Point>
   <gml:coordinates srsName='#localCoodinates'>
    10.0,20.0,30.0
   </gml:coordinates>
  </gml:Point>
  <ddt:noise> ... </ddt:noise>
 </ddt:location>
 <ddt:target>
  <gml:Point>
   <gml:coordinates srsName='#localCoodinates'>
    40.0,50.0,60.0
   </gml:coordinates>
  </gml:Point>
  <ddt:noise> ... </ddt:noise>
 </ddt:target>
 <ddt:validTime>
  <gml:TimePeriod>
   <gml:beginPosition>2005-09-29T23:35:00+09:00</gml:beginPosition>
   <gml:endPosition>2005-09-29T23:35:00+09:00</gml:endPosition>
  </gml:TimePeriod>
 </ddt:validTime>
 <ddt:using xlink:href="MyDigiCam" />
 <ddt:resultOf xlink:href="MyPhoto">
  <ddt:type>image/jpeg</ddt:type>
 </ddt:resultOf>
 <ddt:direction>
  <ddt:DirectionVector>
   <ddt:horizontalAngle>0.0</ddt:horizontalAngle>
   <ddt:verticalAngle>80.0</ddt:verticalAngle>
   <ddt:rollAngle>0.0</ddt:rollAngle>
  </ddt:DirectionVector>
 </ddt:direction>
 <ddt:notes>
  <ddt:viewCone>35.0,20.0</ddt:viewCone>
  <ddt:resolution>640,400</ddt:resolution>
 </ddt:notes>
</ddt:sensedDataInfo>

<ddt:sensedDataEntity gml:id="MyPhoto">
 <ddt:type>image/jpeg</ddt:type>
 <ddt:encoding>base64</ddt:encoding>
 <ddt:data>
   /9j/4SQ+RXhpZgAASUkqAAgAAAAMAA8BAg...
   AQAAABoBBQABAAAAuAAAABsBBQABAAAAwA...
   AgAUAAAA8AAAABMCAwABAAAAAgAAAJiCAg...
   CgEAAKQEAABGVUpJRklMTQAARmluZVBpeC...
   dGFsIENhbWVyYSBGaW5lUGl4IEY4MTAgIC...
   NwAgICAgAABQcmludElNADAyNTAAAAIAAg...
   AQAAAOQCAAAiiAMAAQAAAAYAAAniAMAAQ...
   ...
 </ddt:data>
</ddt:sensedDataEntity>
```

Fig. 8.4 XML example of sensed data representation

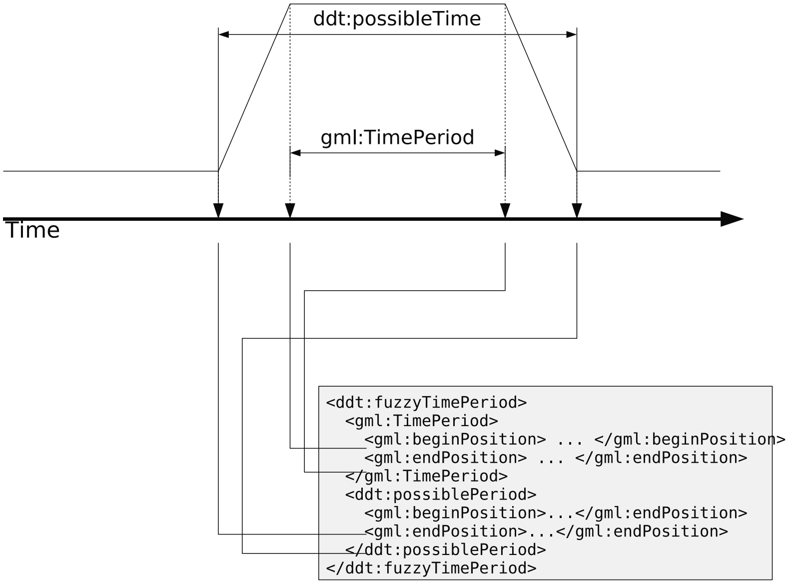


Fig. 8.5 Concepts of flexible time representation

8.4 System Integration via DaRuMa/MISP

As described above, MISP and DaRuMa are designed to integrate various rescue information systems. The method of integration is simple. DaRuMa functions as a type of blackboard to which each information system connects using MISP to write and read shared information, as shown in Fig. 8.6. In this figure, the existing and newly developed systems can connect to DaRuMa directly or via libraries ('lib.' in the figure) and converters (conv.). Because of the generality and flexibility of XML representation, it is easy to develop such libraries and converters. We have already developed such tools called 'DaRuMa tools', which is designed to convert data between CSV and XML for general purpose.

We conducted several experiments to integrate the sensing systems of rescue robots and GIS viewers. Figure 8.7 is a typical schema to connect robotic sensors and GIS viewers. In this schema, a robot collects various types of data such as pictures, sounds, and so on along with the location of the sources of these data, and sends them to a DaRuMa using '`Insert`' protocol of MISP. At the same time, a GIS viewer sends a request by means of the function '`GetFeature`' and obtains the information collected by the robot in real time. When the viewer needs only changes of information from the previous access, it can utilize the `transactionID` facility described in Section 8.2.4. In this case, the viewer can show changes in the previously acquired information in the form of an animation.

Figure 8.8 shows the result of experiments conducted to integrate FUMA, a rescue robot, and DaRuMa Viewer, a universal and simple GIS viewer for DaRuMa. In

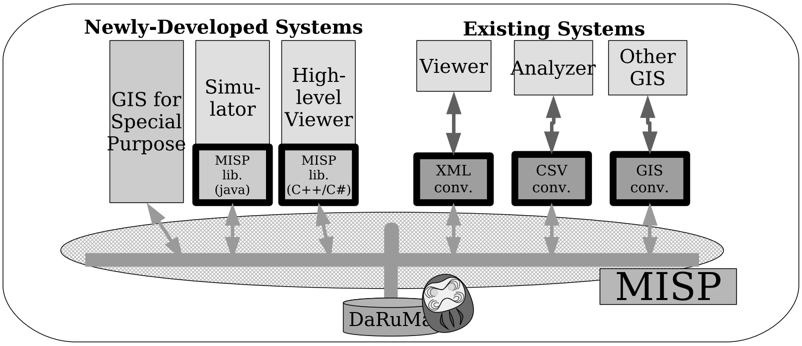


Fig. 8.6 Framework for system integration via DaRuMa

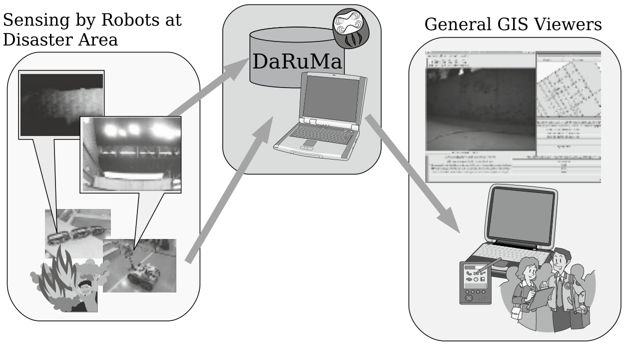


Fig. 8.7 Integration of information sensed by rescue robots

this figure, DaRuMa Viewer shows a trajectory of the movement of FUMA in a test field in the main window, and a piece of picture captured and information gathered by it in the pop-up windows. Because DaRuMa can handle multiple connections, it is possible to simultaneously connect several robots and viewers, as shown in Fig. 8.9. In this figure, IRS Soryu, another rescue robot, connects with DaRuMa viewer running on PDAs and also DaRuMa Earth Viewer, another GIS viewer using Google Earth$^{\mathrm{TM}}$[5].

As shown in the previous example, we can easily utilize existing information systems such as Google Earth. This is important in a rescue situation because we may be required to utilize limited facilities in a disasters. In order to emphasize this feature, we developed a generic tool, called DaRuMa Earth, in order to convert MISP to KML, which is the format used in Google Earth and Google Map (Fig. 8.10). Using this tool, we can visualize various information items collected by robots and other sensing systems. Figure 8.11 shows an example snapshot of GoogleEarth showing the 3D trajectory of a balloon rescue robot running in the Yamakoshi area, which suffered huge damage by the Niigata-Chuetsu Earthquake in October 2004.

Using such flexibility, we also can integrate robotic sensing and simulation systems and provide light-weight tools for the general public in a disaster area. Fig-

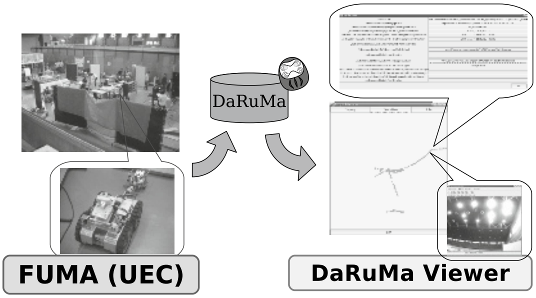


Fig. 8.8 Universal DaRuMa viewer

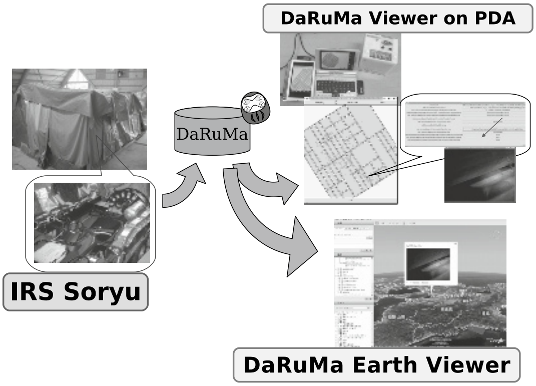


Fig. 8.9 Multiple viewers can be connected with DaRuMa

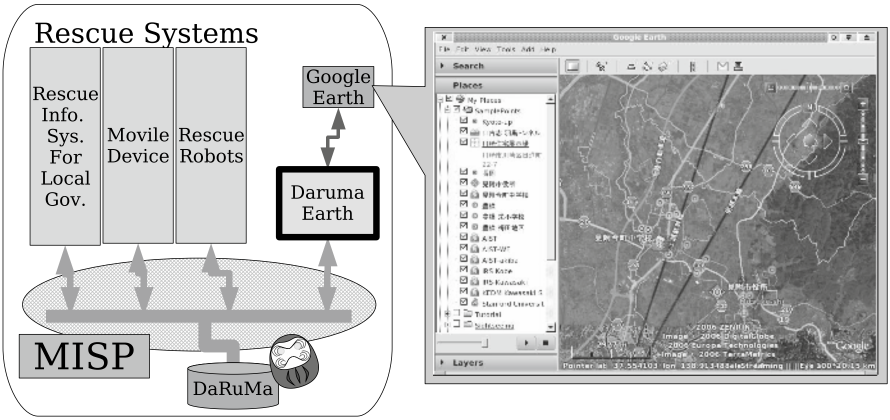


Fig. 8.10 DaRuMa Earth (© 2006 ZENRIN, Image © 2006 DigitalGlobe, © 2006 Europa Technologies, Image © TerraMetrics, © 2006 Google)

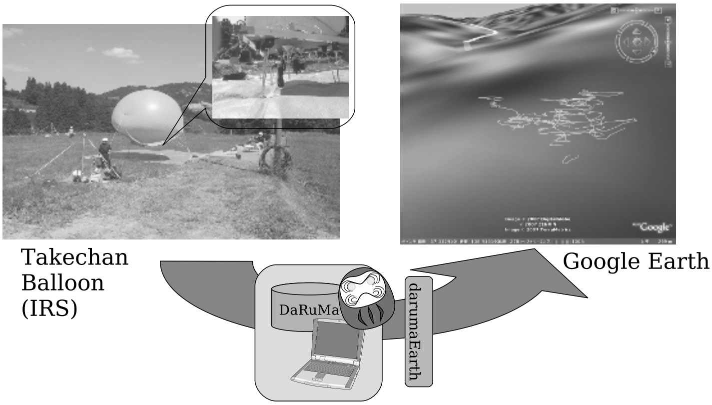


Fig. 8.11 Google Earth is showing 3D trajectories of balloon robots translated by DaRuMa Earth (Image © 2007 DigitalGlobe, © 2007 ZENRIN, Image © 2007 TerraMetrics, © 2007 Google)

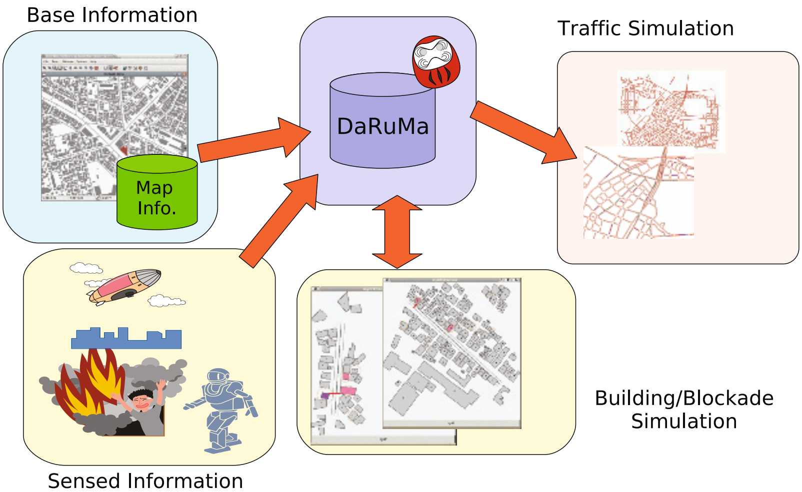


Fig. 8.12 Example of collaboration among robots and simulations via DaRuMa

ure 8.12 shows an example of such integration whereby the data collected by rescue robots is utilized for building/blockade and traffic simulation in order to predict social phenomena under disasters.

8.5 Conclusions

In this article, we proposed MISP, a standard protocol for rescue information sharing platforms, and DaRuMa, a prototype implementation of MISP-compliant databases, as a framework for information gathering/sharing for disaster and rescue. They were designed to answer several requirements of disaster mitigation like *location-related*, *on-the-fly*, and *real-time*. We also proposed a data representation for rescue information sharing systems on DaRuMa/MISP and presented some results of experiments on system integration using these facilities.

As mentioned in Section 8.2.1, a rescue system should be designed from the viewpoint of dual use. While we only described the rescue application, the system also has the capability to handle general-purpose geographical information. We are planning to apply it to daily applications such as town navigation.

There also remain the following open issues:

- **Flexible Knowledge/Inference:** While MISP can accept any type of data structures, it has no mechanism to map data among these structures. In particular, in the case of daily operations of local governments, many types of data overlap in different departments. In general, it is difficult to maintain correspondence between data in different departments. Therefore, we need an ontology mechanism to map such correspondence semiautomatically.
- **System Robustness:** As mentioned in Section 8.2.2, a rescue information system should have the capability to run on GRID/P2P environments. MISP uses SOAP Envelope to guarantee its smooth operation on such a distributed processing framework, but it has not been specified how to realize it.

References

1. Asama H, Hada Y, Kawabata K, Noda I, Takizawa O, Meguro J, Ishikawa K, Hashizume T, Ohga T, Hatayama M, Matsuno F, Tadokoro S (2006) Introduction of mission unit for rescue system infrastructure in Special Project for Earthquake Disaster Mitigation In Urban Areas. Proc 4th Int Rescue System Symp
2. Asama H, Hada Y, Ohga T, Takizawa O, Tadokoro S, Noda I, Matsuno F, Hatayama M (2004) Introduction of task force for rescue system infrastructure in Special Project for Earthquake Disaster Mitigation In Urban Areas. Proc 2004 IEEE Int Conf on Robotics and Biomimetics (ROBIO2004) 404
3. KIWI+ (2002) http://www.drm.jp/KiwiPLUS/index.htm
4. Koto T, Noda I, Kuwata Y, Takeuchi I (2003) The architecture of the integrated earthquake disaster simulation system under Special Project for Earthquake Disaster Mitigation In Urban Areas. Proc 17th Annual Conf of JSAI 1B5-01 (in Japanese).
5. Meguro J, Ishikawa K, Hashizume T, Noda I, Hatayama M Disaster information collection by cooperation of rescue system and geographic information system. Proc 4th Int Rescue System Symp
6. Noda I, Takahashi T, Morita S, Koto T, Tadokoro S (2002) Language design for rescue agents. In Tanabe M, Besselaar PV, Ishida T (eds) Digital Cities II, Chapter Technologies for Digital Cities 371–383. Springer
7. Open GIS Consotium (2002) Web feature service implementation specification (OGC 02-058) ver. 1.0.0 edition. https://portal.opengeospatial.org/files/?artifact_id=7176
8. Open GIS Consotium (2003) OpenGIS Geography Markup Language (GML) implementation specification (OGC-02-023r4), ver. 3.00 edition. http://www.opengis.org/docs/02-023r4.pdf
9. Tadokoro S (2003) An overview of Japan national special project daidaitoku (DDT) for earthquake disaster mitigation in urban areas. Proc 2003 IEEE Int Symp on Computational Intelligence in Robotics and Automation (CIRA2003) Workshop on Advanced Robots and Information Systems for Disaster Response

10. Takahashi T, Takeuchi I, Koto T, Tadokoro S, Noda I (2000) RoboCupRescue disaster simulator architecture. In Kitano H, Tadokoro S, Fischer F, Burt A (eds) Workshop Working Notes on RoboCupRescue (ICMAS-2000 workshop) 97–105

Chapter 9
Demonstration Experiments on Rescue Search Robots and On-Scenario Training in Practical Field with First Responders

Takashi Tsubouchi, Koichi Osuka, Fumitoshi Matsuno, Hajime Asama, Satoshi Tadokoro, Masahiko Onosato, Yasuyoshi Yokokohji, Hiroaki Nakanishi, Tomoharu Doi, Mika Murata, Yuko Kaburagi, Ikuko Tanimura, Naoko Ueda, Ken'ichi Makabe, Koichi Suzumori, Eiji Koyanagi, Tomoaki Yoshida, Osamu Takizawa, Toshi Takamori, Yasushi Hada, and Itsuki Noda

---

Takashi Tsubouchi
University of Tsukuba

Koichi Osuka
Kobe University

Fumitoshi Matsuno
University of Electro-Communications

Hajime Asama
University of Tokyo

Satoshi Tadokoro
Tohoku University

Masahiko Onosato
Hokkaido University

Yasuyoshi Yokokohji and Hiroaki Nakanishi
Kyoto University

Tomoharu Doi
Osaka Prefectural College of Technology

Yasushi Hada and Osamu Takizawa
National Institute of Information and Communications Technology (NICT)

Toshi Takamori, Mika Murata, Tomoko Yamaguchi, Yuko Kaburagi, Ikuko Tanimura and Naoko Ueda
International Rescue System Institute (IRS)

Ken'ichi Makabe
IRS-U

Koichi Suzumori
Okayama University

Eiji Koyanagi and Tomoaki Yoshida
Chiba Institute of Technology

Itsuki Noda
National Institute of Advanced Industrial Science and Technology (AIST)

Abstract This chapter presents a process of making connections between researchers who develop rescue search devices and first responders, and presents scenario training experiments utilizing the devices operated by the responders. The development of the rescue search devices is aimed at practical deployment in the future so that the development researchers must have taken a pragmatic approach. It was crucial that researchers took every opportunity to demonstrate them in the presence of first responders and that they had contacts with several volunteer incumbent firemen who offered practical comments on the developed devices. Such comments will be used in the next stage of the development of rescue search devices.

9.1 Introduction

The development of rescue robots involves a degree of pragmatism. In scientific fiction, a "rescue robot" is a super machine or a super humanoid to rescue injured persons in place of the first responders in a disaster area. However, we might as well call it a "rescue search robot" or a "rescue search device." The present authors at DDT project have endeavoured to develop such a series of devices rather than super robots appearing in science fictions, which can help first responders to search for surviving victims in the disaster area.

The DDT project (Special Project for Earthquake Disaster Mitigation in Urban Areas, III-4 Development of Advanced Robots and Information Systems for Disaster Response) aims at the development of search devices that can provide useful information for rescue activity in several types of locations suffering from a large-scale earthquake. The devices are required to be effectively utilized at actual disaster sites, which motivates us to integrate necessary element technologies, to assemble them into devices and demonstrate the effectiveness of these devices in providing necessary information in the target environment.

9.2 Who Is the User?

Who is the expected or proper user of such rescue search devices? It must be the first responders, for example, firemen or special rescue teams of disaster mitigation organizations.

An engineering device cannot be designed unless its necessary specifications are laid down. This implies that the correct approach to design a device must include the process of observation of its usage. We must observe where and how the device is used by the first responders and what types of functions these devices must be able to perform. If engineer designers could attend every disaster area and observe the rescue activity, it may be possible to draw the specifications considering the necessary functions. However, it is difficult for them to have permission every time to visit specific areas.

Therefore, as another approach, we may take interviews or questionnaire surveys of the first responders. Although this approach seems practical, the authors, as researchers at the DDT project, initially experienced difficulties in obtaining effective and meaningful information from such surveys. The difficulties arose from the following facts:

1. The researchers had few connections with the first responders having practical experience.
2. Even when some of the researchers of DDT questioned some responders as to what type of a device will be useful, the responders offered notional answers or were at a loss to answer the question.

The second fact can be understood because of a lack of communication between researchers and responders. They them had no shared common understanding on the topic of introducing robotic technologies into rescue search devices. The responders did not have sufficient information on what could be possible by introducing new technologies; as a result, they could not give proper answers to the researchers. To say in a figurative dialogue, “Please teach me your idea. We develop useful staffs,” “What could I teach you? I do not know what kind stuffs you can develop!” Time, interest, and effort are required to enable the two parties to reach a common understanding.

9.3 Progress of the Development of the Rescue Search Devices and IRS-U

Intensive academic activities just after the Great Hanshin-Awaji Earthquake in January 1995 triggered the development of rescue robots or rescue search devices. The development was encouraged and accelerated by the grant under the MEXT’s Special Project For Earthquake Disaster Mitigation in Urban Areas, called the DDT project, from 2002 to 2006 for 5 years, where the subproject of DDT, “Development of Advanced Robots and Information Systems for Disaster Response” was assigned. The NPO, International Rescue System Institute (IRS), was established and enrolled as a central organization for the management of the development. Under the leadership and supervision of the IRS, researchers in Japanese universities and research institutes gathered to accelerate the development.

Figure 9.1 illustrates the road map of the project, where

1. the researchers develop prototypes of rescue robots or rescue search devices based on robotic technological elements, which can be used after integration and sophistication of the elements;
2. however, the development must consider possible and realistic scenarios for the use of devices; and finally,
3. the developed prototype must be evaluated in practical environments, which realize actual disaster sites as far as possible.

The primary mission of the DDT project is to show possibilities to realize practically usable high-performance search devices. Thereafter, we can proceed to develop robust devices suitable for repeated use and the deployment of these devices to the first responder organizations.

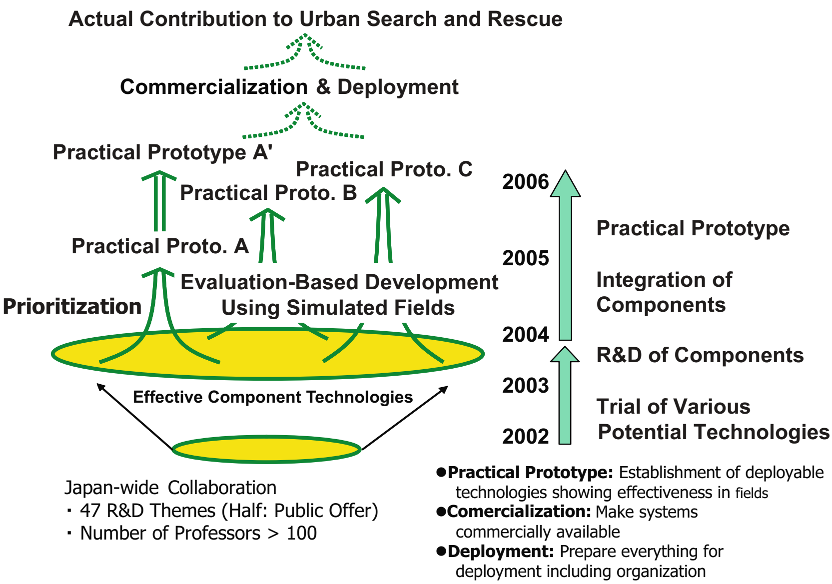


Fig. 9.1 Development mission for high performance devices for search at disaster sites

In mid-2004, i.e., around 3 years after the launch of the DDT project, rescue robots or rescue search devices were developed. For example, "IRS Souryu" (Fig. 9.2) was one of the leading devices. It was equipped with a video camera and aural communication facilities (intercom) on the base mechanism of the original "Souryu," which was developed in the laboratory of Professor Hirose at Tokyo Institute of Technology. For publicity, the IRS or related researchers made efforts to take every opportunity to demonstrate IRS Souryu or other devices available at that time to the staff of fire stations, first responders, and local citizens.

The IRS staff greatly contributed toward receiving publicity, which was a great merit of the project framework that the IRS was enrolled as the central organization for the management. The IRS staff not only received the offers of demonstration opportunities at local events, but also developed opportunities to communicate with the first responders. This opportunity development activity gave strong effect to establish desirable contacts with responders. The usual way of receiving a grant and pursuing research involves a contract directly between the grant support organization and the university or research institute. However, the staffs of the university or the institute could hardly make efforts to negotiate with responders. It is admirable that the IRS has expert staff.

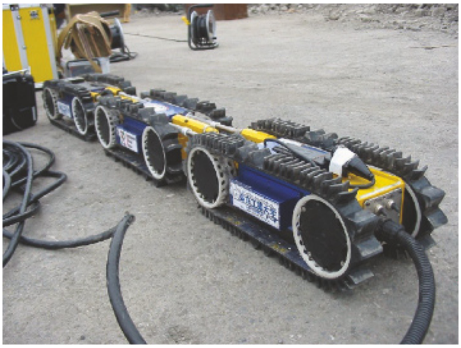


Fig. 9.2 IRS Souryu

In the later half of the year 2005, the efforts of publicity to responder-related organizations showed results. As one of the results, we encountered a fireman in a local prefectural fire station who was very interested in introducing robotic technology into the rescue and search devices. He was interested in using robotic technology for the safe and efficient conduct of rescue activities and the prevention of secondary disasters at a disaster site. Taking the opportunity to make contact with the IRS, he and his colleagues observed and operated the devices developed on off-duty days. They offered practical information on the use-case environment for the functions of a developed device or necessary functions for the device at a practical site. They offered volunteers to prepare an operation manual for IRS Souryu.

This connection served as the background to establish IRS-U and start its activities in March 2006. The IRS-U consists of voluntary members who are employed in fire departments including the one mentioned in the previous paragraph. The mission of IRS-U is:

1. to operate the devices developed by the DDT – and IRS – related research staffs under the assumed scenarios and environments;
2. to evaluate the performance of the devices;
3. to offer evaluation feedback to the development staff;
4. to identify and specify the scenes wherein each device is practically useful;
5. to provide the operation manuals for the developed devices; and
6. to offer publicity for the developed devices under the DDT project to the members of the national first-responder organizations.

The developed devices cannot be put to practical use in the real environment of search and rescue without testing them. They can be tested at the training facilities of fire stations, where firemen receive training everyday in a simulated practical environment. A member of IRS-U presented an idea to use such a training facility to conduct experimental training of the developed devices. In fact, experiments were conducted in training facilities in 2006, the final year of the project. Even after the DDT project was over, such experimental training was conducted several times.

9.4 Toward Practice Experiments and Training

9.4.1 Policies

As mentioned in the preceding section, we can recognize demonstration experiments or experimental training as an opportunity to present the effectiveness of the developed rescue robots or rescue search devices in a simulated disaster environment and to discover the drawbacks of these devices for their practical use in such an environment (Fig. 9.3). Furthermore, according to item 6 of IRS-U mission, for publicity, it is important to disclose the usage possibilities and abilities of the devices to which robotic technologies are applied to the concerned parties.

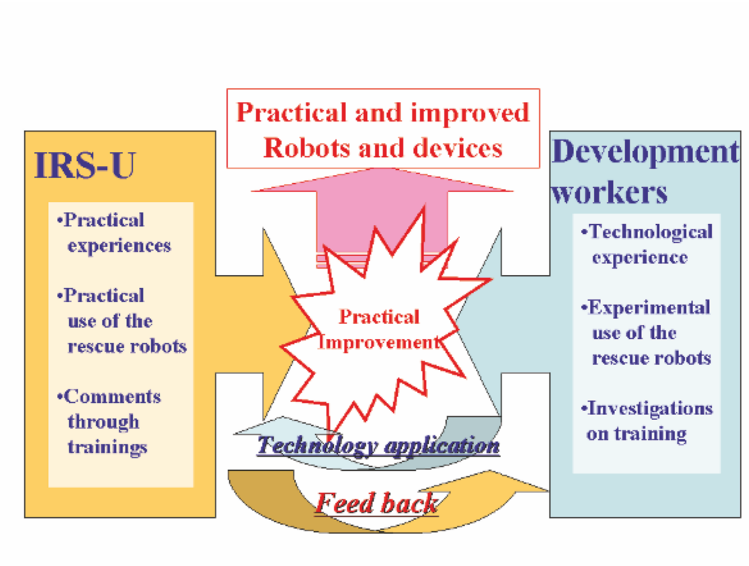


Fig. 9.3 Cooperations of the researchers and users

Usability assessment and establishment of a feedback cycle are important issues. The assessment must be performed under sufficient experience of practical operations in a practical field. For effective experiments, the authors adopted the following policies:

1. A scenario which assumes the use of devices in the experimental or training field as similar as possible to the real scene is composed by the members of first responders.
2. The devices are evaluated by the operation following the scenario.
3. The operation is performed by the first responders and not by the staff who developed the devices.

4. The performance is evaluated by the first responders to offer improvement feedback to the development staff.

The IRS conducted such scenario-based experiments several times in cooperation with IRS-U, the members of fire departments, and local governments.

In 2006, the final year of the DDT project, the IRS and IRS-U conducted scenario-based experiments and training five times in cooperation with Tokyo Fire Department, Kawasaki City Fire Department, Kobe City Fire Department, Kawasaki City, Kobe City, Japan Disaster Relief Team, and Hyogo Prefectural Emergency Management and Training Center. These experiments and training were mainly focused on items 1 to 3 in the IRS-U mission. However, each experiment and training exercise was made available not only to the organizations related to fire departments to accomplish the item 6 of the mission, but also to the press to gain general publicity on these activities.

9.4.2 Commentaries

The experiments and training conducted in 2006 were as follows:

1. Outdoor experiment and training on April 22 and 23, 2006

   Place: Tachikawa outdoor training field in 8th Fire District of Tokyo Fire Department.
   Scenario: IRS-U turns out for an emergency call to rescue a victim from a crushed house after a big earthquake.
   Devices used: BENKEI, BENKEI-2, a jack robot, a cutter robot, intelligent search cam, IRS Souryu, Rescue Dummy and RFID tags.

2. Indoor experiment and training on June 24, 2006

   Place: Tachikawa training building in 8th Fire District of Tokyo Fire Department.
   Scenario: IRS-U turns out for primary scouting activity because of an emergency call for NBC disaster suspicion with bad smell for unidentified reason and nausea sufferer. The mission of IRS-U is to confirm the existence of victims and the identification of suspicious material.
   Devices used: ACROS, TP03, Rescue Communicators, and RFID tags.

3. Outdoor experiment and training on October 3 and 4, 2006

   Place: outdoor training field in the Hyogo Prefectural Emergency Management and Training Center
   Scenario: same as item 1.
   Devices used: IRS Souryu, cutter robot, Rescue dummy, KURUKURU, and RFID tags.

4. Indoor experiment and training on November 5, 2006

Place: underground town of Kawasaki Station of Japan Railway (JR) East.
Scenario: just after a big earthquake, injured victims remains in the underground town. IRS-U and Kawasaki City Fire Department turn out. IRS-U offers primary scouting activity to investigate the inside situation and to identify the victims by operating rescue robots from the ground-level entrance. After receiving the report of the investigation and identification, the members of Kawasaki City Fire Department perform the rescue operation to save the victims.
Devices used: IRS Souryu, Hibiscus, KOHGA2, and IC tags.

5. Indoor experiment and training on November 23, 2006

Place: Collapsed House Simulation Facility of IRS Kobe laboratory.
Scenario: same as item 1.
Devices used: UMRS-NBCT, IRS Souryu, Hibiscus, Rescue Communicator, Fiber scope with propulsion by cilia, and RFID tags.

9.5 Details of Experiments and Training at the Underground Town of JR East Kawasaki Station

This was the first experiment and training realized in the real environment in cooperation with the maintenance company of the underground town, Kawasaki City, Kanagawa Prefecture and Kawasaki City Fire Department. It was a very important event because of the following:

1. It was conducted in a real environment and by the members of IRS-U that developed the robots under the DDT project.
2. It was a cooperative training scenario in which not only the members of IRS-U but also the special rescue members of Kawasaki City Fire Department (Kawasaki CFD) participated and operated the robots.

The fact of cooperation with the Kawasaki CFD seems to have been effective in obtaining publicity of the rescue robots to general members of fire departments. In the scenario: (a) IRS-U offers primary scouting operation; (b) the special rescue members of the Kawasaki CFD share the information from the scouting by the IRS-U; and (c) the rescue members perform the rescue operation, while IRS-U performs the backup operation.

9.5.1 Scenario and Snapshots of the Experiments and Training

The detailed scenario with snapshot pictures is as follows:

A big earthquake has occurred. The IRS-U by chance turned out voluntarily to the underground town at JR Kawasaki Station as the IRS-U was in a training session at the IRS Kawasaki laboratory, which is very near to the station. The members of the Kawasaki CFD took some time to arrive at the town because of several locations where the rescue activities were called for, though Kawasaki CFD covers the underground town under the service area. Therefore, the IRS-U was the first party that arrived at the underground town.

IRS-U decided to begin the primary scouting service. According to the investigation of the ground-level entrance, the inside of the underground town seemed to be dangerous. The IRS-U decided to use and operate the rescue robots as scouting devices. After the scouting service was started by IRS-U, the menbers of Kawasaki CFD arrived at the town.

After the robots were set up (Fig. 9.4 (a)), the IRS-U started to operate the three robots from the entrance of the ground level through the stairs (Fig. 9.4 (b)). In the figure, IRS Souryu appears on the left; KOHGA2, in the center; and Hibiscus, over the stair fence. All the robots arrived at the underground level and scouting operation was started to search for remaining victims and to investigate the inside situation of the town (Fig. 9.4 (c)). Figure 9.4 (d) presents KOHGA2 (fore side) and Hibiscus (hind side), which performed the search operation in the corridor of the underground town, and Fig. 9.4 (e) presents the Hibiscus operator of IRS-U.

An injured victim was found by KOHGA2 (Fig. 9.4 (f)). The operator of the KOHGA2 at the ground level called one of the Kawasaki CFD to rescue the victim; the member came to the victim and saved him (Fig. 9.5 (a)). The operator at the ground level watched the entire rescue operation through the monitoring camera on KOHGA2. After this victim was saved, the search operation by the three robots was continued (Fig. 9.5 (b)). In the situation shown in this figure, the monitoring camera of KOHGA2 on the hind side (on the right side in the picture) continued capturing the other two robots in the view angle. Therefore, the operator at the ground level could continue watching the situation.

Another victim who was under the debris was found by IRS Souryu (Fig. 9.5 (c)). The operator at the ground level called the victim through the intercom installed on IRS Souryu to confirm consciousness of the victim. If the victim was conscious, the operator would continue the voice contact to encourage safe rescue. During the activity, the operator also checked the temperature and CO_2 content of the air at the site. This information was shared by the members of IRS-U and Kawasaki CFD. The members of Kawasaki CFD began the rescue operation for the victim (Fig. 9.5 (d)). The members confirmed the situation of the victim. The robot operators turn the heads of the robots to the scene, and the rescue operation was broadcast to the ground operation manager through the monitoring cameras installed on the robots. One of the rescue members reported the operation by voice, utilizing the intercom facility of IRS Souryu.

Figure 9.6 (a) presents the monitor screen for the operator of Hibiscus. The monitor displayed the image captured by the camera of Hibiscus, which appears in Fig. 9.5 (d) (lower left). It was a “new” experience because the operators at the ground level could monitor the operation inside the underground town. KOHGA2 was situated at a rear location to broadcast the entire rescue operation (Fig. 9.6 (b)). Figure 9.6 (c) presents a snapshot of the rescue operation. The debris was lifted up

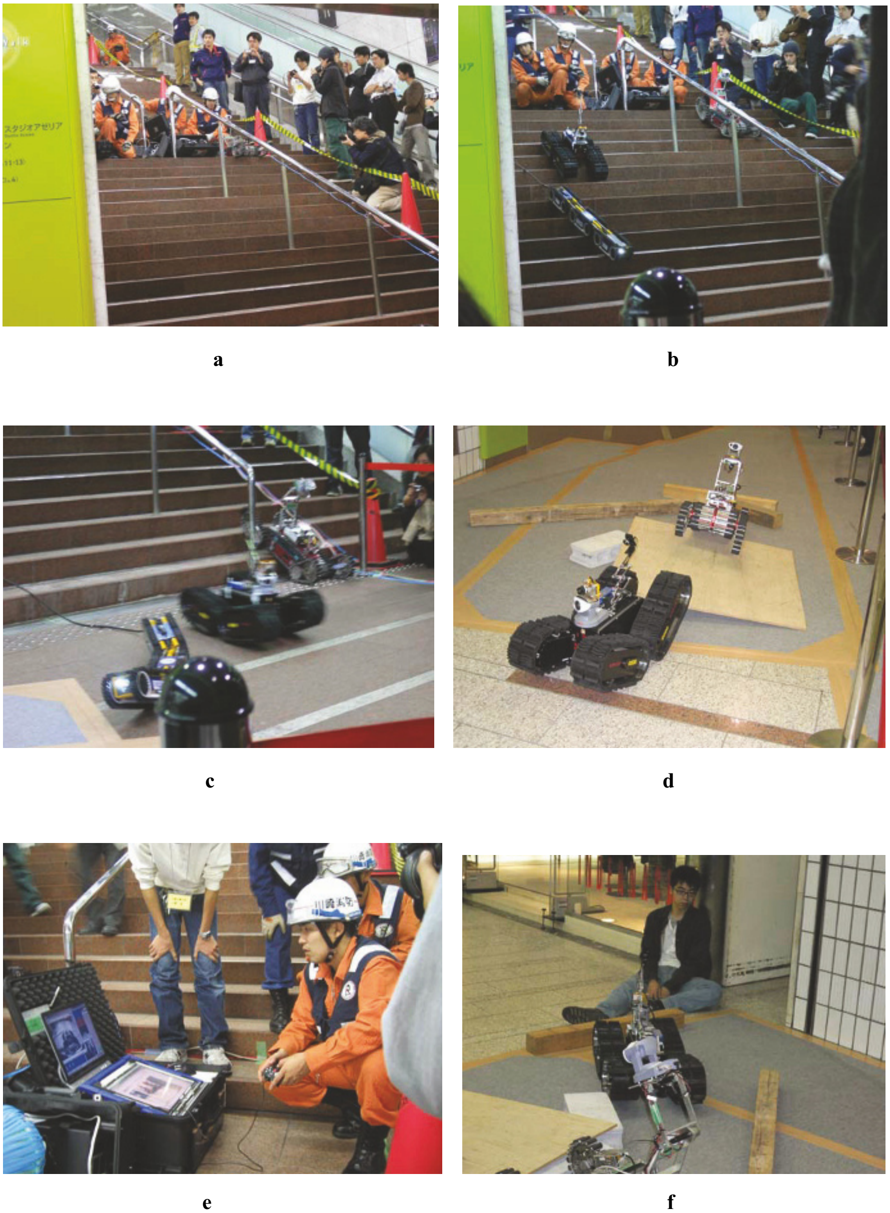


Fig. 9.4 Snapshots of the experiments and training in the underground town. **a** Setting up robots. **b** Robots going down the stairs. **c** Robots arrive at underground level. **d** Search operation. **e** Hibiscus operator. **f** A victim is found

a b c d

Fig. 9.5 Snapshots of the experiments and training in the underground town (continued). **a** A victim is saved. **b** Search activity by three robots. **c** Another victim is found. **d** Sendingimage of the rescue activity by robot

by an air jack. The victim was saved after supporting his backbone with a special support device.

9.5.2 Observation Report from the IRS-U Staff

The following statements were provided by members of IRS-U after the experiments and training.

9.5.2.1 Performance of Robots in Experiments and Training

After the Hyogo experiments, IRS Souryu was improved to equip it with a back view monitoring camera, which had been requested by a member of IRS-U. This

a b

c

Fig. 9.6 Snapshots of the experiments and training in the underground town (continued). **a** Monitor the operation through the camera on the robot. **b** Watch the operation with KOHGA2. **c** Rescue the victim

camera was actually useful to gain the view for reverse motion, which improves the mobility of the robot under teleoperation. A member of IRS-U rated highly the mobility, portability, and ease of operation from the point of view that the member as a beginner of the robot operation could operate the robot easily.

In this experiment, the effectiveness of the intercom facility installed on IRS Souryu, which consists of microphones and speakers, was demonstrated. This wired intercom facility offers bidirectional aural communication like the telephone. In conventional rescue operations, rescuers use transceivers that require them to press the “press to talk” switch to talk with another team member. This requirement forces a talker to momentarily stop work while pressing the switch. On the other hand, the intercom of IRS Souryu enabled rescuers to continuously talk with each other without interrupting the rescue operation and to report the real-time situation to the operators and the commander at ground level while performing a rescue task. It is very important to report real-time changes in the condition of victims. Thus, the intercom enables easy and uninterrupted communication between a victim, a rescuer and other rescuers on the ground.

KOHGA2 was rated highly because of its wide crawlers, high mobility, perticularly on debris and stairs, and the ability to change the angles of the four crawler units relative to its body. A disadvantage reported was that there was a slight delay in receiving images from the camera because of the delay in the digital communication line. Therefore, taking account of this characteristic, the commander assigned KOHGA2 to a mission to watch the situation and the on-going activity in an environment. A zoom function has been requested for the camera on KOHGA2.

The camera image of Hibiscus, displayed on the screen of a teleoperation console, was very clear. The touch panel on the screen was also useful for robot operation. The ability of Hibiscus to overcome debris and to climb stairs was rated high. The subcrawler arm and its motion to change the angle helps increase the mobility. However, some of the IRS-U members report that training and practice with the crawler arm operation is necessary. From the viewpoint of mobility, it appears that Hibiscus can be deployed. However, it is necessary to improve the water and dust proof ability of its body.

9.5.2.2 Overall Evaluation

For IRS-U, there were many "first experiences." It was the first time that experiments were conducted in a real underground town, that there were victims in the scenario, and that the rescue operation was performed in cooperation with other fire departments whose staff were not familiar with the robotic devices for rescue activities. IRS and IRS-U gained valuable experience throughout the experiments and training.

The environment assumed in the scenario was an underground town. The first responders consider an underground town an environment that prevents them from performing activities with high mobility during a disaster because of dangerous factors such as dense smoke and high temperature due to fire, the crowds of people during peak hours, and difficulty in accessing the underground because of the limited number of entrances. As an underground town is surrounded by walls, high-fidelity or high-reliability radio communication becomes impossible. Technology development to overcome this limitation is urgently required. In this scenario, the three robots were assigned with independent missions for the purpose of cooperation. This arrangement of the three robots at the time of the victim rescue operation provided useful information to members and the commander at ground level. This helped the responders to maintain safety.

9.5.3 Overall Evaluation from the Robot Development Team

The experiments revealed that it is most important to establish communication channels between a teleoperated robot and the operating console or operator. It is desirable to maintain high quality, wide bandwidth, high reliability, and no delay. IRS

Souryu used a wired communication channel. On the other hand, KOHGA2 and Hibiscus used a wireless LAN. In the experiments, the air station of the wireless LAN was placed at the underground level to maintain the reliability of communication via the LAN. However, at a more realistic site, this may not be possible. The success of the experiments tends to rely on providing good conditions for the wireless LAN. We should keep this fact in mind.

It appears that the developed robots have high mobility not only on a plane surface but also on debris and stairs. The dust and water proof design of these robots is the next step of the development.

9.6 Conclusions

Experiments and training activity using the devices and robots developed under the DDT project were reported. It is remarkable that in this project, the developed devices were tested in a realistic environment. The development was strongly motivated to have achieved the level of deployment of these devices to first-responder organizations. IRS and its related researchers gained much experiences.

It is remarked that the IRS staff contributed to the arrangements of all the experiments and training. For the arrangements, there were many negotiations and discussions among different organizations. This was a very tough task, which could not have been accomplished by researchers alone.

Chapter 10
Summary of DDT Project, Unsolved Problems, and Future Roadmap

Satoshi Tadokoro

Abstract The DDT Project has created a wide range of solutions for disaster response using robotics and related technologies (RTs) ranging from practical equipment to basic component technologies. This chapter summarizes the results obtained by this project. Problems faced by RTs for disaster response are analyzed by investigation of commercially available RT systems and those under research, including systems developed under the DDT Project. Common open problems are discussed on the basis of this investigation. This chapter also presents the RT roadmap developed by the Working Group on Special Environment RTs of the Future RT Map Committee of the MSTC.

10.1 Summary of DDT Project

The DDT Project focuses on disaster response, particularly urban search and rescue (USAR). It has developed equipment for collecting overview information of disasters (aerial robots and distributed sensors), advanced USAR equipment (in-rubble robots, on-rubble robots, and underground robots), and information integration technologies (a common protocol and a database) [2].

Advanced USAR equipment is in high demand by first responders. It improves their safety and security, enables them to pursue difficult tasks, and ensures rapid and efficient operations. Robotics and related technologies (RTs) can be used for this purpose as a humanitarian contribution on a global scale.

This project was managed by the International Rescue System Institute (IRS), utilizing seed technologies and resources of universities, research institutes, and companies throughout Japan. Four mission units (MUs) were organized as research management groups. A committee comprising MU leaders decided the project policy, managed, liased, and coordinated the MUs; planned frequent verification tests,

Satoshi Tadokoro
Tohoku University, and International Rescue System Institute (IRS)

training, demonstrations, and development camps; and achieved integration of the collected information into a common database. It also enhanced the collaboration among researchers, particularly on the integration of component technologies.

In order to promote practical applications, the IRS repeatedly conducted verification tests, training, and demonstrations with the assistance of a volunteer troop IRS-U comprising active firefighters, the training sites of Hyper Rescue of the Tokyo Fire Department, those of the Federal Emergency Management Agency, the training events of the Japan Disaster Relief Team, the local government of Yamakoshi Village, etc. By these activities, research products were found to be highly rated. First responders recognized some products to be valuable and their commercialization is now being planned.

Many component technologies are sufficiently advanced to be implemented practically, and some practical systems have been developed using these technologies. First responders rated the systems highly by performing frequent evaluation tests, training, and demonstrations. These efforts have aided the development of the research area of rescue robotics, and many researchers throughout Japan have recognized this field as an important application area of robotics. This implies that rescue robotics has been established as an academic field and a research trend. Commercialization of part of the research results is being planned. Some technologies have not yet advanced sufficiently for practical implementation, although they appeared to be useful.

The following are some of the most practical systems:

- rescue tools;
- Active Scope Camera;
- UGV technologies on rubble piles and underground;
- rescue radar systems using ultrawideband (UWB) electromagnetic wave;
- intelligent aerorobot; and
- serpentine robots.

The following advanced component technologies have been developed, some of which are highly rated:

- various types of mobilities in a rubble pile environment;
- teleoperation;
- position measurement and identification;
- mapping;
- sensing;
- ad hoc network; and
- disaster information database.

From the viewpoint of disaster response and mitigation, the following points have been deemed to be important:

- **In-rubble Robots:** very great enhancement of searchable area and ability to obtain a variety of information.
- **On-rubble and Underground Robots:** teleoperation in half-collapsed buildings and prevention of secondary disasters.

- **Aerial Robots:** robustness to wind, autonomous collection of information, and image cleaning.
- **Information Equipment:** rescue function for fire alarms and digitalized triage tags.
- **Information Integration:** proposal for standardization of the disaster information sharing protocol MISP.

The following social parameters are important from the viewpoint of the abovementioned field:

- establishment of research area of rescue robotics;
- first responders' evaluation of robotics and RTs, and their high expectations; and
- foundation for using research results.

Table 10.1 lists the statistics of the DDT Project. These figures show the level of activity of this project.

Table 10.1 Statistics of DDT Project

Item	Number
Ex-post valuation by MEXT	S (highest among the 4 levels of "S-A-B-C")
Media coverage (newspapers/journals/TVs/radios)	778
Reviewed technical papers	254
Other papers and oral presentations	589
Patents/softwares/specifications/standards	24
International symposiums	Annual
Open demonstrations, verification tests, etc.	110
Web page	`http://www.rescuesystem.org/`

The contributions of the DDT Project are summarized as follows:

- development of a variety of advanced technologies;
- contribution to disaster response, particularly to USAR;
- enhancement of application area and feedback to disaster problems;
- establishment of the field of rescue robotics; and
- continuous contribution of robotics and RTs to disaster problems.

The following factors are considered to be important for further contribution of the DDT Project:

- necessity of an industrial market;
- planned procurement by governments and public sectors; and
- continuous investment for research and development.

The Ministry of Education, Sports, Culture, Science and Technology (MEXT) performed an ex-post valuation in 2007. The valuation result was "S," which denotes the highest score.

By considering all the abovementioned factors, it is concluded that the research purpose has been achieved.

10.2 Unsolved Technical Problems

Many technical problems remain unsolved. Further research and development are necessary for the full contribution of robotics and RTs. This section summarizes unsolved issues revealed by the discussion by the Working Group on Special Environment RTs of the Future RT Map Committee, Manufacturing Science and Technology Center (MSTC) [1]. The following analysis includes fires and water disasters.

The Japan Fire and Disaster Management Agency (FDMA) surveyed the expectations of firefighters from robotic systems by administering a questionnaire to the fire departments of 49 major urban cities in Japan in 2003. The results of the questionnaire are shown in Table 10.2.

Table 10.2 Expectation of fire departments of major urban cities in Japan regarding robotic systems

Category Expected function	Rating (out of 49)	Percentage (%)
NBC attacks		
Identification of NBC materials by sensors	39	80
Transfer of victims to safe area	30	61
Removal of NBC material	24	49
Fires		
Extinguishment in buildings	30	61
Search in buildings	25	51
Extinguishment irrespective of heat radiation	24	49
Earthquakes		
Search from above the rubble pile	26	53
Search within the rubble pile	22	45
Removal of heavy rubble	21	43
Water Disasters		
Search for victims	27	55
Rescue from water	24	49

This result shows that nuclear, biological, or chemical (NBC) attacks are serious problems for firefighters because NBC materials are not visible, and secondary damage has been reported in all past incidences. The expectations of firefighters regarding robotic systems are high in the case of fires since fires are the most frequently occurring disaster. Earthquakes are also very important disasters, although their occurrence is not as frequent. Water disasters are also serious because they are occasionally caused by bad weather.

10.2.1 Collection of Overview Information of Disasters

Overview information is necessary for disaster control centers to plan disaster response. Rapid surveillance is most important at the initial decision-making stage. Aerial vehicles and distributed sensor networks are particularly effective for this purpose.

Manned helicopters are deployed in many large cities. However, they have the following problems. Pilots have to be ready at all times, which is expensive. Further, the loud noise of a helicopter interferes with search activities on the ground. Moreover, they cannot fly over volcanoes because of safety reasons. According to the safety regulations in Japan, helicopters must fly at altitudes greater than 300 m.

Small-sized unmanned helicopters have been developed and put into practical use; two such helicopters have been deployed in Hokkaido, Japan. The reliability and environmental tolerance of helicopters, including robustness to gust, rain, birds, and electric cables, are important issues. Re-allocation of wireless frequencies, high-power electromagnetic waves for stable video transmission, and deregulation of flight area in times of emergency are also necessary.

Small-sized unmanned aircrafts are practical, and recently, they have been widely used because of their portability. However, they have the same problems as unmanned helicopters. A small payload and significant wind effect are additional problems faced by such aircraft.

Unmanned airships and balloons are currently under research. In addition to a small payload and slow speed, the effect of wind on such airship and balloons is significant.

Satellite data can be used only if a satellite appears over the disaster site during its orbit. The effect of weather and clouds on satellite operations is serious. Therefore, their application to emergency use is limited.

Distributed sensing has commonly been employed in the past; examples of this technology include fire alarms, smoke detectors, security sensors, etc. Recently, fire alarms have become obligatory even in wooden houses in Japan, and it is high time advanced services began using such equipment. Home networks and ad hoc networks are expected to find practical applications soon. The Rescue Communicator (IRS, RIKEN) is one such recently developed system.

10.2.2 Search and Diagnosis of Victims and Quantitative Investigation of Structural Damage

10.2.2.1 Information Collection in Indoor or Underground Structures

Unmanned ground vehicles (tracked-type and wheel-type) are used for indoor search and diagnosis, particularly in buildings and underground structures. However, they are used only in hazardous environments which humans cannot enter.

Their information acquisition capability, speed, mobility on rough terrain, obstacle avoidance, etc., are inferior to those of human rescuers, and they are incapable of physical rescue and removal of rubble. In addition, instability, limited capacity, long latency period, and short communicable distance of wireless communication pose serious problems for teleoperation and data transmission. In Japan, FRIGO (National Research Institute of Fire and Disaster), HELIOS IV, ACROS, UMRS, Ali-baba, and Toin Pelican (International Rescue System Institute and collaborating universities/institutes) have been developed. The RoboCupRescue Robot League, a contest for robots applicable in this domain, was started in 2001.

Mobility is fundamental; however, it is one of the most serious problems in disaster situations. Human first responders can navigate through rubble piles at high speed by capturing beams, climbing high bumps, traversing wide gaps, and crawling under rubble. Mechanisms and control for performing physical tasks, sensing and analysis for recognizing situations, and strategy and tactics for completing missions are essential.

Semi-autonomy of operator support is necessary for the practical mobility of robots; however, the recognition of an environment by operators is insufficient. Video information (cameras, IR cameras, etc.) should be effective for teleoperation but is insufficient in terms of resolution, real-time capability, size, stability and reachable distance, mainly because of restrictions on wireless power and frequency bands. Unevenness of lighting, dirt on lens, blind areas, and integration of multiple images are important issues with regard to video information. 3D images (multi-eye cameras, 3D CCD cameras, pattern projection, laser range finders, etc.) are effective; however, accuracy of a 3D image, measurable distance, environmental conditions, sensor size, and sensor weight pose problems in acquiring such images. Map information is effective; however, indoor data are presently unavailable, and accuracy, real-time capability, 3D information, indoor GPS, and indoor localization pose problems in acquiring such information. Human-in-loop systems and the cooperation of distributed systems are also important issues. Sound is effective for calling or speaking with victims and detecting abnormal conditions.

Measurement of CO_2, urine, smoke, and hazardous gases are important functions of sensors; however, the size and response speed of sensors pose problems in their operation. Sensors should be actively moved by a robot arm. However, the arms occasionally cannot reach the target point, and the robot body becomes heavier and unbalanced. Information acquired by multiple sensors should be integrated to improve recognition capability, avoid oversight, and increase the amount of collected information.

UGVs are used for sampling suspicious materials and sensing environmental conditions in the case of nuclear, biological, chemical, and radiation (NBCR) attacks and explosive ordnance disposal (EOD) operations. TALON (Foster-Miller) and PackBot (iRobot) are well-known robots used for these purposes. In Japan, robots were developed and tested by FDMA. IRS developed UMRS-NBCT and displayed it at EXPO 2005, Aichi, Japan. Important problems in this domain are motion speed, mobility at the locations of victims, movement in/from/to train platforms/rails where large gaps exist, small-sized sensors for hazardous materials, rapid sampling, distributed sensing for coverage/efficiency improvement, and decontamination after operation, in addition to the problems of hindering teleoperation, wireless communications, sensing, motion of sensors, and cooperation with humans, which have been explained above.

10.2.2.2 Information Collection in Confined Spaces such as Rubble Piles and Soil

Fiber scopes and search cameras equipped with sensors are used for information collection in rubble piles. A short reachable distance, difficulty in ascending steps, difficulty in insertion in the upward direction, poor operability, insufficient durability, narrow field of view, unknown position and orientation, and lack of intelligent support for operator recognition are the current problems faced in information collection in confined spaces.

Robots capable of burrowing into rubble piles (serpentine-type, reconfigurable tracked-type, multiple-actuator-type) are currently under research. IRS Souryu, MOIRA, and Active Scope Camera (IRS and collaborating universities) are examples of such robots under development. Such robots face problems such as mobility in narrow spaces, cable handling, and miniaturization, in addition to the same problems as those faced by UGVs. Firefighters are currently testing such robots, and their deployment is expected in the near future.

Underground sound detectors collect acoustic information from outside rubble piles and soil. All other search and rescue activities must stop in order to avoid audible noise. The inhomogeneity of rubble and reflection of sound degrade the sensitivity of detection. Life search systems employing microwave radar (SILIUS) are deployed in major cities; however, their accuracy and reliability are insufficient. UWB radar is expected to be a better replacement for microwave radar.

Distributed network sensors and RFID tags have been studied intensively for this purpose. The Rescue Communicator (IRS) was developed in Japan.

10.2.2.3 Detection of Fire

One of the main functions of most night security guard robots in buildings is to detect fires, which is also the function of fire alarms.

10.2.2.4 Information Collection in Water

Small-sized teleoperated underwater vehicles find practical application especially in places where the flow rate is slow, for example, at ports and harbors. In most cities, the visible distance is very short because of water contamination, and new sensors to enhance the working range are expected to be developed. Further, localization in water is also difficult.

10.2.3 Physical Rescue of Victims and Prevention of Damage Propagation

In the case of earthquakes and building collapses, the removal of heavy rubble, cutting or holing through reinforced concrete (RC) structures, jacking up, and supporting rubble piles to prevent collapse are necessary. Some of these tasks could be performed by construction machines (particularly by double-arm-type machines). The manipulation technology of robotics can improve their performance. However, regulations for hedging or acceptance of the risk of critical operations have not yet been established. Access to disaster sites is affected by road collapse. Enryu (Tmsuk) was developed as a robotic system for the removal of rubble piles.

In the case of large-scale fires, technology for minimizing the risk to firefighters is expected to be developed. For this purpose, unmanned water cannon vehicles have been developed by the Tokyo Fire Department and others, and some of them are deployed during large-scale fires. Most of these vehicles have large bodies because of the requirement to hold and spray large amounts of water and extinguishant onto the fire, therefore, these vehicles face difficulty in entering narrow fire fronts. Small vehicles cannot carry water hoses if water is stored inside. In addition, easy teleoperation, easy handling of hoses and cables, removal of obstacles, and heat resistance are important issues for such vehicles. There is a requirement for intrusion into and extinguishment of fires in confined spaces and removal of parked cars on access paths; however, these requirements are not considered because they are very difficult to satisfy using current RTs.

With regard to NBCR attacks, decontamination technologies implemented by spraying neutralizing agents and water, a sealing method for hazardous materials, evacuation guidance, emergent medical examinations, medication, transportation, and logistics are important.

10.3 Common Problems of Robot Technologies

On the basis of the analysis of the various challenges mentioned in the above discussion, common technical problems faced by RTs for disaster response are summarized as follows.

10.3.1 Mobility and Task Execution Performance

Conditions necessary for an RT to replace human workers in current tasks are as follows, and include both positive factors and risk factors:

1. The RT can perform tasks that cannot be performed by humans, e.g., entering a thin slit in a rubble pile (feasibility factor).

2. The RT can improve human safety and avoid secondary damage (risk factor).
3. The RT is more efficient than humans; e.g., it is time-saving, labor-saving, and economically efficient (efficiency factor).

In order to improve efficiency and provide high mobility, it is important to create accurate yet rapid situation awareness among operators, improve operability, and perform high-precision position measurements in addition to improving the mechanical performance by optimal design and increasing actuator output.

10.3.2 Human Interface for Teleoperation and Information Transfer

Fully autonomous RTs can perform only limited tasks that are routine and simple in nature, particularly under disaster situations. Even for movement by wheels or tracks on rough terrain, it is difficult to achieve satisfactory speed and reliability using autonomous navigation, although this is one of the simplest tasks.

Therefore, providing the shared autonomy as a combination of teleoperation by human operators and semi-autonomy of operator support is the most practical approach at present. In the fields it is important to have the best performance of the deployed systems. For example, human intervention is necessary for recognition in disaster situations because automatic recognition is highly dependent on environmental conditions and is inferior to human ability in a disaster situation. Improving visibility by employing intelligent computer vision is a good example of a function of semi-autonomy. With regard to commands from human operators, intelligent command functions save human effort for performing tasks, and first responders can concentrate on other jobs. If they can navigate robots on rough terrain in a manner similar to navigation in flat rooms, for example, finding victims becomes easier.

In all teleoperated systems, creation of situation awareness among operators is important. It is desirable that the performance of task execution by human operators by making observations from a distance is similar to that by on-site observation. Humans should be able to operate rescue systems in a short period. Responders must be able to use these systems immediately after a short period of training.

In order to satisfy the abovementioned requirements, (semi-)autonomous functions for supporting human operations are important. The synthetic performance of rescue systems is maximized by shared autonomy between RTs and humans.

10.3.3 Wireless Communications

Large-sized data such as video image data and range finder data must be transferred from robots to operators and first responders located away from robots. This is essential in order to support teleoperation and search tasks by creating effective situation awareness among operators.

Transmission of large-sized data is adversely affected by a narrow allocated frequency range and limited maximum output power of wireless LAN and SS wireless modems. Multiple 3G mobile phones are expensive, and their service area is limited, particularly when disasters occur. Commercial wireless LAN has a limited area of service, and we cannot expect communication to be of high quality at times of disaster.

10.3.4 Localization, Information Mapping, and Integration

Collected information should be mapped on a GIS because it is used with position information in many applications. Localization is a serious technical problem in buildings, rubble piles, and underwater, where GPS cannot be used.

The integration of all data from distributed heterogeneous systems is desirable for use in decision making. This is also important for the task execution of distributed robots that exchange data mutually for further information collection and cooperative activities. However, the required ontology and communication protocols are not standardized for using a GIS. Data fusion, keeping consistency of collected data, and data mining are future issues as application of a GIS for supporting decision making.

10.3.5 Cooperative Task Execution

Most conventional rescue systems have been used separately. Therefore, technology that facilitates cooperative task execution of multiple systems and humans should be developed.

10.3.6 Reliability in Disaster

Reliability and stability are the most fundamental requirements for disaster response. For example, it is reported that under normal circumstances, wireless LANs function effectively; however, at times of emergency, these LANs are occasionally ineffective for communication.

10.3.7 Evaluation Metrics

It is necessary to quantify the effectiveness of these systems. It is known that every disaster situation is unique. Because of this characteristic of disasters, the requirements for and evaluation metrics of rescue systems are different for every disaster.

10.3.8 Improvement of Fundamental Performance

Fundamental performance requirements such as high power of actuators, high stiffness of mechanisms, high-performance sensors, miniaturization, lightweight design, long-life battery, power saving, etc., should be satisfied for all robots and rescue systems. In rescue systems, robustness to extreme environmental conditions is important; i.e., these systems must be durable, waterproof, dust proof, and explosive proof, and they should be able to withstand heat.

10.4 Future Roadmap

The Working Group on Special Environment RTs of the Future RT Map Committee, MSTC, has developed an RT roadmap by the order of the Ministry of Economy, Trade and Industry, Japan (METI). The RT roadmap for rescue robotics is summarized below [1].

10.4.1 Roadmap for 2010

10.4.1.1 Collection of Overview Information of Disasters

A large number of small-sized unmanned helicopters or aircraft will be deployed. Further, airships and balloons will become more practical. Technical problems to be solved with respect to these vehicles are as follows:

- development of on-board sensors and cameras;
- development of lightweight design for long-time long-distance flights; and
- standardization of long-range broadband wireless communication for emergency.

10.4.1.2 Collection of Information of Victims and Structural Damages in Indoor or Underground Structures

Teleoperated tracked-type robots will be able to penetrate into damaged structures up to a depth of 200 m if the floor and steps are not very rough. The following requirements should be satisfied in this case:

- wireless communication should be stable;
- ad hoc communication of multiple video image data should be possible;
- a 2D map should be generated in real time;
- sensing and recognition of victims and disaster situations should be more accurate;
- the mobility of robots should be greater than that of humans, and they should avoid obstacles;
- semi-autonomy should be able to provide support to operators; and
- development of small-sized, lightweight, and highly durable machines should be possible.

10.4.1.3 Collection of Information of Victims and Structural Damages in Confined Spaces such as Rubble Piles and Soil

Multi-actuator-type teleoperated robots will be able to penetrate into rubble piles up to a depth of 10 m for search and surveillance. The following requirements should be satisfied in this case:

- mobility should be stable;
- situation awareness among operators should be high; and
- victims should be sensed.

In addition, the following issues must be addressed for developing intelligent search cameras:

- the problems of field of view, light conditions, and orientation awareness should be resolved;
- small-sized, thin, lightweight, and highly durable mobile devices should be fabricated;
- evaluation metrics must be established; and
- these cameras should be commercialized and deployed.

UWB radar can be used practically after the following requirements are satisfied:

- equipment is miniaturized; and
- resolution and accuracy are increased.

10.4.1.4 Collection of Fire Information

More robots can be deployed practically; however, the following requirements should first be satisfied:

- manipulators should generate large force using small-sized high-power energy sources; and
- mobility and operability should be increased.

10.4.1.5 Physical Rescue of Victims and Prevention of Damage Propagation

Robotic systems for debris removal are expected to be improved. Further, public consensus on robotic rescue is expected to be established. The following points should be considered:

- semi-autonomy should support operators to improve operability; and
- required specifications should be elucidated.

10.4.2 Roadmap for 2015

10.4.2.1 Collection of Overview Disaster Information

Multiple helicopters/aircrafts/airships/balloons will intelligently collaborate with ground vehicles to contribute to search and information collection. Then, the following technical requirements should be satisfied:

- sensing technology for obtaining information on disaster situations and for searching for victims from the sky should be established;
- relay station functions of information must be established;
- broadband mobile communication should be stable during disasters; and
- information collection by distributed sensors, home networks, and ad hoc networks should be possible practically.

10.4.2.2 Collection of Information of Victims and Structural Damages in Indoor or Underground Structures

Tracked robots will be able to penetrate into damaged structures up to a depth of 200 m irrespective of rough terrain and gaps (e.g., to subway rails) for information collection. The following technical requirements must be satisfied in this case:

- ad hoc communication of broadband data should be effective and practical;
- 3D maps must be generated in real time;
- emergency diagnosis of victims should be possible;

- in the case of accidental events, situation awareness among operators should be adequate;
- an ecological operator interface must be established; and
- strain on operators must be reduced sufficiently.

10.4.2.3 Collection of Information of Victims and Structural Damages in Confined Spaces such as Rubble Piles and Soil

Multi-actuator-type robots will penetrate rubble piles up to a depth of 30 m to collect information. Further active fiber-scope-type thin robots will be able to enter narrow spaces to collect information. Then, the following developments are necessary:

- robots must be mobile in rubble piles to perform practical tasks;
- twine around obstacles must be avoided;
- sensors and computers must be miniaturized;
- semi-autonomy should provide support to human operators efficiently; and
- localization in rubble piles must be of sufficient accuracy.

UWB radar can be deployed and used without difficulty by satisfying the following requirements:

- establishment of sensed data processing;
- miniaturization of equipment; and
- development of a user friendly interface.

10.4.2.4 Collection of Fire Information

Robotic systems can find greater applications if the following developments are made:

- broadband data communication must be of high performance to realize rapid teleoperation with accuracy;
- high-pressure light-weight hose for large-quantity water cannons is to be developed; and
- heat resistance must be improved.

10.4.2.5 Physical Rescue of Victims and Prevention of Damage Propagation

Teleoperated high-power rescue robots can be deployed after achieving the following:

- stabilization of broadband wireless communication; and
- provision of support to operators by autonomy and intelligence.

10.5 Conclusions

This chapter summarized the results of the DDT Project. Problems faced by RTs for disaster response were analyzed by an investigation of commercially available RT systems and those under research, including systems developed under the DDT Project. The future RT roadmap developed by the Working Group on Special Environment RTs of the Future RT Map Committee, MSTC, was discussed.

Large-scale earthquake disasters are predicted. All the project members anticipate that the research results of the DDT Project will provide impacting solutions for emergency situations, because of which many lives can be saved. Moreover, it is expected that these results will aid international relief teams empowered by robot technologies, which spring into action during large-scale disasters occurring worldwide, and contribute to the safety and security on a global scale.

Collaboration among many people and continuous action are necessary to achieve the abovementioned goals. Cooperation between and integration of multidisciplinary research fields are essential because the problem of disasters is diverse. In order to respond to disasters effectively, not only the deployment of equipment by first responders but also its development, distribution, and maintenance are necessary. For the development of tangible equipment, basic research and fundamental science and technology are necessary in addition to a conducive environment in which it can be sustained. The author believes that a wide range of people must contribute to develop this field over a long period in order to save human lives in the future and to create a safe and secure society using robotics.

Acknowledgements The contributions of research members, first responders, government officials, and supporting staff members were remarkable. In particular, the efforts of the mission unit leaders and core members were significant. The author, as the project leader, deeply appreciates their dedicated commitment.

References

1. Manufacturing Science and Technology Center (2006) Report of rolling investigation of robot technology strategic map. Ministry of Economy, Trade and Industry (in Japanese)
2. Tadokoro S et al (2003-2007) Reports of Special Project for Earthquake Disaster Mitigation in Urban Areas, III-4 Development of Advanced Robots and Information Systems for Disaster Response. Ministry of Education, Sports, Culture, Science and Technology, National Research Institute of Earth Science and Disaster Prevention, International Rescue System Institute (in Japanese)

Index