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.

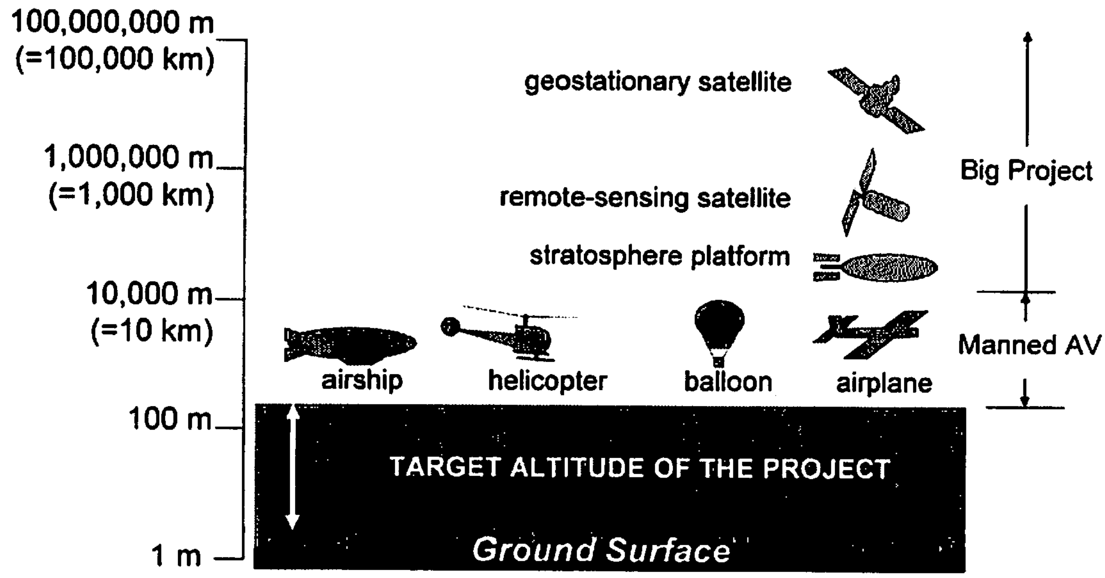

Fig. 3.1 Operating altitude of airborne systems

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

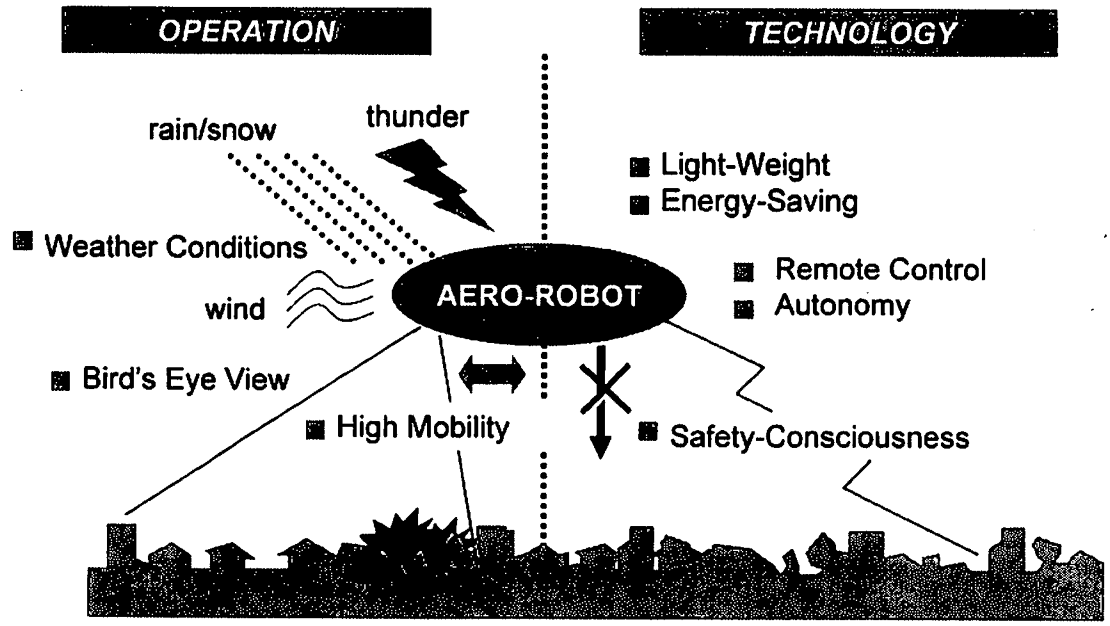

Fig. 3.2 Requirements in aerial-robot design

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.

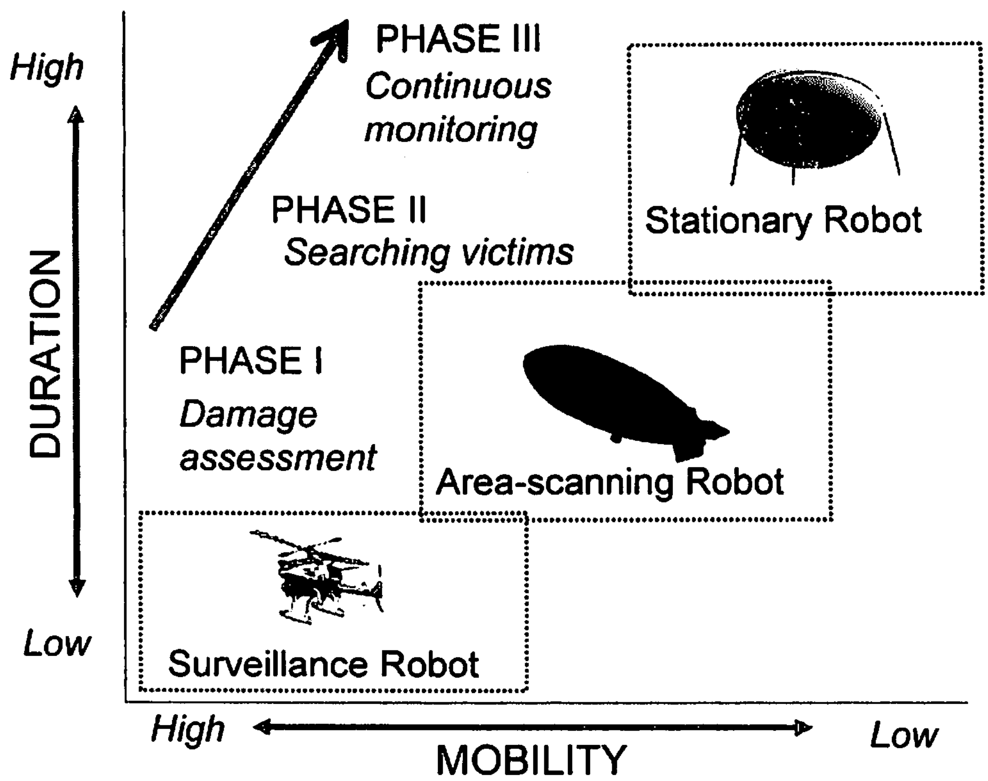

Fig. 3.3 Role-sharing of aerial robots for USAR

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.

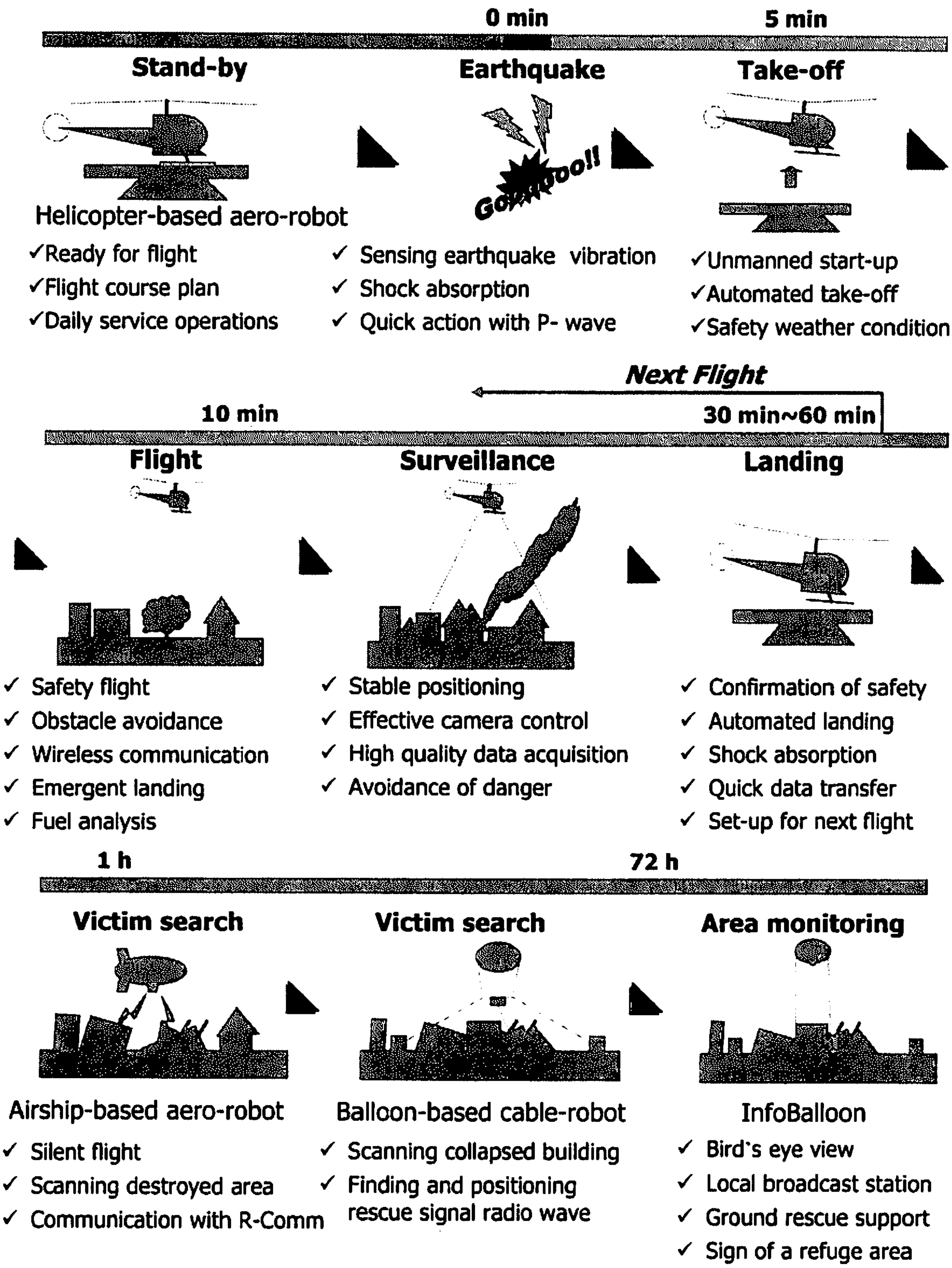

Fig. 3.4 Action scenario of aerial robot systems for USAR

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.

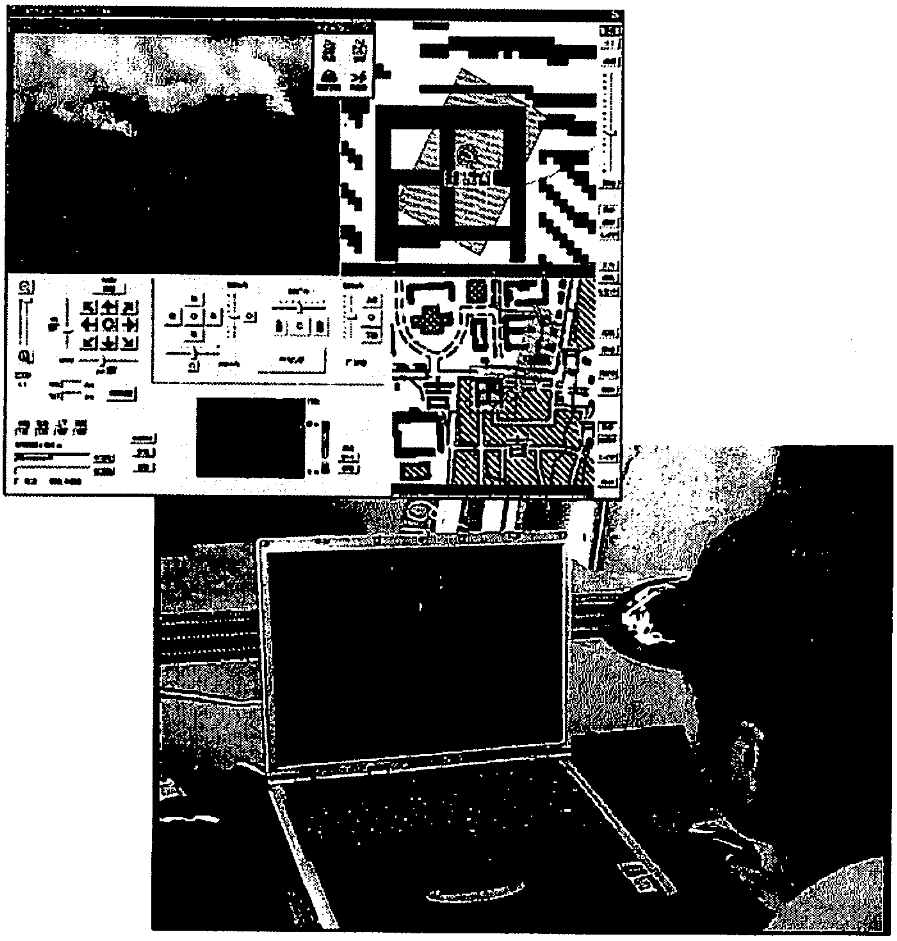

Fig. 3.6 Easy operation of the intelligent aerorobot with GUI on a notebook PC

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

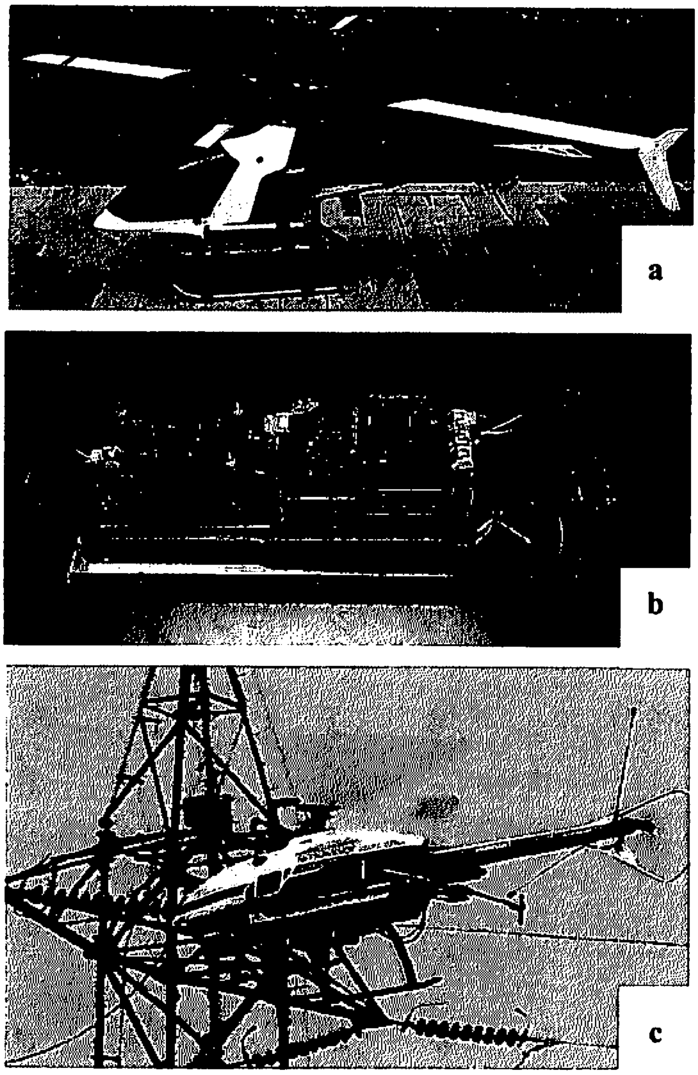

Fig. 3.7 Small-size autonomous unmanned helicopter developed by Chiba university. a SST-eagle2-EX (gross load 5 kg). b Autopilot unit (weight 0.5 kg). c Power-line inspection patrol helicopter (gross load 48 kg)

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

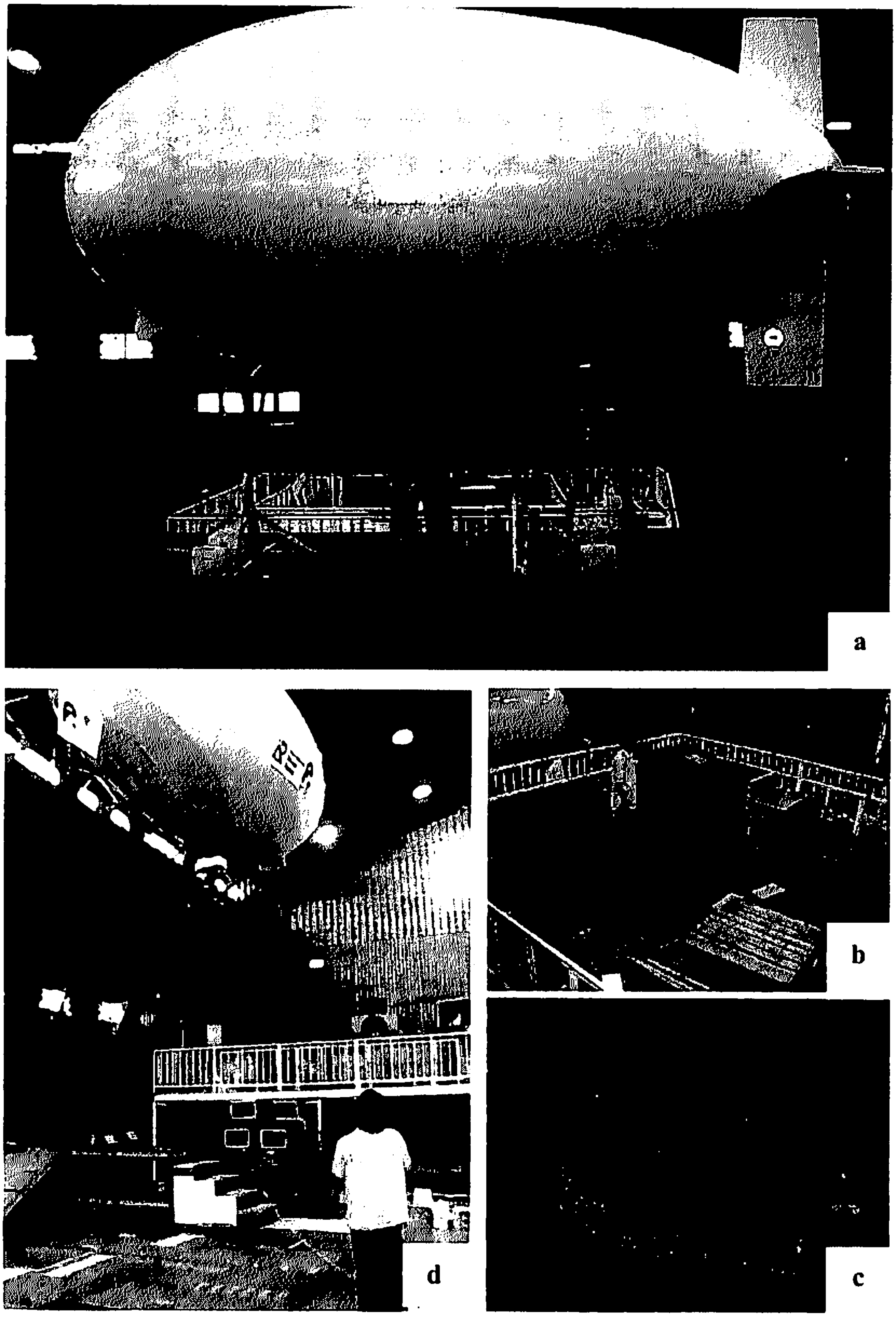

Fig. 3.8 Autonomous blimp-type robot system develped by RIKEN and the University of Tokyo. a Overview. b Sweeping an experimental section at Kawasaki Laboratory, IRS. c Collapsed house experiment facility. d Measuring image from a 3D profiler

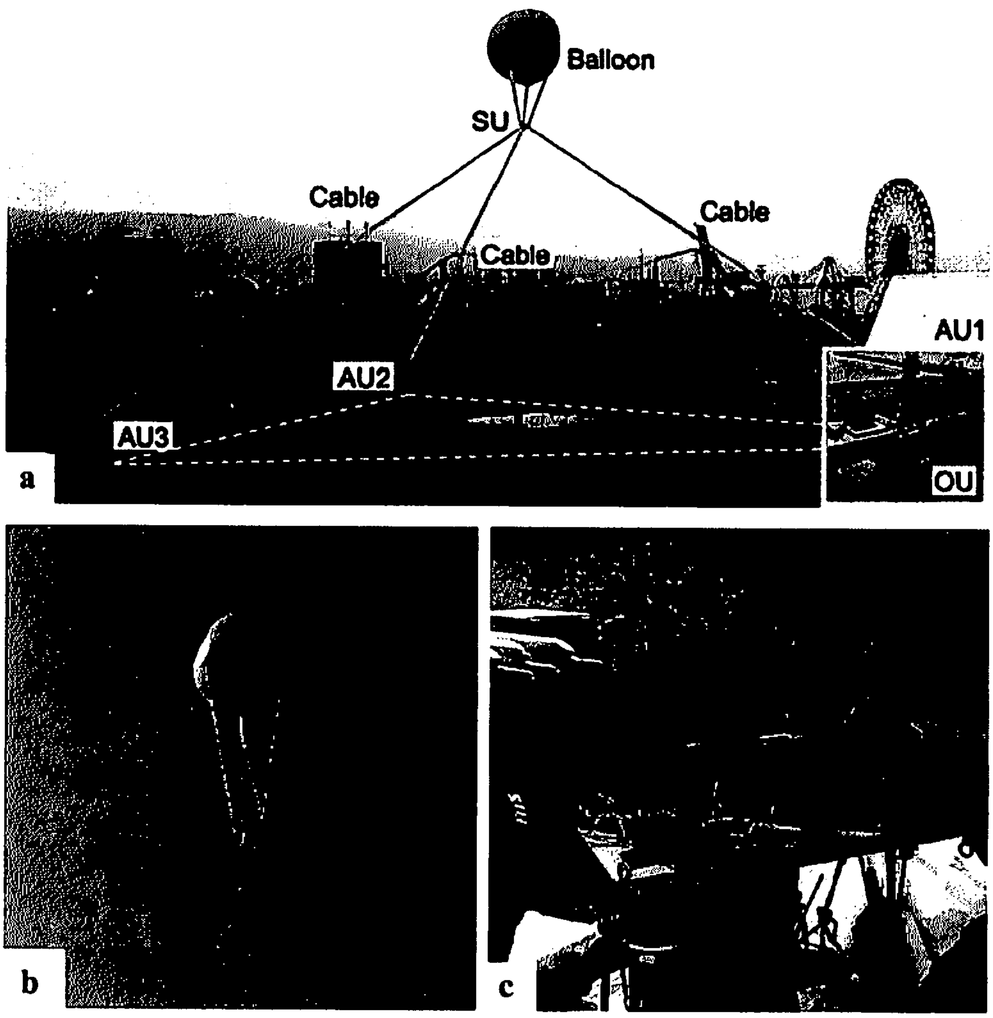

Fig. 3.9 Cable-driven balloon robot system. **a** Overview. **b** A balloon body lifting a triangle base. **c** Mounting mechanical elements on a machine base frame

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.

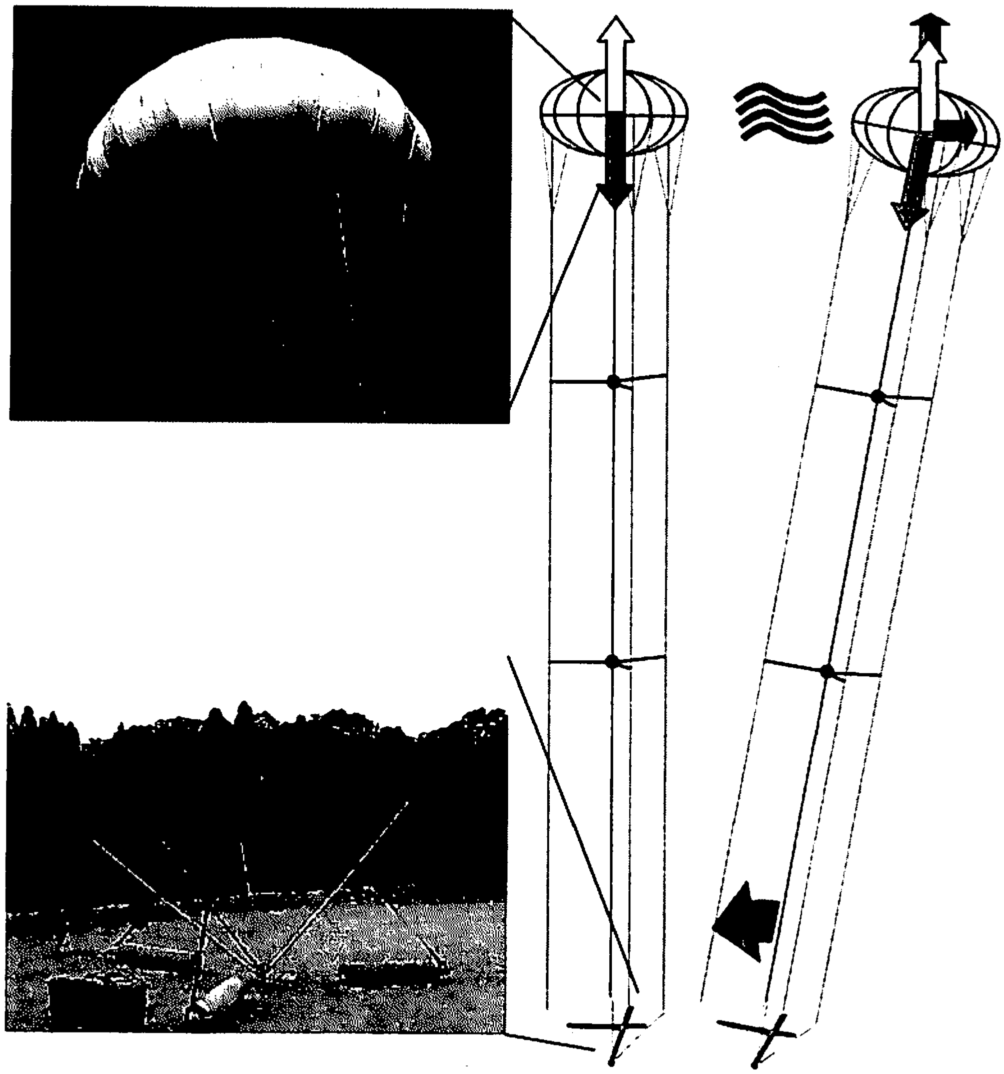

Fig. 3.10 Captive balloon robot system: InfoBalloon

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.

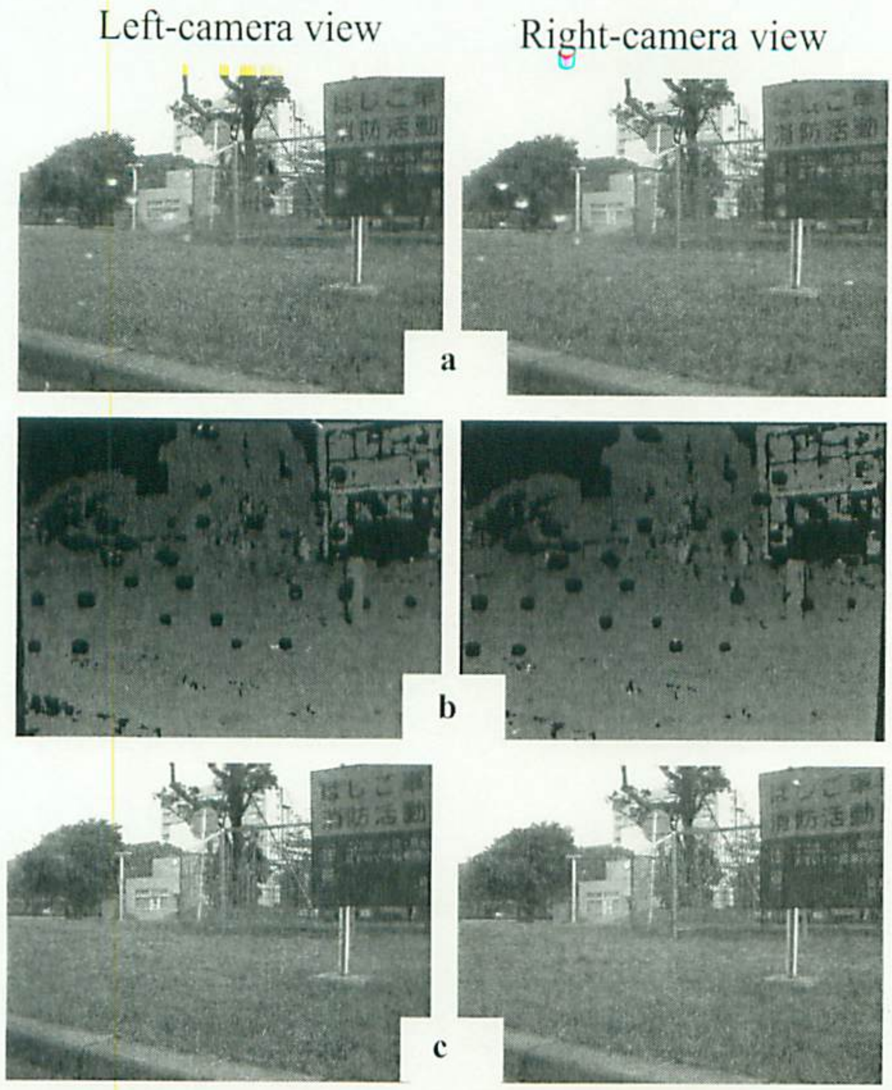

Fig. 3.12 Example of image restoration. **a** Original images. **b** Noise detection by disparity estimation. **c** Noise removal

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.

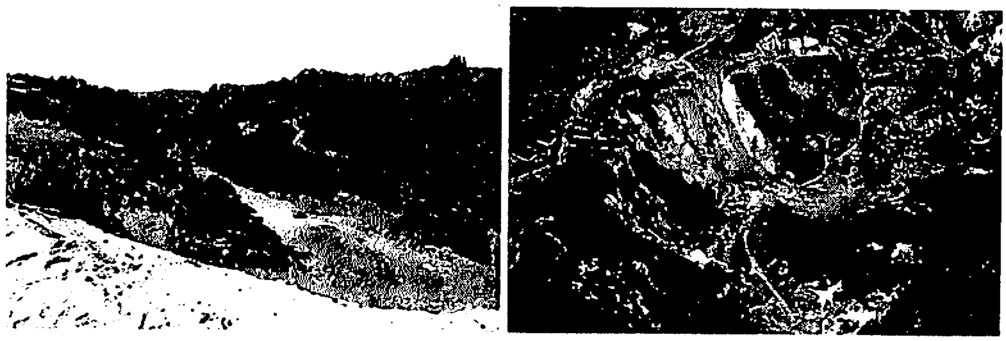

Fig. 3.13 Overviews of the test site at Yamakoshi region

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

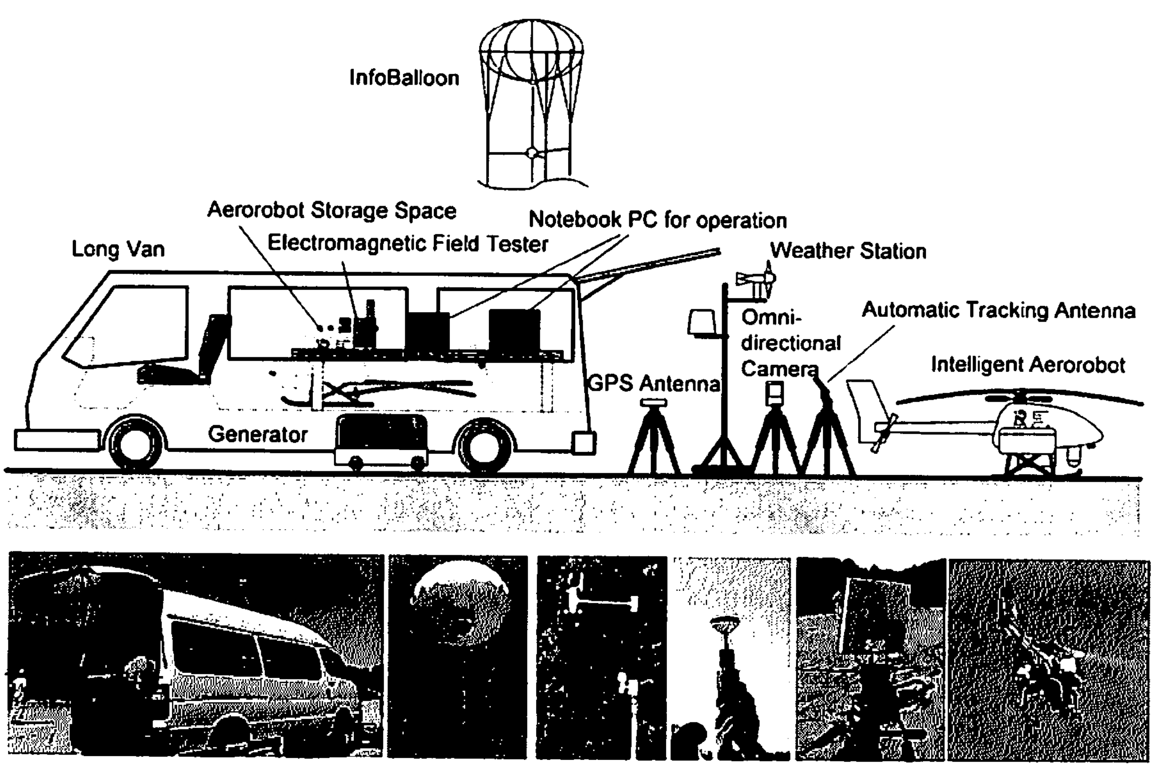

Fig. 3.15 Overviews of ground facility for aerial robot systems

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.

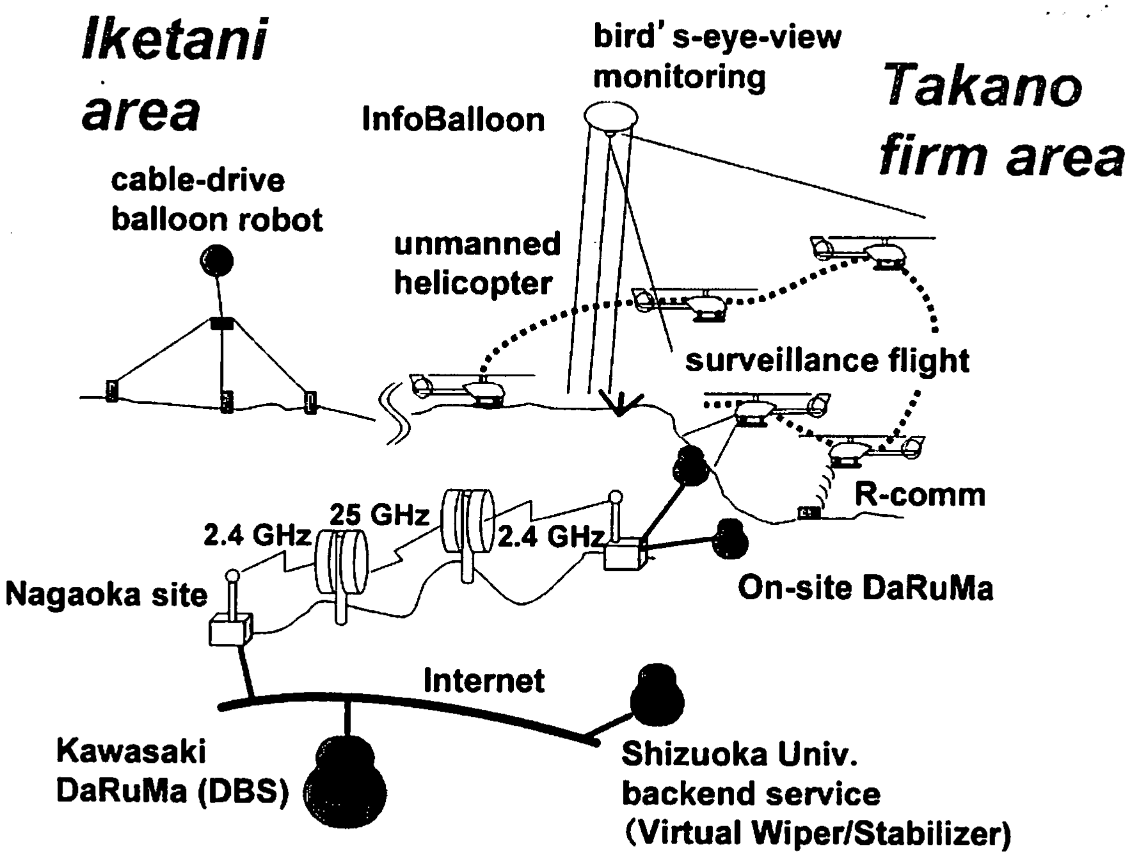

Fig. 3.16 Overview of robot system configuration for Yamakoshi test

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.

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