Disaster Information Gathering by Aerial Robot Systems

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Abstract. This report introduces R&D results of aerial robot systems development for urban search and rescue (USAR). Different types of aerial robot systems have been developed and they are systematically combined so as to offer continuous information gathering in a suffered area. Autonomous helicopters are collecting disaster situation data from the sky for USAR first operation planning. Then, a blimp-type robot system and a cable-driven robot system start to survey victims under collapsed houses in the destroyed areas. Continuously a captive balloon system with a monitoring camera presents bird's eye views of the disaster area continuously. These robots and other developed technologies are integrated to a total solution for a quick information gathering in USAR.

1 Introduction

This paper reports prime research results by a mission unit of 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 [1]).

Fig. 1. Destruction examples of surface structures by large earthquakes

The mission unit of aerial robot systems, called the AIR MU for short, was organized to realize disaster information gathering by robot systems working in the sky as quick as possible[2]. A large scale disaster, such as the Hanshin-Awaji earthquake attaching Kobe city and its environs in 1995, destroys a number of structures on the ground and makes it difficult to access to destroyed areas by using ground moving vehicles quickly due to many blocked roads and heavy traffic as shown in Fig. 1. Aerial robot systems directly approaching to target points from the air are expected to be free from a such chaos on the ground[3].

2 Aerial Robot Systems for USAR

2.1 Utilization of aerial robot systems

As utilizations of the aerial robot systems, you can think following USAR activities.

1. Information gathering: Information of the disaster-stricken area is collected in various media such as pictures, videos, sounds, and other sensing data by using measuring equipment.
2. Information relay: Communication between two ground sites is relayed by the station in the air which is free from obstacles on the surface.

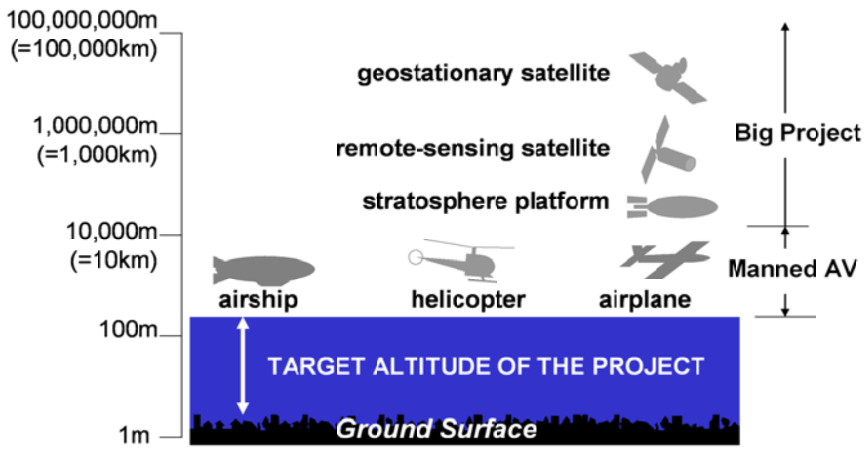

Fig. 2. Operation altitude of aerial systems

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 supports such as medical supply and the communication equipment are transported from one site to the other site isolated by the disaster.
5. Material spreading: Materials such as the fire extinguisher and the ubiquitous sensing devices are spread from the air to the disaster area.
6. Other uses: lighting the ground from the air in the nighttime, the landmark for the refuge location, et. al.

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

2.2 Information gathering from the sky

At the present there are several methods practically used for information gathering from the sky. Figure 2 shows some typical systems for aerial surveillance. In the figure we see no practical system in the low altitude space under 150m, where the operations of manned air vehicle is more dangerous. Aerial robot systems automatically working in this space are expected to gather close view information of the damaged areas quickly and safely. The AIR MU has set its main target of aerial robot system development to the space between the ground surface and the low altitude sky. Space satellites and manned air vehicle, which are effective ways to collect wider area information, are not included in the AIR MU's research objectives.

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 in the technological aspect and operational aspect. For examples, following items should be carefully examined in the design and operations of aerial robot systems.

- Weight saving: The most sever condition in aerial robot design is to reduce its weight without violating required functionality and safety.
- Energy saving: Most aerial robots are designed to be self-contained in power source. To keep longer operational time, on-board equipment of aerial robots are required to have energy saving feature.
- Safety-conscious: A trouble of aerial robots in the air may cause a serious crash accident on the ground. Safety-conscious design and operations are most important criterion in aerial robot systems.
- Remote control and autonomy: Aerial robots are usually controlled by an operation agent on the ground with wireless communication. In case of a communication failure, aerial robots should autonomously keep the stability and take a safe action avoiding the unexpected crash.
- Weather conditions: Aerial robots are more affected by weather conditions than robots on the ground. Aerial robot operators should care about temperature, wind, rain, snow, fog, thunder and other weather conditions for successful operations.
- High mobility: Aerial robot systems have high mobility in the three dimensional space. It means that they should have higher level function for control its mobility appropriately.
- Bird's-eye view: Bird's-eye view is the most important advantage of aerial robot systems. Careless use of bird's-eye view from the lower attitude may raise privacy concerns.

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

In other word, we cannot expect an almighty aerial robot system which is always available for any purpose in any situation.

3 Designing Aerial Robot Systems

3.1 Three phases of USAR operations

The AIR MU divides USAR operations into following three phases based on the request for the disaster information after the disaster occurring.

1. phase-I: The aim of this phase is to capture the entire image of suffering circumstance immediately after the disaster occurring. The initial disaster information would be available in 30-60 minutes after the disaster occurrence for USAR planning at the disaster headquarters.

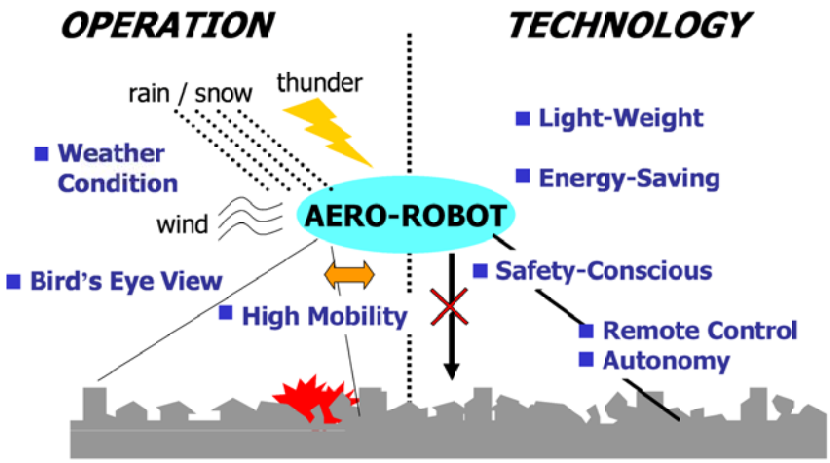

Fig. 3. Operation altitude of aerial systems

2. phase-II: The USAR operations at this phase is to find the victims who are buried under collapsed houses. The important point of this phase to determine primary searching points with high probability of victim existence for effective allocation of rescue teams on the ground. The activities of this phase will be usually carried on for more than 72 hours.
3. phase-III: After lifesaving rescue activity at the disaster area 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 long term.

These phases are not exclusive and they are usually overlapped. For example, phase-I and phase-II would be alternatively iterated in order to investigate the wider disaster area. The phase-III actions are desirable even in the ordinary time to check the safe of the community.

3.2 Aerial robot team for USAR

As discussed above, it is very difficult for us at present to develop an almighty aerial robot which can complete every mission in phase-I, II and III. Practical approach to aerial robot system development for USAR is to organize a aerial robot team which consists with multiple aerial robots of different functionality 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 just after the disaster and collects disaster information automatically. It has high mobility in the air, but it's continuous operation time is usually less than one hour.

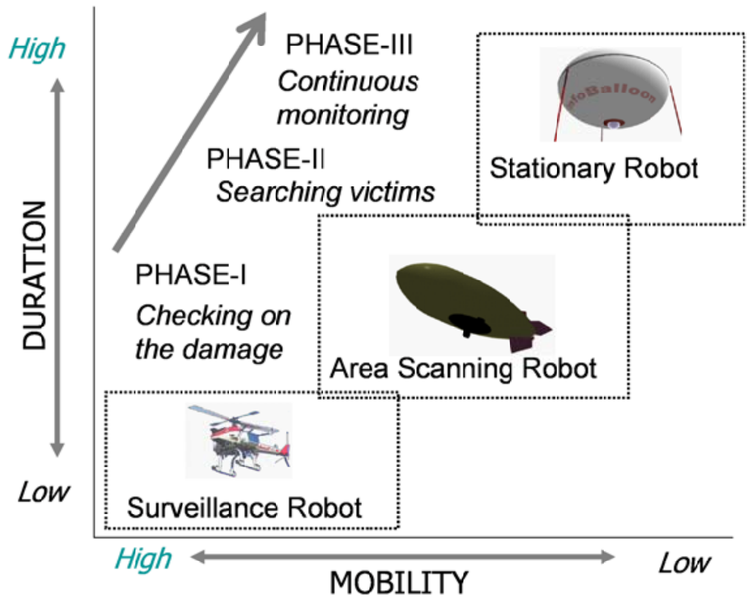

Fig. 4. Role-sharing of aerial robots for USAR

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 the destroyed area closely from low altitude without interfering flight noise. Robots for phase-II have medium performance of mobility and continuous operation time.
3. phase-III: The phase-III's aerial robot system provides continuous information service to the disaster-suffered community. An aerial robot system based on a captive balloon is adequate to this requirement.

Figure 4 illustrates the role-sharing of aerial robot systems in USAR. Three different types of aerial robot systems are assigned to a graph with two axes, mobility and duration.

3.3 Action scenario of aerial robot systems for USAR

According to 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[4][5] respectively. These aerial robot systems are expected to execute the initial investigation for collecting damage data of suffered areas by using their high mobility in PHASE-I.

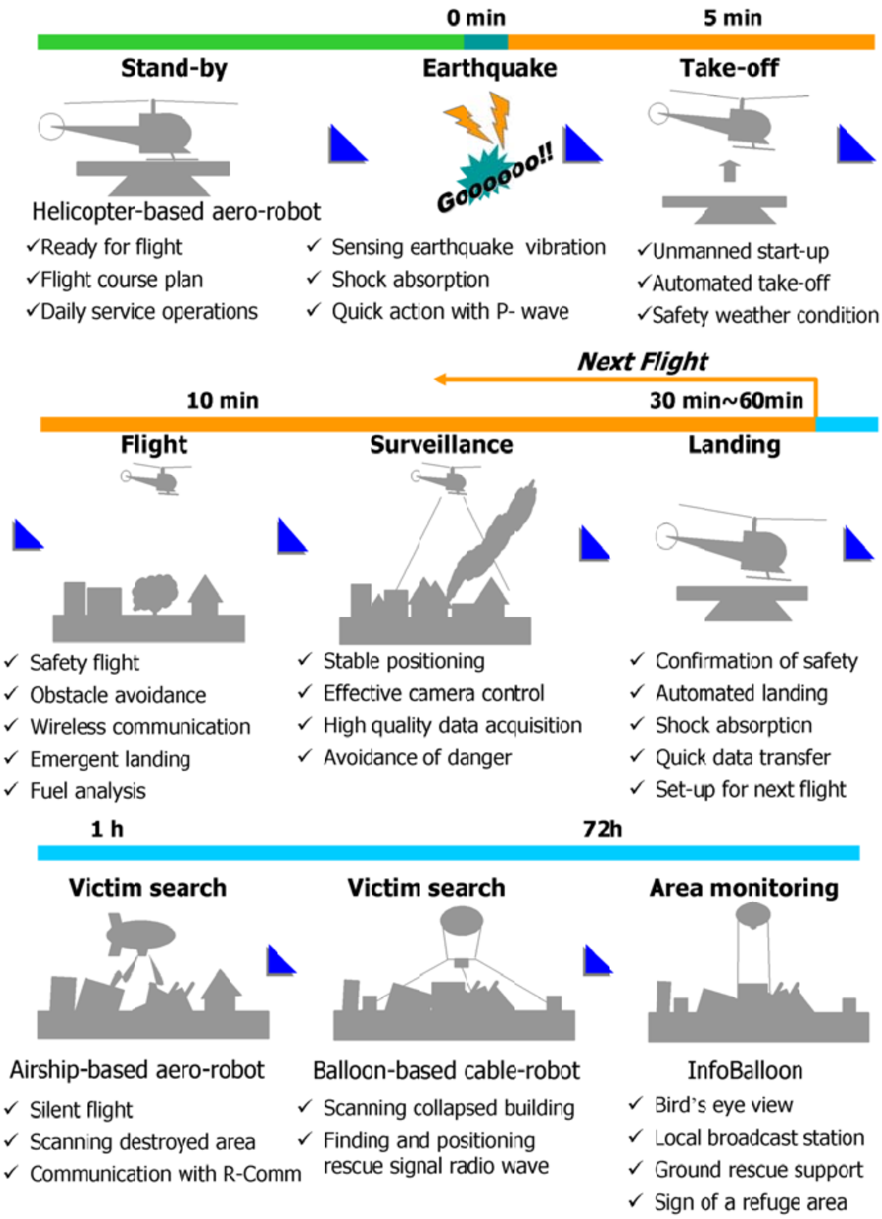

Fig. 5. Action scenario of aerial robot systems for USAR

A joint research group of RIKEN and the University of Tokyo has been developing a rescue request collection system by using a blimp and intelligent communication devices named Rescue Communicator (R-Comm)[6]. A joint research group of IRS, Machine Technical College and Tohoku University has been developing an aerial robot system which is supported with three cables and lifted up by a balloon[7]. This robot system has sensing devices for searching a victim under the rubbles. 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 on which information acquisition and communication devices are mounted[8]. 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 a method development for image processing with which low quality camera images are appropriately clarified. This method realizes a virtual wiper for monitoring cameras in dust-laden environment[9].

Figure 5 illustrates an action scenario of aerial robot systems developed in the AIR MU. In following several sections of this report, each aerial robot system is explained in detail.

4 Aerial Robot Systems developed by AIR MU

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 the unmanned and middle-sized helicopter manufactured by Yamaha Motor Co. Ltd. for agricultural chemical spreading. Based on this platform, the 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 the inertial navigation system (INS) developed at Kyoto university.

The stability and accuracy of the flight by the hybrid controller are superior to ones by expertized human operators, especially in doing the hovering even in windy condition.

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

Figure 6 (A) and (B) show the side view and rear view of the intelligent aerorobot respectively.

In addition to the flight performance, the intelligent aerorobot has great advantage in easy operation compared with other remote controlled aerial vehicles. The intelligent aerorobot can be monitored and controlled on a simple control

Fig. 6. Intelligent aerorobot by Kyoto University group
(A) intelligent aerorobot's side view, (B) rear view, and (C) a van for robot transportation, equipped with control and monitoring devices.

panel on a note PC. An operator just specifies the flight target points on GUI by using a mouse and it is not necessary for an operator to have knowledge about flight mechanism and vehicle flying state for operating the intelligent aerorobot. Figure 7 shows an overview of the control panel for the intelligent aerorobot and a test operation by a guest visiting a flight demonstration.

The intelligent aerorobot can be transported by a usual van and requires only two operators for robot set-up and operations. The console panel equipped with a control and monitoring PC, wireless communication equipment is compactly placed in the luggage compartment of a transporting van. Such a high mobility of the total intelligent aerorobot system is desirable functionality for practical operations in USAR.

Fig. 7. Easy operation of the intelligent aerorobot with GUI on a note PC

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 the automatic control rule which realizes stable flight of various scale helicopters, and also developed an autopilot unit applicable for various scale helicopters.

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

The Chiba University group has also developed an important technology for safety operation of helicopter-based aerial robots. When the engine of a helicopter stops in the sky, the controller controls the rotation of the main rotor so as to fall down slowly and make safety landing. This technology, autorotation landing, can decrease the risk of crash caused by fuel starvation and engine stop.

Small aerial robots based on helicopters have several restrictions compared with medium-sized ones. For example, a full flying speed, continuous working time and a payload are limited lower. Small aerial robots are more affected by

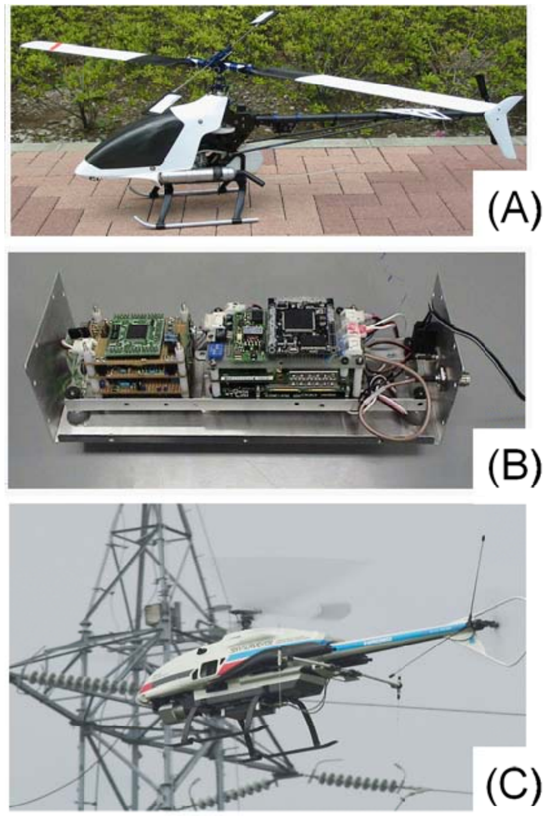

Fig. 8. Small-sized autonomous unmanned helicopter by Chiba university (A) SST-eagle2-EX (gross load 5kg), (B) an autopilot unit (weight 0. 5kg), (C) Power line inspection patrol helicopter (gross load 48kg)

bad weather condition like heavy winds. The advantage of small aerial robots is easiness and cost economy in operation. Thus, it is necessary for us to choice medium-sized aerial robots or small ones in consideration for the condition of USAR missions.

4.3 Autonomous blimp-type robot system

A joint research group of 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, sweeping any sign from victims under collapsed structures. The sweeping areas are decided in accordance with the collected disaster information by the unmanned helicopter systems.

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

Basic specification of this blimp-type robot system is as follows.

- Fill gas: He, 24.9 m^3
- Size: length 6.5m, width 3.0m, height 4.1m
- Propulsion: two electromotive thrusters, more than 8.0N
- Payload: 8.0kg

When the robot system is flying in a closed environment or in a light wind, it is possible to move spatially with computer control.

Small blimps like this robot system are usually uncontrollable in a windy conditions due to lack of propulsive force against wind flows.

More powerful propulsion machines will increase the weight of the robot system, and it requires a bigger helium gas chamber and causes more wind resistance. Larger robot systems lose much mobility and cost economy. New development of higher energy density batteries and higher efficiency thrusters are necessary to solve this problem. One practical solution for this problem, blimp operation in windy condition, is to use anchor ropes to hold the blimp at downwind position. This idea is related to the wire-driven balloon robot system explained in the next section.

Sweeping tests using the blimp-type robot system were carried on in the rescue robot test field at IRS's Kawasaki Laboratory as shown in Fig. 9(B) and (C). A rescue communicator (R-Comm), developed in DDT project, was loaded on the blimp-type robot system and receiving rescue request messages from other rescue communicators distributed on the test field. On the robot system, a three dimensional laser profiler was loaded and three dimensional models of swept areas were constructed. (See Fig. 9(D))

4.4 Cable-driven balloon robot system

In addition to the blimp-type robot system described in the last section, a cable-driven balloon robot system has 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 belongs to Okinawa National Technical College. The cable-driven balloon robot is supported in the air by three extensible cables. At each apex point of a big base triangle, a computer-controlled winder is fixed on the ground. (See Fig. 10(A).) The winders are controlled from a mobile PC via wireless communication. By changing each cable length according to commands from the control PC, the balloon body changes its 3D position in the air. Thus, the robot can sweep the ground inside the base triangle of winders' positions. The balloon body filled with He gas lifts a machine base frame for mounting a CCD camera, wireless communication devices, and a measurement equipment to catch the rescue request signs from collapsed structures. (See Fig. 10(B) and (C).)

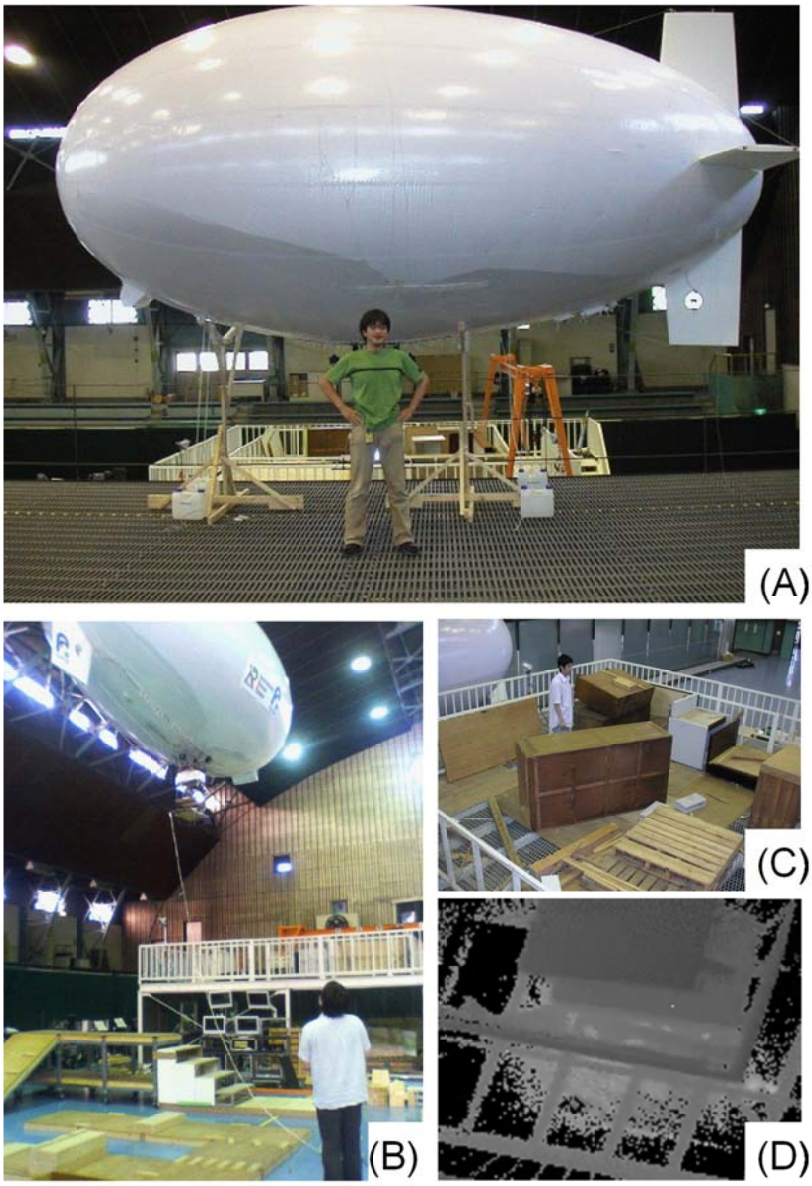

Fig. 9. Autonomous blimp-type robot system by RIKEN and the University of Tokyo (A) overview, (B) sweeping an experimental section at Kawasaki Laboratory, IRS (C) collapsed house experiment facility, and (D) measuring image by a 3D profiler.

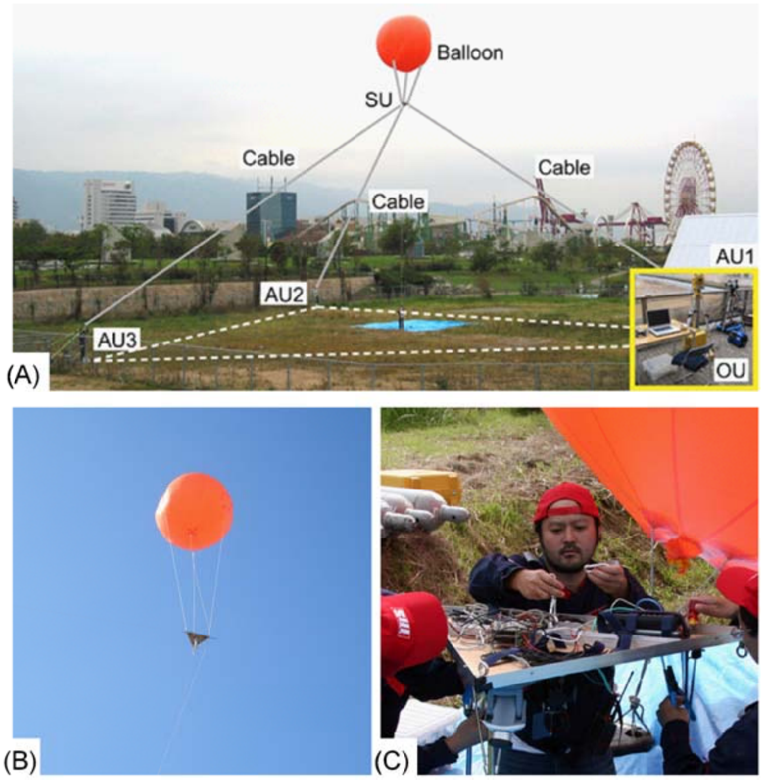

Fig. 10. Cable-driven balloon robot system
(A) overview, (B) a balloon body lifting a triangle base (C) mounting mechanical elements on a machine base frame.

Compared with the blimp-type robot system, the cable-driven balloon robot system has limited sweeping 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 is convenient for sensing devices. In addition, the cable-driven balloon robot system has a power supply line connecting a triangle base in the air and a power source on the ground. Thus, this robot system can be operated for long time continuously.

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-stricken community. The system was named InfoBalloon.

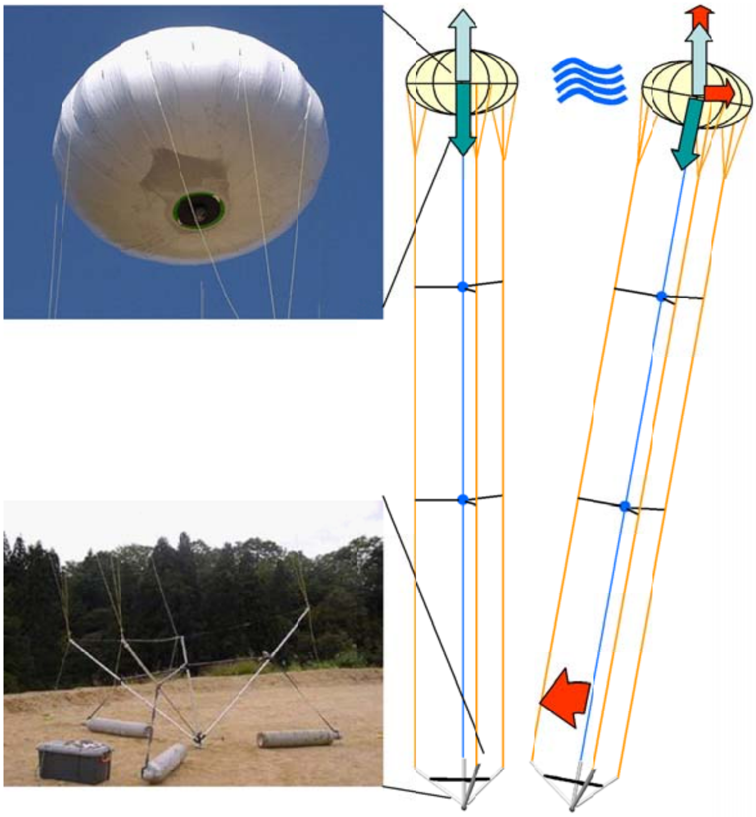

Fig. 11. Captive balloon robot system : InfoBalloon

In development of aerial robot systems using He balloon, some problems should be solved for long-term and stable operation.

- Balloons made of PVC or latex sheet cannot hold He gas for long term. It is necessary to add or replace gas in a balloon body every few days.
- When a balloon body bursts in the air, its mechanical unit will fall down with high speed and may give serious damage to ones on the ground.
- Spheric form balloons commonly used for ad-balloons have higher wind resistance than kytoon type balloons.
- Captive balloons with single wire are easily swept away downwind and lose altitude.

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

Fig. 12. InfoBalloon-TETRA and its bird's eye view photograph

- InfoBalloon's body has double layer structure which consists of outer envelope for mechanical strength and inner film for keeping He gas. InfoBalloon can keep its buoyancy for more than a month.
- The double layer structure of InfoBalloon has less risk of fall accident by gas body burst.
- InfoBalloon adopts a balloon form of vertically depressed sphere.(See Fig. 11.) The height of InfoBalloon's body is 2.3m and its radius is 4.0m. This shape has less wind resistance and produces some lifting force by wing effect against wind flow.
- InfoBalloon is supported with three parallel wires fixed to a tetrahedral frame with a pivot base. With this captive method and a balloon shape, InfoBalloon autonomously tries to keep its position in the air.(See Fig. 11 right part.)

On InfoBalloon, a CCD camera with Pan-Tilt-Zoom control is loaded and send video images using wireless communication. In addition to equipment for disaster information gathering, small equipment for communication relay and radio broadcast can be loaded on its chamber space. In experimental operations, InfoBalloon was successfully held at 100m altitude and sent continuous video images by a mounted PTZ camera via wireless LAN connection.

As a part of InfoBalloon project, a simplified balloon system for one-time use has developed. A balloon with a rounded tetrahedral shape is easy to make because its every sealing part of gas barrier film is straight lines. The simple balloon, named InfoBalloon-TETRA, with a tele-operation digital camera, can take hight quality photographs from the sky. Figure 12 shows an overview of InfoBalloon-TETRA and a bird's eye view photograph.

4.6 Image clearing for field camera systems

A research result introduced in this part is not development of a robot system itself but a common technique for every robot system working in a real field.

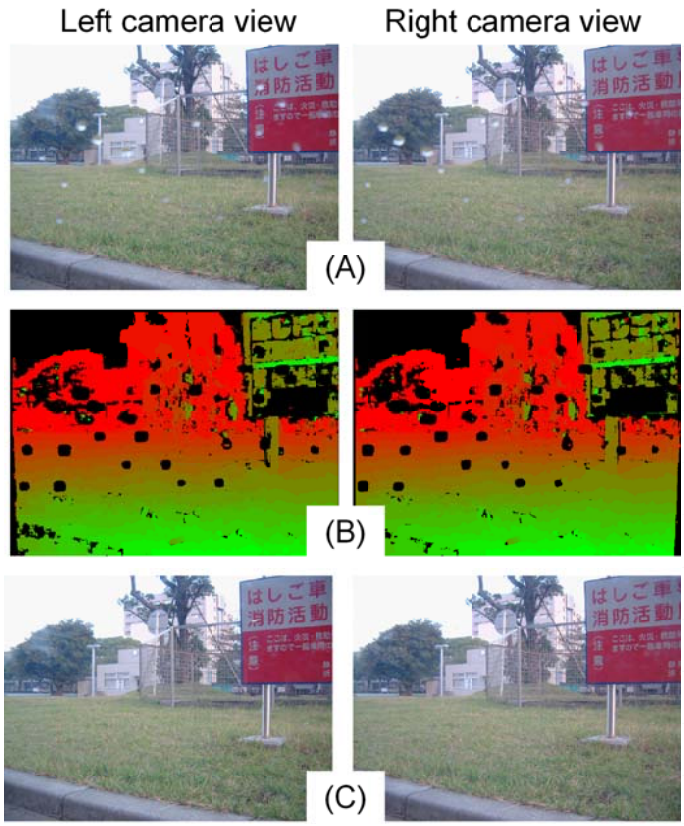

Fig. 13. Example of image restoration
(A) original images, (B) noise detection by disparity estimation, (C) noise removal

Shizuoka University group directed by K. Miura has developed a image clearing method for field camera system.

Robots used for USAR are usually working in dusty environment and lens are protection glass of camera systems mounded on robots are frequently dotted with spots of mud and water drops. Some camera systems are equipped with a cleaning wiper to remove such spots from lens and protection glass. Such equipment is expensive and heavy, but monitoring cameras loaded on aerial robots should be compact and light weight.

The Shizuoka University group has proposed a new image clearing method, named 'virtual wiper", based on image restoration technique. In this method, two more more cameras are used to separate dirty spots on lens or protection glass from scene images. Figure 13 shows an example of clearing images for a stereo camera system. The concept of virtual wiper will be widely used for field camera systems in USAR and other field activities.

5 Field Test of Aerial Robot Systems at Yamakoshi

The aerial robot systems developed by the AIR MU were tested at Yamakoshi region in September, 2006. Yamakoshi region, a part of Nagaoka City and Niigata Prefecture, was severely damaged by the Mid Niigata Prefecture Earthquake in 2004. Yamakoshi region is a mountain village and divided by many mountains and deep valleys. The earthquake caused a number of landslides and blocked most roads connecting to the other neighboring towns. Thus, Yamakoshi region was completely isolated both in traffic and in communication, and it was important for rescue activity to gather disaster information around Yamakoshi region from the air as quickly as possible. Figure 14 shows two photographs around the test site, Takano firm, at Yamakoshi region. At the time of the field test, the test field was specified as restriced area for damage repair.

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

- Intelligent Aerorobot (autonomous unmanned helicopter :medium size)
- Cable-driven balloon robot system
- InfoBalloon (captive balloon system)
- Rescue communicators
- Omni-directional camera system

The Shizuoka University group joined this test from the remote site in Hamamatsu and cleared dirty images sent from Yamakoshi site via INTERNET by using Virtual Wiper technique. Long-distance wireless communication facility was temporally located for this field test.

Purposes of this aerial robot systems test were summarized as follows.

- Tests of each robot system in a natural environment including shape of land and weather condition.
- Tests of collaborative operations by multiple robot systems.
- Tests of long-range wireless communication in mountain areas.
- Demonstration of aerial robot system availability for disaster-prevention organizations.

Most of these test items were successfully carried out. In addition to high performances of the developed robot systems, the field test also demonstrated the easiness of system setup operations. A small staff was enough for system preparation and operations. For example, the intelligent aerorobot was quickly prepared by two operators. Figure 15 and Figure 16 shows a snapshot of aerial robot system preparations.

The system configuration of the Yamakoshi field test is illustrated in Figure 17. Only the cable-driven balloon robot was tested at Iketani area because the scheduled test place for the robot at Takano farm area was just closed for disaster-relief work. You will find detail explanations about DaRuMa and R-Comm in the other MU reports.

Fig. 14. Overviews of the test site at Yamakoshi region

Fig. 15. Set-up of aerial robot systems at Yamakoshi test site

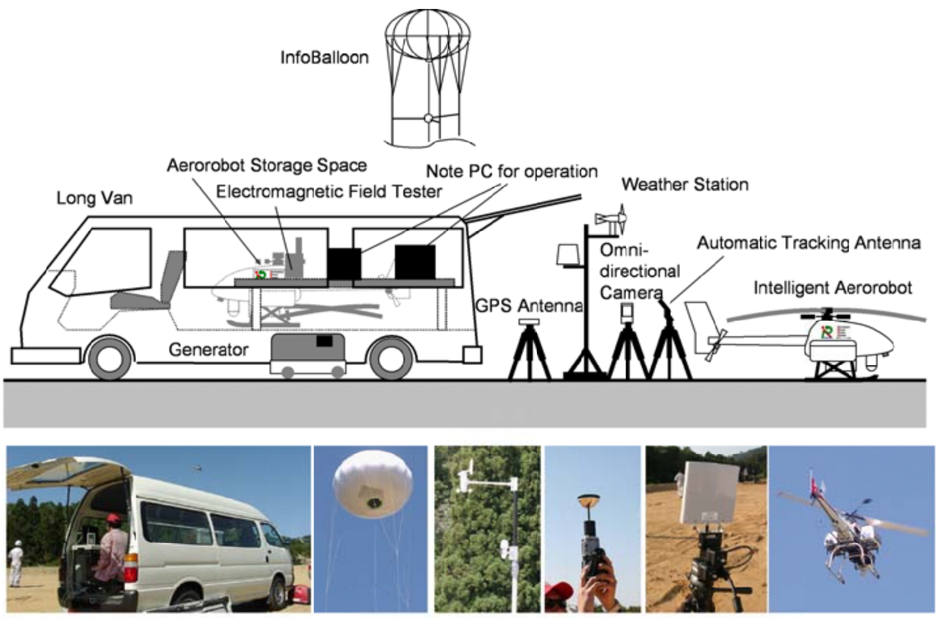

Fig. 16. Overviews of ground facility for aerial robot systems

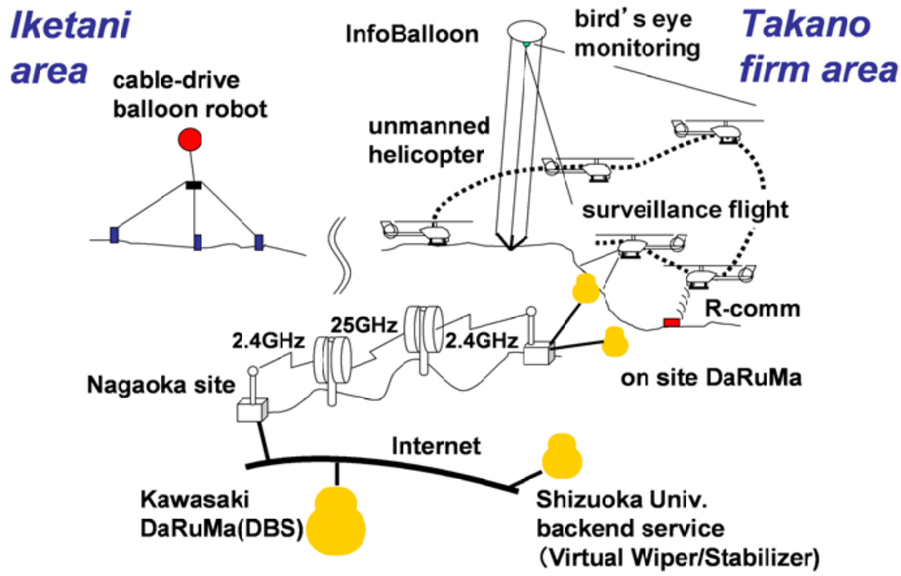

Fig. 17. Overview of robot system configuration in Yamakoshi test

6 Summary of R & D Results by the AIR MU

This report can only introduce a part of The R & D resutls by the AIR MU among many other interesting and important results. Important R & D resutls of the AIR MU's development are summarized as follows.

unmanned autonomous helicopters

- autonomous and stable flight by a intelligent control unit 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
- 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 by three extensible cables
- vertically depressed sphere shape of a balloon body for wing effect
- double layer strucuture of a balloon body for gas barrier properties and mechanical strength
- 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)
- quick search of interest point from aerial video archive using GIS

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

7 Conclusions

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

The main results of the mission unit's R&D in the research project should be examined in more practical fields, and the part of the the action scenario in which different rescue robots make effective collaboration must be demonstrated. The information services 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 done by the AIR MU has made a contribution to the technological advancement of aerial robots for USAR. Some aerial robots already have enough functionality for unmanned operations in disaster situation, but it is still difficult to carry out the action scenario by the aerial robots described in this paper. Aerial robots are not allowed to fly over people and construction even in the disaster area due to the risk of aerial robot's crash. Establishment of community's consensus for aerial robot service in a time of disaster is most important thing to realize the scenario for disaster information gathering.

Acknowledgement

Nost 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 executing this project. The authors would like to thank them for their significant contributions.

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