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Development of a Networked Robotic System for Disaster Mitigation

-System Description of Multi-Robot System and Performance Tests of the Robots-

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Summary. In this paper, the research project named "networked robotic system for disaster mitigation" is introduced. The project aims to develop key technologies for multiple robots to be teleoperated through a wireless communication network, which includes a satellite communication link, for surveillance tasks at a disaster site. The robotic system consists of a large-scale outdoor robot and a group of smaller indoor robots. The large-scale robot will serve as a carrier for the smaller robots which are deployed inside a partly-collapsed building. A three-dimensional range sensor and an omnidirectional camera are used as tools to ease the teleoperation for the human operator. This paper presents the mission scenario and the development status of the proposed networked multi-robotic system. The results of the performance tests are also reported.

Key words: Disaster mitigation, Surveillance robots, Ad-hoc network, Teleoperation, Omnidirectional camera, Laser range sensor, Augmented reality

1 Introduction

Development of the robotic systems for search and rescue operations receives increasing attention and national priority after the Hanshin-Awaji earthquake in 1995 (Japan) and the World Trade Center attack in 2001 (U.S.A.). In such disasters or incidents, priority tasks are grasping a whole picture of the damages and gathering the information on the victims' locations as quick as possible. To reduce the risk of human rescue crews and to help their operation, the introduction of remotely operated robots for immediate surveillance is strongly expected to the robotics community [1].

Since 2003, we have been working on a newly initiated project based on a networked robotic system to help mitigating the damages of disasters [2], under the support of the Japanese Ministry of Internal Affairs and Communications (MIC). The project is organized by Tohoku University, Osaka University, IHI Aerospace, Eizoh Co., Ltd and NICT (National Institute of Information and Communications Technology), aiming at the development of a robotic system for surveillance of a remote disaster site.

The target environment is assumed as a disaster area under a large-scale urban earthquake. There are concrete buildings half collapsed or almost destroyed. Road networks are damaged so that firefighters have a difficult access. Conventional communication networks may be also damaged. In such conditions, the first priority in any rescue procedure is to gather the information for the immediate assessment of the damages and locate the victims in each specific site. To be able to tackle such tasks with the robotic technology, we have developed a robotic system which consists of a large-scale outdoor robot (hereafter termed as a "parent robot") and small-scale indoor robots (hereafter termed as "child robots"). There have been several robotic research projects related to marsupial type robots to deal with uneven and hazardous environments (e.g.[3]). One of the features in the proposed system is that each child robot has a relatively higher locomotion capability (without cables).

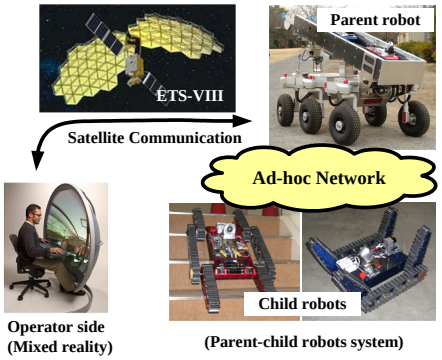

Fig. 1. Project overview

The proposed mission scenario is described as follows:

1. A set of the "parent-child robotic system" is carried and deployed as a cargo of a large-scale helicopter onto a disaster site. (This part is out of this project.)
2. The parent robot navigates the outdoor and acquires 3-dimensional range data of the environment to construct a map of the site.
3. If a half collapsed building in which some victims may exist is identified, the parent robot approaches and deploys child robots from the opening of the building. Using an extendable ramp, the child robots can be deployed from a window on a higher floor (see Fig 2).
4. The child robots explore inside the building to map the environment and to find victims.
5. Both of the control commands and the obtained data of the site are transmitted via wireless network from and to the operators located in a safe, remote site.

Three key issues to realize the above scenario are summarized as, (1) **development of a robotic system** that can be deployed in the disaster site and can

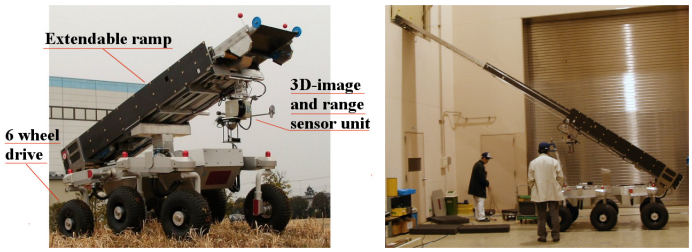

Fig. 2. An overview of the parent robot "MURROS-Grande" and its ramp

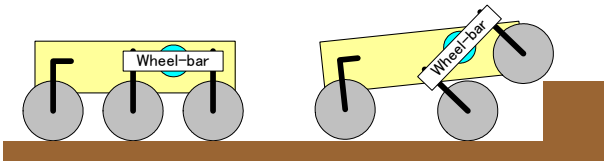

Fig. 3. Description of the wheel-bar of the parent robot

perform surveillance tasks remotely, (2) **development of the augmented reality technology** to display 3-dimensional geometry of the disaster site in a fashion that remote human operators can grasp the images of the site with reality and, (3) **development of a combined satellite-based IP communication and local ad-hoc networking system** to secure the control and data transmission of the robots. Generally, satellite-based communication links have the disadvantage of a lower transmission bandwidth and time-delay, however they have greater advantage given by the fact that the satellites are not damaged by the disasters on the ground. A concept figure is depicted in Fig.1.

Each research institute in this project is assigned to one of the above issues as sub-goals. Finally, the project will perform the demonstrations of the integrated technologies.

In this paper, interim progress reports on each sub-goal are made from Section 2 to Section 4. Preliminary integrated performance tests of the robots are summarized in Section 5.

2 Parent-Child Robotic System (Sub-goal #1)

2.1 System description of the parent robot

The parent robot named MURROS (Multi-Purpose Rescue Robot System)-Grande is required to negotiate uneven terrain such as a boulder field or rubble strewn surface, and to locate itself to deploy the child robots into higher floors of the collapsed buildings. Therefore, the Grande is designed to have six wheels with a linkage suspension and carry an extendable ramp, then developed by IHI Aerospace Co., Ltd. An overview of the robot is shown in Fig.2.

The locomotion is based on an electrical 6-wheel-drive and a 6-wheel-steering, with the maximum traveling velocity of 4.0 [km/h]. The dimensions

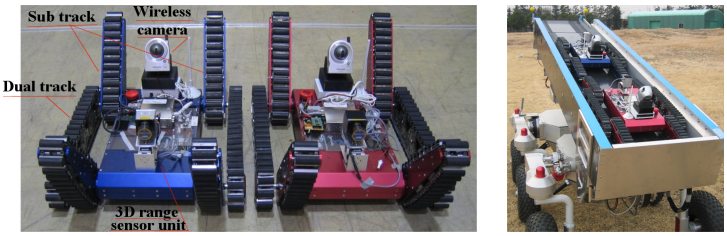

Fig. 4. The child robots "MURROS-Piccolo" (left) and mounted on parent robot (right)

of the robot are 2.3 [m] in length, 1.3 [m] in width, and 0.8 [m] in height. It mounts the three-segmented extendable ramp which can deploy child-robots up to the height of 5 [m]. The maximum length of the ramp is about 7 [m]. The Grande weighs about 300 [kg] without the ramp.

One of the features in the locomotion mechanism of the Grande is that front two wheels on each side are connected by an active connecting rod called wheel-bar. If the wheel-bars on both sides are harmonized as with a differential mechanism, they perform like a passive rocker-link suspension and contribute to equalize the vertical loads on each wheel. Bt making most of its active motion capability, the Grande can go over 0.5 [m] steps as shown in Fig.3.

As for the mapping and localization, the robot equips a 3-dimensional image and range sensor unit (shown in Section 3.4). It also mounts GPS receivers, inclination sensors and rate gyros.

2.2 System description of the child robots

The child robot named MURROS-Piccolo is required to be capable of climbing up/down stairs and overcoming obstacles to search victims inside the buildings or houses. Therefore, the locomotion mechanism with segmented multi-tracks designed by Technocraft was used as a mobile base (6 tracks in total). An overview of the Piccolo is shown in Fig.4.

Also as shown in Fig.5, by changing the up/down angles of the front and rear pair of sub-tracks, the Piccolo can overcome an obstacle. The dimensions of the Piccolo are 1.0 [m] in length, 0.5 [m] in width, and 0.5 [m] in height. It weighs about 30 [kg]. The maximum speed of locomotion is about 1.8 [km/h], skid-steer is used for steering maneuvers.

As for the sensors, the robot equips a 3-dimensional range sensor unit, a conventional pan-tilt web-camera, inclination sensors and rate gyros. Particularly, the 3-dimensional range sensor is useful in the teleoperation system discussed in Section 2.3.

2.3 Teleoperation using 3-dimensional maps

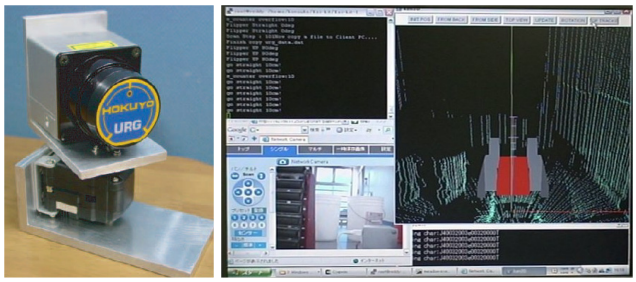

Fig. 6. The 3-dimensional range sensor (left) and the operator's GUI (right)

Fig. 5. The child robot overcoming an obstacle

The time delay and narrow bandwidth are major drawbacks in the satellite-based communication. In such situation, transmitting the video stream is not a smart idea since it requires a huge bandwidth though its content information is very dilute. On the other hand, 3D ranging date is much more informative and useful for the display of the robot working site to remote operators.

The left picture in the Fig. 6 depicts the range sensor unit mounted on the MURROS-Piccolo. The sensor unit is composed of a small laser range finder (URG-04LX, Hokuyo Co. Ltd.) and a Smart Motor (DX-117, Dynamixel) that rotates the laser range finder around the vertical axis in 180 [deg]. It can obtain range data in every 0.35 [deg] in both vertical and horizontal directions, and the maximum measuring range is about 4.0 [m]. The scanning speed is about 1 [min / 180 deg], but it can be increased by rotating the the Smart Motor faster although the horizontal resolution will be decreased accordingly.

For the teleoperation of the robot, "Stop-and-Go" strategy was taken to cope with the bandwidth limitation and time delay issue. The procedure is as follows:

S1: [robot] Stop and obtain a local 3-dimensional map by the laser sensor. (hereafter called "3D-map").
S2: [robot → operator] Send the 3D-map data to the operator.
S3: [operator] Display the 3D-map from an arbitrary view point and superimpose a virtual robot model on it.
S4: [operator] Drive the virtual robot using an input device such as a joystick in the 3D-map.
S5: [operator → robot] The motion trace of the virtual robot is sent to the real robot as its reference trajectory.
S6: [robot] Move along the given trajectory based on the on-board odomeory and rate gyro measurment.
S7: Go back to S1 to obtain a new 3D-map.

The right side of the Fig. 6 depicts the operator's GUI for the teleoperation of the child robot. Based on the above procedure, the operator controls the real robot as if controling the virtual robot in the virtual environment.

Advantages of this strategy are as follows: (1) The operator can choose any view direction and any zoom-size of the virtual environment. In general, the images of a bird-eye view is much more useful and comfortable than those of an on-board camera. (2) The proposed procedure requires far small amount of data to transmit, comparing to the video stream. (3) The proposed procedure can cope with any amount of time delay. For example, some 10 to 30 minutes are needed for the remote driving of a Mars rover, but the proposed procedure is still effective.

There are some points to be improved: (1) The robot motion control in the step S6 relies on the onboard odometory, but when the wheels or tracks slip, the odometory becomes unreliable. Particularly, the skid-steering of the tracked robot generates large odometry errors. The problem of track's slippage is well described in [4], and we already proposed how to improve the reliability of the odometry for the tracked robots. Details are in [5]. (2) The mapped area can be extended by combining multiple 3d-maps. For this purpose, an improved scan-matching technique should be applied. (3) The virtual environment represented by a 3D-map looks artificial, not realistic. To improve the reality, the technique to superimpose real picture images onto the map segments as texture is proposed in the following section.

3 Omnivision and 3-dimensional Range Sensor Unit for Effective Telepresence (Sub-goal #2)

3.1 Development of a hanging mechanism

When a robot runs on bumpy terrains, the acquired map data are tilted if the sensor is fixed to the robot's body, then the transformation is necessary to fit in a vertical-horizontal coordinate system. In the proposed prototype model, a "hanging mechanism" was developed using a passive gimbal mechanism (shown in Fig. 7) which consists of two rotary-disk-dampers (FDT-47A, Fuji-Latex Co., Ltd). By hanging the sensor unit, it passively keeps the sensor's pose vertically and horizontally by its own weight.

Fig. 7. Hanging mechanism

3.2 Non-isotropic omnidirectional imaging system

Considering both high-speed locomotion and surveillance tasks, high-resolution image and wide-angle-view are effective, but both are under the trade-off usually. To achieve these two features simultaneously, non-isotropic omnidirectional imaging system has been developed in Osaka university [6]. The sensor has the Horizontally fixed viewpoints Biconical Paraboloidal (HBP) mirror

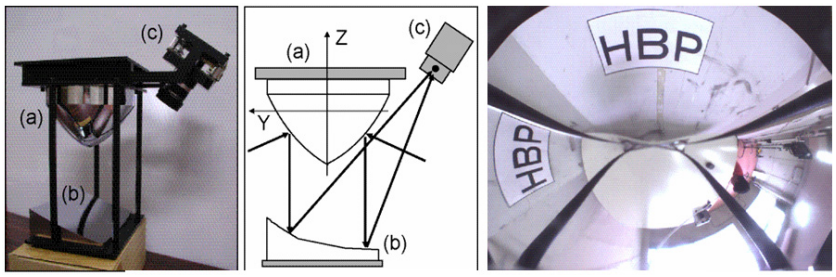

Fig. 8. Non-isotropic omnidirectional imaging system and obtained image

Fig. 9. Proposed sensor unit and obtained 3-dimensional information

which generates an inhomogeneous angular resolution. It enables the operator obtain not only an omni-directional scene but high-resolution views in a particular direction (in our case, in front). Figure 8 shows an overview of the sensor and an obtained image. We can see that the resolution at the front view is larger than at the side view (by comparison between the characters "HBP").

3.3 The 3-dimensional range sensor for outdoor

To obtain 3D map data in outdoor environment, a scanning system is developed, which has almost the same design as indoor-type shown in Section 2.3, but SICK LMS291 is used as the laser range finder. The scanning speed is about 1 [min / 180 deg]. In this case, the sensor acquires range data in every 0.5 [deg] in both vertical and horizontal direction, and the maximum range is about 30 [m].

3.4 Integration of the sensor unit

Integrating the above sub-components, "Omni-Vision and 3-dimensional Range Sensor Unit" was completed [7]. In Fig. 9, the sensor unit mounted on the parent robot is shown on the left, and an example of the textured 3-dimensional map is shown on the right.

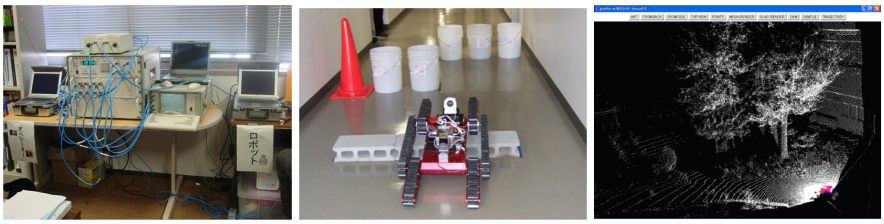

Fig. 10. The satellite simulator and the teleoperation performance tests

4 Combined Satellite and Local Ad-hoc Network System (Sub-goal #3)

4.1 Engineering Test Satellite VIII

The Japanese Engineering Test Satellite VIII (ETS-VIII), developed by Japan Aerospace Exploration Agency (JAXA), is a technology demonstration satellite for providing IP-based wireless network connection all over Japan and nearby countries. This satellite works as a repeater station between two portable terminals. One is located at the operators' side, and the other is located in disaster site. The satellite has the capability of up to 1.5 [Mbps] communication link, but in the experiments, we anticipate much lower bandwidth.

4.2 Wireless ad-hoc network

In this research, commercial ad-hoc network systems (produced by Decentra and Thinktube) were tested and evaluated for the operation of the child robots using multi-hop capabilities.

4.3 Performance test of teleoperation using satellite simulator

As the ETS-VIII is not opened for the user experiments, the system performances were tested using the satellite communication simulator provided by JAXA. The appearance of the simulator is shown in the left of Fig. 10. It simulate the transmission throughput under the bandwidth limitation, time delay, and packet loss in a realistic situation.

Using the simulator, three basic performance tests were carried out on December, 2006. The first test was to measure the effective time delay in transmitting data files. Packet-collision problems were observed in the case of a communication rate of 768 [Kbps] or lower, when sending 2 [MB] data of the map data with 5.0 [sec] intervals. Depending on the collision, the time delay varied between 1 and 2 seconds.

The second test was to remotely operate the MURROS-Piccolo in the indoor environment. The setup for the test is shown at the center of Fig. 10. To operate the robot, the 3D-map-based teleoperation system described in Section 2.3) was used. Ten people (that includes three skilled operators)

performed a short course teleoperation based only the virtual model in the 3D-map without any other clues.

During the performance test, we observed that a conventional velocity-based control (the traveling speed of the robot is given by the tilt-angle of the joystick-bar) was very hard even for experienced operators in the case of unstable 1-2 [sec] time delay. Therefore, in the performance test, we updated the control scheme from the velocity-based one to an "inching" position control. In this new control interface, if the operator clicks a button once the robot is commanded to move a fixed distance (10 [cm] in our case) or certain rotational angle (10 [deg] in our case). After that, total navigation time and safety were improved drastically. We did not perform a quantitative test yet, but obviously, the result suggests that a position-based-control has a big advantage under time-delay conditions.

The third test was to remotely operate a robot in the outdoor environment. The robot carries the 3-dimensional range sensor described in Section 3.3 and a pair of RTK-GPS for the localization. The right side picture of Fig. 10 is one example of the 3D-map obtained in the outdoor environment, and the position and pose of the robot is superimposed based on the RTK-GPS data. The teleoperation by skilled operator was succeeded in navigating the robot slowly. However, sometimes, the GPS denied cases were caused by the occlusion and multi-pass of the GPS satellite signals due to the surrounding buildings, then the accuracy was disturbed in the localization.

5 Performance Test of the Proposed Parent-Child Robotic System

To confirm the proposed parent-child robotic system for disaster mitigation tasks, an open-demonstration was organized on March 10th, 2006. It was performed in a field and a building of IHI Aerospace Co., Ltd. in Kawagoe, Saitama, Japan. In this performance test, the following scenario was demonstrated.

1. The parent robot, MURROS-Grande is controlled through a visual feedback.
2. The Grande performs the acquisition of 3-dimensional range data and image to construct a textured 3D-map.
3. The Grande approaches a building and extends the extendable ramp to the second floor's opening in the height of 4.2[m].
4. Two child robots, MURROS-Piccolos climb the ramp to enter the building.
5. Two Piccolos are operated for remote searching mission with constructing 3D-maps. One tries to climb up the staircases and the other goes down the stairs.

At the time of this performance test, as the ad-hoc network system was not implemented yet, a conventional wireless LAN (IEEE 802.11 b/g) was preliminary set inside the building.

The parent robot, Grande, succeeded in negotiating with bumps and gaps in the outdoor environment, and deploying two child robots, Piccolos, onto the 2nd floor of the building. (A picture is shown in Fig. 2). One of the two child robots climbed up to 3rd floor through the stairs and found a dummy victim successfully. The other child robot stepped down to the 1st floor smoothly.

The whole scenario was performed as expected, then we concluded that the installation of the basic functions for the proposed robotic system was successfully completed, except the ad-hoc network system.

6 Conclusion

In this paper, the research project named "networked robotic system for disaster mitigation" was introduced. The project has three sub-goals, which are (1) the development of parent-child robotic system, (2) the development of omni-vision and 3-dimensional range sensor unit, and (3) the development of a combined satellite-based IP communication and local ad-hoc networking system. This paper described the system concepts and state-of-the-art of the project. Finally, the performance tests at the open demonstration on March 10th, 2006 was summarized along with the proposed mission scenario. The performance tests validate the advanced technologies for rough terrain mobility in both outdoor and indoor environments, 3D ranging data acquisition and 3D-map-based teleoperation, which were developed in this projects and applicable to many other mobile robots for the search and rescue missions.

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