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HELIOS System: A Team of Tracked Robots for Special Urban Search and Rescue Operations

M. Guarnieri, R. Kurazume, H. Masuda, T. Inoh, K. Takita, P. Debenest, R. Hodoshima, E. Fukushima and S. Hirose

***Abstract*— Fire brigades and special agencies are often demanded to operate for search and aid of human lives in extremely dangerous scenarios. It is very important to first verify the safety of the environment and to obtain remotely a clear image of the scenario inside buildings or underground spaces. Several studies have been addressing the possibility of using robotic tools to carry out safe operations.**

This contribution presents the development of the HELIOS team, consisting of five tracked robots for Urban Search And Rescue. Two units are equipped with manipulators for the accomplishment of particular tasks, such as the handling of objects and opening doors; the other three units, equipped with cameras and laser range finders, are utilized to create virtual 3D maps of the explored environment. The three units can move autonomously while collecting the data by using a collaborative positioning system (CPS).

After an overview on the specifications of the team of robots and with respect to previous publications, detailed information about the improvements of the robot mechanical design and control systems are introduced. Tests of the CPS system and HELIOS IX vehicle together with a typical mission experiment are presented and discussed.

I. INTRODUCTION

Teams committed to urban search and rescue operations have to operate in extreme environments, such as areas stricken by earthquakes or by terrorist attacks. In these scenarios, explosions and the collapse of buildings may always occur. By using mobile platforms with high terrain adaptability and advanced arrays of sensors, operators can in first place size the area of operation and reach dangerous locations, bringing to the spot cameras and tools.

There are several mobile platforms so far proposed for these kinds of applications. However these solutions are often addressing only very specific problems: machines with only very high terrain adaptability, robotic tools and or machines capable to accomplish one task such as the opening of the door, the grasping of objects, or the creation of 3D virtual maps [7]. Moreover when these solutions have to be utilized for real applications, several issues ranging from the lack of mobility to the capability of utilizing different platforms together must be addressed. An analysis of the state-of-the-art of the Japanese robotic developments for USAR operations has been presented in [8]; also, a tentative proposal for a set of machines has been introduced for practical operations in [9]. However, proposing several types of vehicles with different capabilities can become a problem due to their limitations when deploying them in real scenarios.

The HELIOS vehicles team proposed in this contribution is a system of five cooperative tracked mobile platforms. The vehicles can be utilized separately and also together in more complex missions. Their adaptability to uneven terrain and mobility have been already illustrated in [1] and [2].

Three tracked vehicles called hereafter *HELIOS carriers* consist of one parent robot and two child robots as shown in Figure 1. The parent robot is equipped with a highly precise laser range finder. Child robots are quipped with 2D laser range finders, a pan-tilt camera, and an image sensor for acquiring texture images. By making use of the laser range finders and corner cubes, the system of the three carriers can move autonomously in unknown environments, carrying out the CPS system procedure [4]. Two other units of the team are called hereafter HELIOS IX and they are utilized for the accomplishment of specific tasks in the scenario.

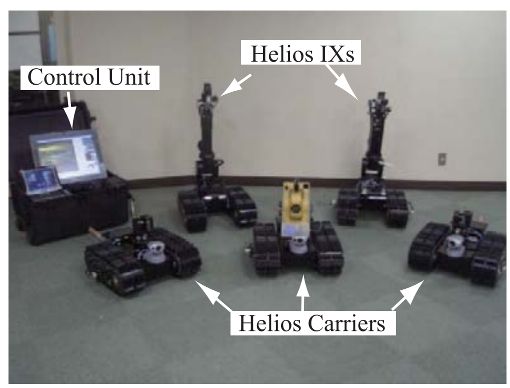

Fig. 1. Total system of HELIOS IXs and carriers

HELIOS IX, introduced in [1], consists of two tread units connected to a base that acts mainly as a manipulator for task based operations. The arm end-effector offers high maneuverability for precise handling operations, making use of a special hybrid parallel linkage consisting of only 2 active DOFs. Two CCD cameras are installed on the platform: one with a 360° degrees view directly connected at the end effector for grasping operation, and another utilized

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for driving the robot and for inspecting the environment, installed at the extremity of a 2 DOF arm.

The next section will introduce the specifications that were defined for this development. The following section will introduce in detail the improvements and the control system of each robot. Several experiments are then introduced and presented together with conclusions and future works discussions.

A. Specifications

For this development the following specifications list was defined by the NEDO sponsor of the project *(NEDO is the largest public R&D management organization for promoting the development of advanced industrial, environmental, new energy and energy conservation technologies in Japan)*:

- The system can be only remotely controlled by wireless communication;
- The map of the explored buildings must be realized together with the eventual presence of stairs and doors;
- Robots must have a minimum speed of 5km/h;
- The types of environment to be explored are civil, such as: subways, tunnels, airports, offices and malls;
- The environment may be crowded with people and several obstacles;
- Eventually doors must be opened;
- The luminosity of the environment is unknown;
- The system can utilize only the onboard power;
- Video of the explored buildings must be also taken;

II. Mechanical Solutions and Control Architecture Improvements

This section will introduce the proposed system in detail. All machines make use of brushless motors to avoid explosions in case of environments filled with gases.

A. HELIOS IX

Fig. 2. HELIOS IX lifting a 7kg chair

The mechanical design of HELIOS IX vehicle shown in Figure 2 was presented in details in [1]. This section will depict a few improvements that were introduced after several tests with the first prototype. Table I shows the dimensions of

TABLE I
HELIOS IX Specifications

Item	HELIOS IX	Carrier
Mass	40kg	18kg
Width	490mm	490mm
Length	570mm	570mm
Arm (extended)	1220mm	NaN
Gripper Payload	8kg	NaN
Track unit (width)	160mm	160mm
Track unit (height)	202mm	202mm
Speed on flat ground	over 7km/h	over 7km/h

HELIOS IX. The arm length was extended 200mm in order to be able to reach the door knobs/handles when operating inside buildings. In this way it was possible to open space for the installation of a corner cube utilized for the vehicle tracking system. Besides, the gripper, that presented with the first prototype a pitch range of $\pm 50°$, has been improved in order to obtain a $\pm 90°$. The two active links have been in fact shifted backward with respect to the end effector in order to allow the rotation of the gripper. In addition the camera arm has been shifted forward on the forearm, so that it may be rotated together with the end-effector.

B. HELIOS Carrier

Each HELIOS Carrier consists of a simple tracked base composed by two of the same treads of HELIOS IX. Two extra motors are utilized for the tail mechanism, previously introduced in [2] for the autonomous control of the vehicle on stairs and for the pan control of the sensing devices. Figure 3 shows the PAN actuation and the sensors installed on the carrier.

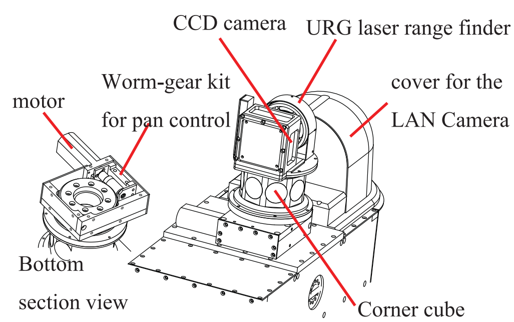

Fig. 3. PAN control and devices on the child carriers

Each track, as in the case of HELIOS IX is equipped with its own motor driver controlled by an SH2 based microcontroller and batteries. These are connected by CANbus to one main HiBot SH2 Tiny installed in the main body, which is interfacing by serial communication the lower system with a small laptop pc also housed inside the body. One extra SH2 Tiny inside the CANbus network is instead utilized for the control of the tail and the pan mechanism. In the main body is installed also one extra battery and one router for the network communication introduced in the next section.

C. HELIOS carriers sensing system

The parent vehicle is equipped with a highly precise laser range finder (GPT-9000A, TOPCON LTD), a pan-tilt camera (VB-C50i, Canon Inc.), and an attitude sensor (MD900T, Applied Geomechanics Inc.) as shown in Figure 4. Child robots as seen before are equipped with corner cubes, 2D laser range finders (TOP-URG, Hokuyo Automatic Co.,LTD), a pan-tile camera, and an image sensor for acquiring texture images. The highly precise laser range finder and corner cubes are used for the positioning of robots by CPS. The specification of the laser range finder is shown in Table II.

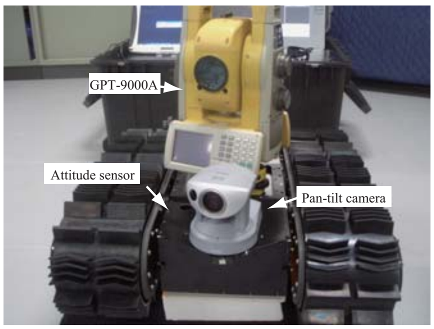

Fig. 4. Parent robot

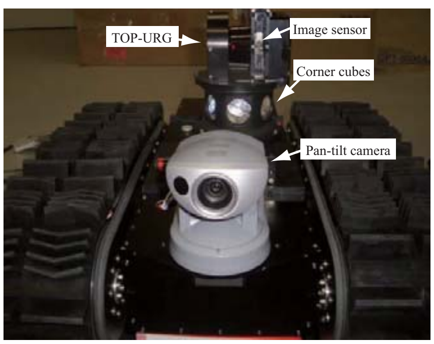

Fig. 5. Child robot

The basic procedure of CPS is shown in Figure 6. The laser range finder can measure the relative positions of the child robots from the parent robot. Considering that the initial position of the parent robot is measured or defined beforehand, these are the steps followed by the CPS algorithm:

(1) Child robots 1 and 2 are moved and stopped.
(2) The parent robot measures the distance, azimuth, and elevation angles to child robot 1 and identifies its position.
(3) The position of child robot 2 is identified in the same way as in Step 2.
(4) The parent robot moves and stops. The distances, azimuth, and elevation angles to child robots 1 and 2 are then measured, and the position of the parent robot is calculated using the triangular surveying technique.
(5) Steps 1 through 4 are repeated until the target position is reached.

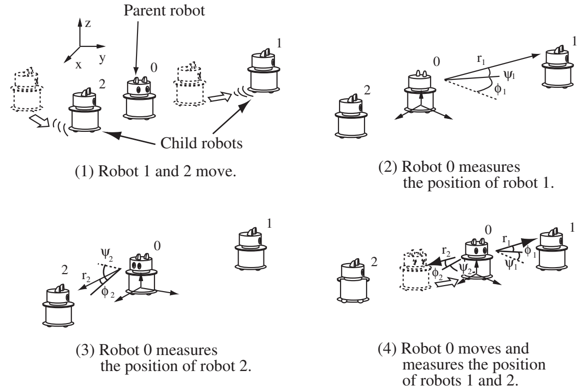

Fig. 6. Cooperative Positioning System (CPS)

The 2D laser range finder installed on the child robots are used for taking 3D geometrical information of the environment. The sensor can acquire 2-dimensional slit-like range data within the range of 20m and 270 degrees, as shown in Table III. The 2D laser range finder was placed on the rotating table, presented earlier, so that the laser slit is vertical to the ground. By rotating the table around the vertical axis while scanning with the 2D laser range finder, 360° 3D range images can be acquired in 39 seconds. Figure 7 shows an example of obtained 3D and 2D maps.

TABLE II
SPECIFICATIONS OF THE TOTAL STATION, GPS-9000A

GPT-9000A (TOPCON Ltd.)	
Range	1.3 ∼ 3000 [m]
Resolution (distance)	0.2 [mm]
Resolution (angle)	3”
Precision (distance)	± 2+2ppm [mm]
Precision (angle)	±5”

TABLE III
SPECIFICATION OF THE LASER RANGE FINDER, TOP-URG

TOP-URG (Hokuyo Automatic Co.,LTD)	
Range	30 [m]
Field of view	270°
Resolution (distance)	1 [mm]
Resolution (angle)	0.25°
Precision (distance)	± 30 [mm]

D. HELIOS IX and Carriers Control System

Although the basic control system of Helios IX was not changed with respect to the previous publication, many improvements were added to the controllability of the vehicle. The graphic interface using the feedback data from the machine shows three different 3D virtual views of the robot for remote control as pictured in Figure 8. Also, images acquired with the two CCD cameras can be included in the GUI by user selection. The following modes were also added:

- Direct control of each actuator of the robot;
- Simple inverse kinematics control for the manipulator;

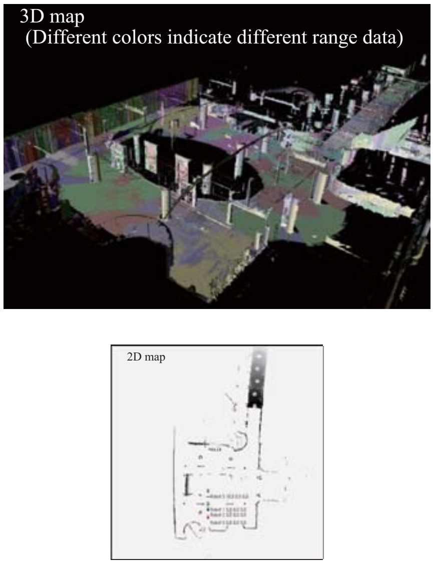

Fig. 7. An example of obtained 3D and 2D maps

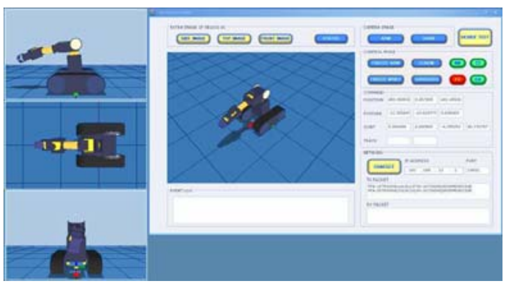

Fig. 8. HELIOS IX User Graphic Interface

- Semi-automation of the stairs climbing motion by using the onboard attitude sensor for stability control.

The vehicle can be controlled using both: a normal game console joypad and a pair of Nintendo Wii controllers installed in a control box as shown in Figure 9 and 10. It consists of a touch monitor, a computer and batteries.

Wii input devices were introduced in order to test an intuitive control of the 6 degrees of freedom installed in the manipulator. As shown in Figure 9 two Wii remote controllers and one Wii Nunchuck are utilized. Using the data extracted from the Nunchuck attitude sensors, it is possible to obtain the roll and pitch attitude of the operator wrist.

Yaw, as well as Y,X, and Z coordinates, are instead extracted by tracking (with the infrared camera of controller A) the position of two infrared LEDs that were installed on the Nunchuck front panel. Controller B is utilized for the mode selections and for the feedback vibration when grasping an object by the end effector. In order to avoid sudden unwanted motions of the vehicle, the data collected by the attitude sensors are sent to the robot only if the operator keeps pressed one particular controller button according to the selected mode. When gripper mode is selected, the

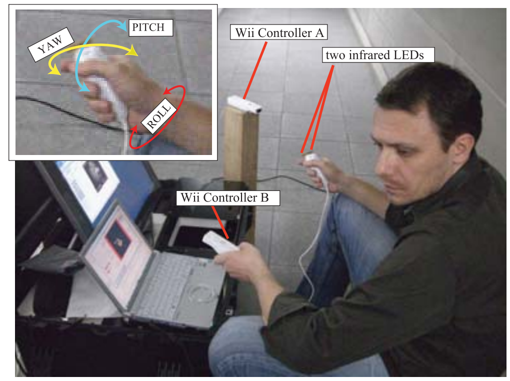

Fig. 9. Input device controller for HELIOS IX

wrist position of the user drives directly the end-effector. In manipulator mode, the wrist position (x,y,z) in the space is utilized for the inverse kinematics control of the manipulator. The analog joystick is instead utilized when controlling the vehicle crawlers and when the user directly actuates separately each motor.

HELIOS carriers are simultaneously controlled by one control box shown in Figure 10. The operator can easily switch the display mode between 3D and 2D (Figure 7). In 3D mode, the acquired 3D models are virtually displayed on the screen and the virtual robots move in the 3D model. The operator can check the movements of the robots (including the two HELIOS IX vehicles) from the panoramic view. The snap shots taken by cameras can be attached along the moving path as shown in Figure 11. On the other hand, in the 2D mode, the operator can plan search and rescue missions and send movement commands to the actual robot by indexing the target positions with a touch pen on the screen.

Fig. 10. Control box

E. WiFi Communication

The network utilized for the communication between the robots and the operator is based on the IEEE802.11n network by 5GHz dual band routers. Each vehicle is equipped with

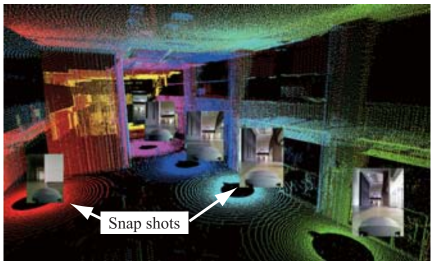

Fig. 11. 3D model with snap shops

one router. For the first tests of HELIOS system, a total of 5 access points equipped with a small slim battery were displaced on different floors during field tests. In future works the displacement of each access point device will be also addressed by using the carriers for their positioning. Each router firmware was changed in order to allow each vehicle (i.e. movable router) to connect to the strongest signal router in the network while moving in the environment.

III. Tests

A typical operation utilizes first two HELIOS Carriers to start to analyze the environment and to send to the user 3D images of the scenario. In the meantime, one unit of HELIOS IX can be also deployed by using the onboard cameras and the carrier cameras as external points of view for controlling the vehicle. Eventually, tasks like opening doors, removing objects and obstacles up to 8kg can be carried out with it. The parent robot carrier is then deployed and the automatic 3D analysis of the environment can be carried out.

A second unit of HELIOS IX can be deployed for additional tasks of search and rescue. The control of this second unit can be effectively carried out by using the information of the 3D environment and the tracking system offered by the parent carrier.

The new HELIOS IX control system based on Wii controllers was tested in different situations. Several handling tasks were carried out. Although when operating with the team of robots it is possible to make use of the carrier cameras to view and control HELIOS IX, this first part presents tests carried out with using only the on-board cameras.

Figure 12 shows the opening of a door with knob. The gripper eye camera while approaching the knob is reported in Figure 12-1 .

The time to accomplish these kinds of operations is dependent on the familiarity (i.e. training) that the user has with the control of the robot. The positioning of the machine with respect to the door is also very important. By using the analog joystick on the nunchuck, once the door is opened, it is possible to control the base assigning the velocity vector direction and amplitude of the vehicle and push or pull the door as shown in Figure 13. The use of the Wii has been proven to be very effective and intuitive in this kind of task.

On the carriers sensing equipments, several modeling experiments were carried out in a large hall area. Figure 14 shows the total view of the 3D model of the hall. The size of the hall is about 60 m × 25 m.

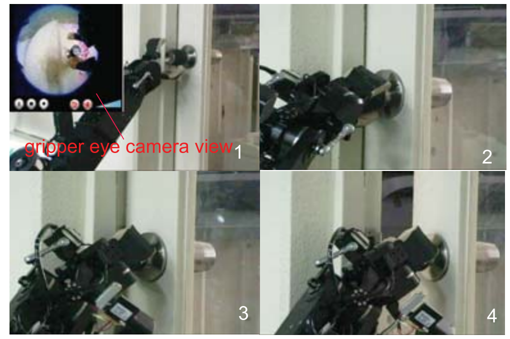

Fig. 12. Door opening tests

Fig. 13. Door opening tests

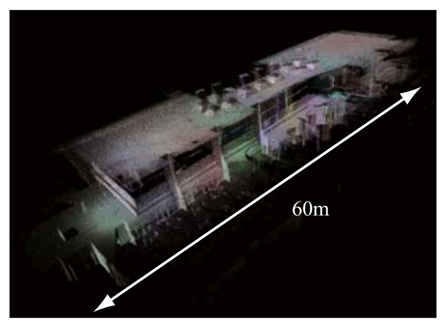

Fig. 14. The 3D model of the hall

Figures 15(a) and 15(b) show the comparison of the accuracy of the obtained 2D maps by CPS and dead reckoning method using the rotation of crawlers. The number of the laser measurements was 10 for the dead reckoning, and 9 for CPS. The total distance covered by the robot was 54 m and 42 m, respectively. As seen from these figures, the map created by dead reckoning curved due to the error accumulation, while the map by CPS is quite accurate even after several movements. The Figures illustrate the collected data overlapped to the floor map image.

Figure 16 illustrates a few frames of one mission experi-

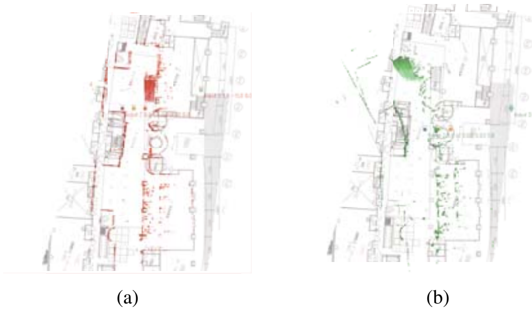

Fig. 15. Precise 2D map by CPS and by Dead Reckoning

ment carried out between two floors of a building. The video attached with the submission of this contribution illustrates the test. First the HELIOS child carriers are deployed from the first to second floor, to create a 3D map of the area as in Figure 16-1. Along the stairs, operators supply a simple forward command while the machines are autonomously controlling the tail mechanism in order to move smoothly on stairs (Figure 16-2).

In Figure 16-3 after the virtual map is created, HELIOS IX is deployed. The control of the robot is made easier by using images coming from the child robots network cameras. Last, in Figure 16-4, the parent carrier robot is taken to the upper floor for robot tracking and for the CPS system.

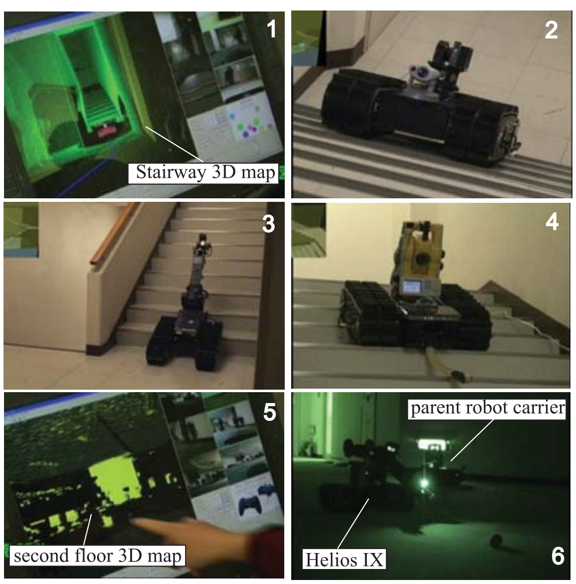

Fig. 16. Typical mission application

By using the 3D virtual map, the operator can move within the GUI inside the environment and can eventually define or locate spots to be confirmed as shown in Figure 16-5. In this case the second floor was not illuminated and HELIOS IX was using the on board LEDs to remove an object from a small bag located in the floor in Figure 16-5. In Figure 16-6 the parent robot carrying out the robot tracking is marked.

IV. Conclusion and Future works

Several experiments were carried out by using separately each machine to confirm their features. Other tests with the whole team of robots were also performed in real conditions: in one of the Tokyo subways stations, inside a building hall and in different floors. A more intuitive control device based on Wii Nintendo controllers has been also confirmed to be effective when handling objects or opening doors with HELIOS IX. In this case, the use of camera views coming from the carrier robots displaced around HELIOS IX was proved to be useful for fast operations. The vehicles can reach over 7km/h in speed (a feature useful when deploying the vehicles from a remote spot); however, when utilizing the automatic tracking system, due to the GPT-9000A specifications and to avoid measurement errors, the speed had to be set to 2km/h.

The creating of large 3D maps can be time-demanding and critical for real rescue operations. However, this can be addressed by carefully planning the deployment of each robot. After part of the 3D map has been generated, one HELIOS IX can be in fact operated while carriers accomplish the realization of the remaining map.

Future improvements on the motion automation are to be addressed in order to obtain a more effective control of HELIOS IX. Also, further development on the control box units should be considered in order to allow one single user to control the whole team of robots. In the mission experiment shown previously, two users were operating respectively the two HELIOS IXs and the three HELIOS Carriers.

V. ACKNOWLEDGMENTS

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