Rough Terrain Negotiable Mobile Platform with Passively Adaptive Double-Tracks and Its Application to Rescue Missions and EOD Missions

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Abstract: This paper presents design and integration of the ROBHAZ-DT3, which is a newly developed mobile robot system with chained double-track mechanisms. A passive adaptation mechanism equipped between the front and rear body enables the ROBHAZ-DT3 to have good adaptability to uneven terrains including stairs. The passive adaptation mechanism reduces energy consumption when moving on uneven terrain as well as its simplicity in design and remote control, since no actuator is necessary for adaptation. Based on this novel mobile platform, a rescue version of the ROBHAZ-DT3 with appropriate sensors and a semi-autonomous mapping and localization algorithm is developed to participate in the RoboCup2004 US-Open: Urban Search and Rescue Competition. From the various experiments in the realistic rescue arena, we can verify that the ROBHAZ-DT3 is reliable in traveling rugged terrain and the proposed mapping and localization algorithm are effective in the unstructured environment with uneven ground. The another application is an military robot for an EOD(Explosive Ordnance Disposal) and reconnaissance mission. The military version of the ROBHAZ-DT3 with a water disrupter, a thermal scope and a long distance wireless communication device is developed and sent to the area of military tactics in Iraq. Consequently, the feasibility of the military version of ROBHAZ-DT3 is verified.

Keywords: rescue robot, EOD robot, double track mechanism, passive adaptation, tele-operation

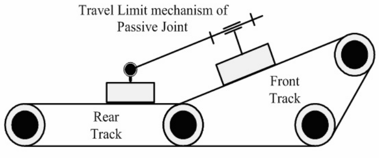
1. INTRODUCTION

In this century, robots take the place of human labor in many areas. Actually, they attempt to perform various hazardous duties like fire fighting, rescuing people, demining, suppressing terrorist outrage, and scouting enemy territory even in warfare area. There are three types of moving mechanisms for this kind of robots in general: wheel type [1-3], track type [4-9], and walking type mechanism [10]. The wheel-type mechanisms are inferior to track-types when they are to move on rough terrain. Walking robots have good dexterity on rugged terrain, but its complex structures usually make its control difficult. In that sense, the track mechanism has good mobility under rough ground conditions. In spite of these merits, it consumes more energy than the wheel-types one and has relatively poorer dexterity than the legged one. To overcome these drawbacks, some recent researches have proposed novel track mechanisms with flexible configuration adaptive to various ground conditions. Iwamoto and Yamamoto developed a mobile mechanism with tracks which could change its configuration during traveling [4]. Hirose, et. al. suggested a moving carrier to obtain stable traveling on a slope [5]. Schempf, et. al. suggested a robot with reconfigurable tracks that has a similar structure to the robot proposed in this paper, but this robot must changes its configuration actively to adapt to the ground condition [6]. For inspection in a disaster field, multi-track vehicle was presented by Takayama and Hirose [7]. It consists of three track bodies and can move on rugged terrain such as stairs, since it can lift or twist each track body like a snake. Yoneda, et. al. suggested a track type moving mechanism that uses a track consisting of a material having higher friction coefficient and wider contact area between the track and steps [8].

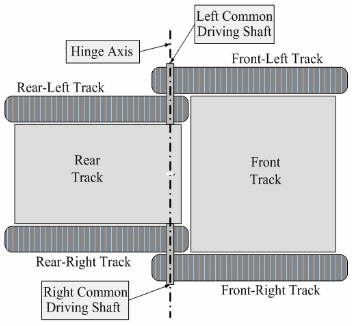
Although previous researches show good mobility on the rugged terrain, most of them use additional actuators to obtain adequate adaptation on the irregular surface [4-7]. As generally known, automatic control of robot's configuration is difficult and unreliable due to noisy data coming from the unconstructed environment. Also it would be a burden to a human operator to remotely control robot's configuration for stable motion, since he/she could not obtain full information due to the remote operation. However, in the wheel type vehicles [1-3], the passive adaptation to rugged terrains has been attempted and shows good mobility even though they usually require complicated adaptation linkage.

In this paper, we propose a new version of ROBHAZ for rescue and EOD applications. Since 1999, we have developed robots called ROBHAZ (ROBot for HAZardous application), which have the passive adaptation function [2, 9]. By improving our previous work [9], a simple and compact double-track mechanism called ROBHAZ-DT3 is developed. And the rescue version of the ROBHAZ-DT3 is proposed, which possesses various sensors for rescue operations. In the competitions of the RoboCup2004 US Open (Urban Search and Rescue Robot Competition) [17], the mapping and localization algorithms were successfully executed together with the good mobility of the ROBHAZ-DT3. Also we developed the military version of the ROBHAZ-DT3 and apply the robot system to the area of military tactics in Iraq. Consequently, the feasibility of the military version of the ROBHAZ-DT3 is verified.

This paper is organized as follows: section II deals with design of double track mechanism and ROBHAZ-DT3; section III describes the rescue version of the ROBHAZ-DT3 and RoboCup2004 US Open – Urban Search and Rescue Robot Competition; the military version of the ROBHAZ-DT3 is introduced in section IV; finally concluding remarks are summarized in section V.



(a) Side view



(b) Top view

Fig. 1 Design of passive double-track mechanism (patent pending)

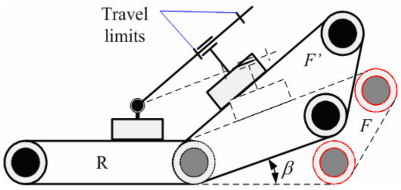
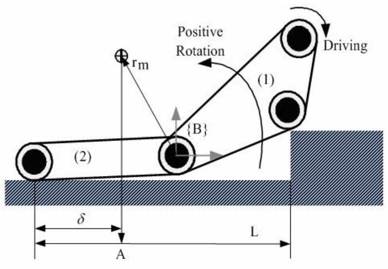
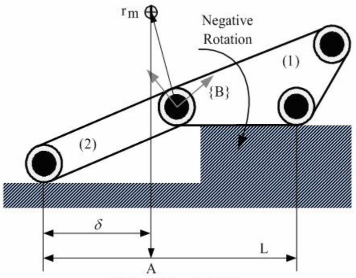


Fig. 2 Relative motion on the hinge axis



(a) Positive deflection



(b) Negative deflection

Fig. 3 Passivity in stairway climbing

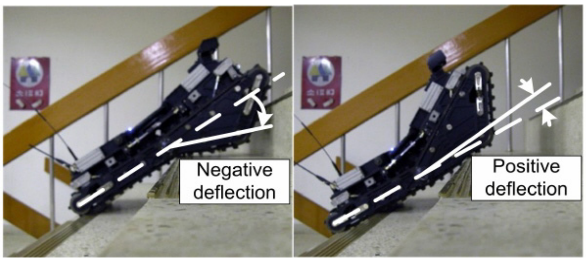


Fig. 4 Landform adaptability of passive mechanism

2. DESIGN OF THE DOUBLE TRACK MECHANISM AND ROBHAZ-DT3

2.1 Passive double-track mechanism

A novel double-track mechanism, which can give a passive adaptability based on a sample link mechanism, is exploited for the ROBHAZ–DT3 to increase its mobility on rough landform. Fig. 1 shows a recently upgraded design of the double track mechanism of the ROBHAZ-DT3. The ROBHAZ-DT3 consists of three parts: the front body, rear body, and a passive joint with travel limit connecting the two bodies. The two tracks at each side in Fig. 1(b), have a common driving shaft and each motor is equipped for actuating the shaft. Thus, the two tracks at each side rotate in the same direction as that of the driving shaft.

The passivity is simply acquired by attaching the front and rear body through a hinge joint without any actuator. The hinge axis is marked in Fig. 1(b), and is coincided with the axis of the driving shaft. Fig. 2, illustrates a passive relative motion between the front and rear bodies. As the front track rotates in the angle of β as marked in Fig. 2, from the initial state F to the arbitrary final state F'.

Changing configuration moves the weight center or ZMP (Zero Moment Position), which gives influence on stability of a vehicle in rough terrains. It is generally known that single-track mechanisms have limitation in rugged terrain due to a fixed weight center in the body coordination frame, which greatly affects the stability margin (the minimum length between weight center and the closest edge of a supporting area). The stability margin in the case of a single-track vehicle is only determined by the inclination of landform. Therefore, it is needed to design to have chained mechanism with multiple track bodies to overcome this limitation. This is a main reason that we designed the double track mechanism. In case of the double-track mechanism, the center of mass varies and the supporting area also changes by the passive motion when traveling over the landform. The effect of the passivity is investigated in an example of stairway climbing as shown in Fig.3. Stairway is one of the good landform to verify the mobile capability of a vehicle, and it is widely used among many researches related in developing a vehicle for such irregular terrain. For simplicity, the example is drawn in 2D vertical plane. {B} is a body fixed coordinates frame and $\mathbf{r}_m$ is a position vector of center of weight. L is a projected line representing the supporting area as depicted in Fig.3(a). The point A is a center of weight projected on a supporting area, and δ is a stability margin. During climbing the stairs, both the positive and negative rotations are observed in Fig.3. In the situation of Fig. 3(b), for instance, a supporting area increases compared with that of Fig. 3(a). Since the support area is added by the front body on the next step. The L would be shorter in case of single track. It means that the double-track design has advantage in low gravity center and large stability margin. Finally, the advantage of the double track mechanism is verified through the result of experiment in a real environment of stairs as shown in Fig.4.

2.2 Hardware integration and Stairway climbing

Fig. 4 shows a picture of ROBHAZ-DT3 and its remote control station. The basic double-track mechanism is composed of chained double-tracks driven by a single motor for each side. The transmission system has two speed modes. In low speed mode, ROBHAZ-DT3 can climb up to 40^{o}-slope or stairways. It has 60kg payload for level ground. In high speed mode, maximum velocity of ROBHAZ-DT3 is 10km/hr. By using this two speed modes, ROBHAZ-DT3 can be used for various military or civilian missions by mounting mission-specific equipments such as a water-disrupter, a manipulator, a mission-specific sensors and so on. In many of real situations of hazardous duty, the robot should be deployed into the site as soon as possible. It requires minimum setup time and simple and intuitive user interface. Thus the tele-operator station with small size and light weight for easy operation, as shown in the left side of Fig. 5 is necessary for practical use. The detail specification is listed in Table 1.

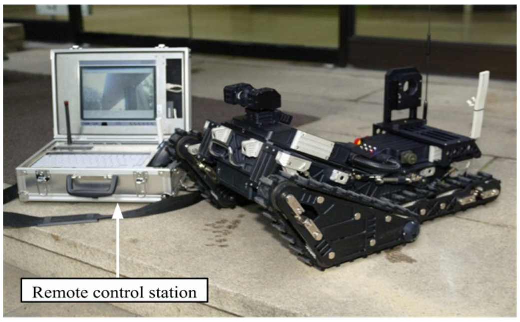


Fig. 5 Picture of the ROBHAZ-DT3 and control station

Table 1. Specification of ROBHAZ-DT3

External size (W × H × L)	740 × 470 × 290 mm
Weight (Battery included)	39 Kg
Max. Velocity (Low speed mode)	0.7 m/sec (2.5Km/h)
Max. Velocity (High speed mode)	2.7 m/sec (10.0Km/h)
Maximum angle for going up steps	40°
Passive joint limit	+10° ~ -30°
Power	Lithium-polymer rechargeable Battery
Time of operation	1hrs

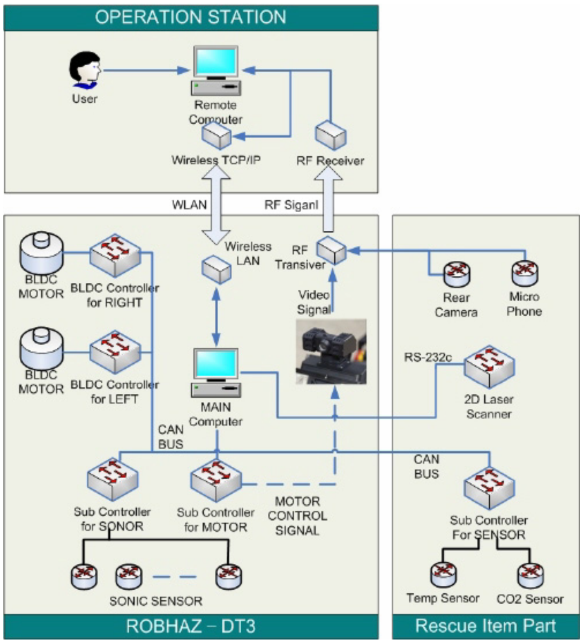


Fig. 6 Block diagram of integrated control system of the robot

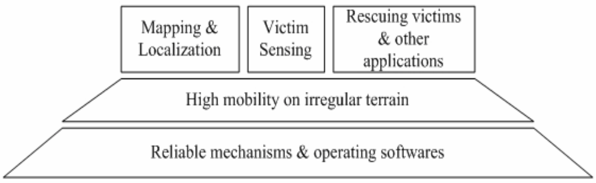


Fig. 7 Required functions for rescue robot

2.3 Control System and Software integration

The block diagram of an integrated control system of the ROBHAZ-DT3 is illustrated in left side of Fig. 6. Linux (Kernel 2.4.18-4) operating system is used for main control operating system of ROBHAZ-DT3.

The integrated robot control system is composed of a Linux-operating CPU board, two sub-controllers, and two BLDC motor drives. The sub-controllers and BLDC motor drives are connected to the PC through CAN (Control Area Network) bus and exchange the speed data of BLDC motors, the position data of Pan/Tilt and various sensors information. This control structure enables a highly responsive control by coordinating the sub controllers and distributing the computation load of the total system. The information exchange between the robot and tele-operator station is carried out through wireless LAN.

3. ROBAHZ-DT3 FOR RESCUE MISSION

Based on the design of the mobile mechanism with the passive double-tracks, the ROBHAZ-DT3 has been integrated into a rescue version which requires various sensing and control algorithms to successfully perform the rescue missions. In this section, the integration of the ROBHAZ-DT3–Rescue version is described in detail.

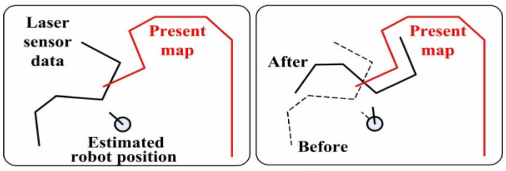
3.1 Functional requirements for rescue application

The mission and required functions of a rescue robot is as follows [11,12]:

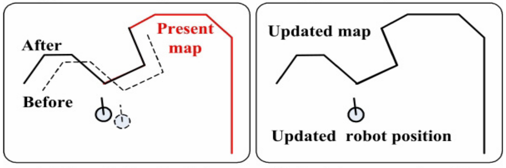
When disaster happens, minimize risk to search and rescue personal, while increasing victim survival rates, by fielding teams of collaborative robots that can:

- Negotiate compromised and collapsed structures
- Find victims and ascertain their conditions.
- Produce practical maps of the environment
- Deliver sustenance and communications
- Embed sensors and communication networks
- Identify hazards
- Provide structural shoring

These requirements for rescue missions can be summarized in the function diagram as shown in Fig. 7. As a basic requirement for a rescue robot, it should have reliable hardware and control software to successively conduct given missions. Furthermore, it could negotiate irregular terrain very well, since it would be operated at unconstructed area like a collapsed building. Once a robot satisfies these basic two requirements, it can be applied to rescue missions. Third-level blocks present more specific functions for rescue mission. The function of mapping & localization provides victims' locations and a 2D map of the disaster environment. The function of victim sensing measures victim physical conditions. From two functions, an operator can obtain the rich information of victims and the disaster area with minimum risk. ROBHAZ-DT3 for the rescue missions is developed to meet the requirement of rescue robot by three steps. First, a reliable hardware and software system has been designed and integrated based on the double-track mobile mechanism. The reliability of the hardware and software of the ROBHAZ-DT3 has been verified through various experiments. Secondly, we have developed the manual mapping method which can be used in highly unconstructed area such as a field of disaster. Finally, rescue-mission specific several sensors are installed to ROBHAZ-DT3 to gather the victims status as much as possible.



(a) Measure range data (b) Rotating the data



(c) Translating the data (d) Update map and position

Fig. 8 Sequence of the manual mapping

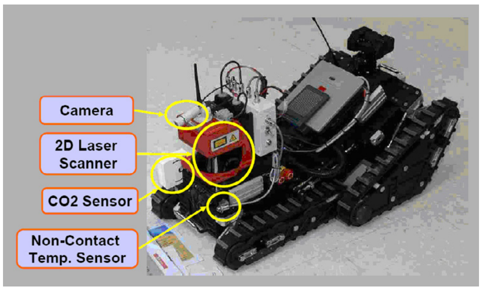
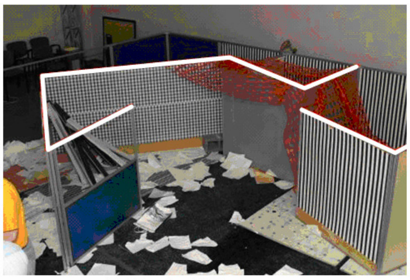
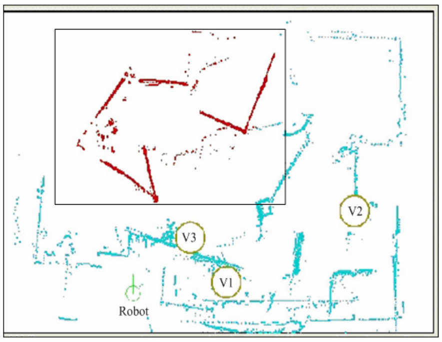


Fig. 9 ROBHAZ-DT3 with sensors for rescue application



(a) Simulated disaster area



(b) Results of mapping

Fig. 10 Results of mapping for the simulated disaster area of the RoboCup2004 US Open

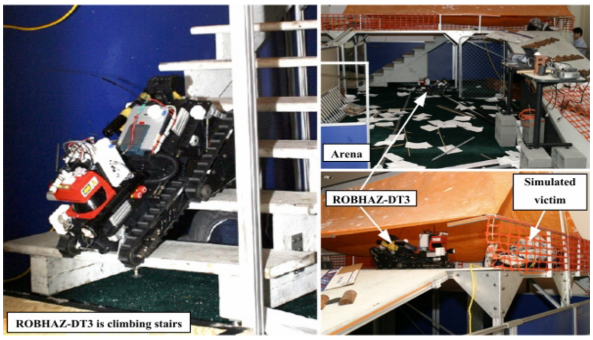


Fig. 11 The ROBHAZ-DT3 in the simulated disaster area of the RoboCup2004 US Open

3.2 Sensors for rescue robot

Right side of Fig. 6 illustrates the block diagram of an integrated additional control part for the rescue missions. The optional control part consists of one sub-controller and a 2D Laser-Scanner. The sub-controller interfaces a non-contact temperature sensor and a CO_2 sensor. The 2D laser scanner communicates with main computer via RS-232c.

To enable map building, localization, and victim sensing, a rear camera, 2D laser scanner, CO_2 sensor, and non-contact temperature sensor ware installed as shown in Fig. 8, to enable. The 2D laser sensor is equipped for map building and localization, and measures distances in the range of 0 to 15m within 190^o angle area. Since a human emits CO_2 during breathing, measurement of CO_2 can tell us victims' vital condition. Also the body temperature of a victim is useful information to identify his/her status. Hence, a CO_2 sensor and a non-contact temperature sensor are mounted. Rear camera transmit the rear view of the robot to the operator

3.3 Mapping & localization

The mapping and localization function are essential for a rescue robot. More technical advances are still required to localize and rescue a victim with a robot. The most important function of a rescue robot is to provide accurate information such as the localization in the map and physical status of a victim to a rescue team. But, in order to carry out the rescue mission, a fast mapping and lo-algorithm is essential not to make the robot's velocity slow down.

Most previous methods for mapping and localization are assumed to be automatically conducted by using numerical computation or the notion of the probability. However, a rescue robot is operated in highly unstructured area, whereas most mapping and localization method have been developed for structured environments. That is, the most algorithms are very sensitive to noises in range sensor measurements. Precise localization requires lots of computation time and it consequently makes the speed limitation of a robot. Although a few algorithms are known to be robust even for the irregular surface conditions, they generally take too much computing time [13-15]. Thus, reliable mapping and localization in rescue missions are hard to be achieved by fully automated methods.

In order to overcome the current limits above, we apply a manual mapping technique to the ROBHAZ-DT3 rather than fully automated one. That is, the human intelligence is used for judging the final decision. In our manual mapping method, when the laser sensor measures range data at an instant, the operator matches them to the present map, thereby updating the map and performing localization at the same time. These sequences are depicted in Fig. 8. In the first place, the laser sensor measures data only when the operator trigger sensor. Then, the sensed range data are transmitted to the operator, and he/she handles the data on the monitor screen. The data can be translated and rotated by dragged with a mouse interface. Finally the operator matches the data and update to the present map. This method is very easy and reliable. Furthermore, since this process runs only when the operator triggers, it minimize the processing time.

The result of this method, however, resorts to the operator's decision, and thus this would be a burden to the operator in emergency situation. Hence, some kind of semi-automated features are necessary. We apply a function of *snap* to the manual mapping method. This function superimposes patterns obtained from the laser sensor into those obtained from the map data if both data are matched. And this function works before step (d) of Fig. 8.

We use the *iterative point matching for registration algorithm* to implement the snap function [16]. The key idea underlying the algorithm can be summarized as follows: Given that the motion between two successive frames is small, a curve in the first frame is close to the corresponding curve in the second frame. By matching points on the curves in the first frame to their closet points on the curves in the second, we can find a motion that brings the curves in the two frames closer.

Let x_i and y_i be the point on the laser data and map data. The objective is to find the motion between the two frames (i.e., **R** for rotation and **t** for translation) such that the following criterion

$$F(R,t)=\frac{1}{N}\sum_{i=1}^{N}\left\|Rx_i+t-y_i\right\|^2 \tag{1}$$

is minimized, where N is the number of point pairs. Fortunately, several much more efficient algorithms exist for solving this equation.

Thus, the operator just roughly decides the value of rotating and translating, drags the data curve, and then the exact values are obtained automatically from the snap algorithm. It is useful function to the operator in rescue mission and also result of mapping & localization is reliable and precise.

3.4 Winning RoboCup 2004 US-Open – Urban search and Rescue Robot Competition.

A rescue version of ROBHAZ-DT3 is designed based on the requirements of the rescue area of the RoboCup [17]. Three major functions are required for rescue applications: Mapping & localization; Victim sensing; Rescuing victims. By the proved performance of the ROBHAZ-DT3, its modification to a rescue robot was simply conducted by mounting sensors on the robot platform to provide the three major functions.

With the rescue version of the ROBHAZ-DT3 as shown in Fig. 9, we participated in the RoboCup2004 US Open – Urban Search and Rescue Robot Competition. During the RoboCup2004 US Open, seven different rounds were held for three days. Fig. 10(a) shows a part of simulated disaster area at the RoboCup2004 and its mapping results are presented in Fig. 10(b). The white lines drawn in Fig. 10(a), represent walls and obstacles and were mapped into the lines in the box area of Fig. 10(b). In the figure, V*i* denotes an identified victim's position. The manual method can produce reliable results, although range data is not reliable due to the complex environment and irregular terrain. Photographs of the ROBHAZ-DT3's playing at the RoboCup2004 round are presented in Fig. 11. By the rugged mechanism with a good mobility of ROBHAZ-DT3 and the stable mapping and localization algorithms, we could win the *championship* at the RoboCup2004-US Open - Urban Search and Rescue Robot Competition with the remarkably high score. The obtained scores of the competitions are listed in [18]. Consequently, we can verify the reliability of the mechanism and software of the ROBHAZ-DT3 through competitions.

4. ROBAHZ-DT3 FOR MILITARY MISSION

In this section, the military version of the ROBHAZ-DT3 with a tilt-mechanism equipped with a water disrupter, a thermal scope and a long distance wireless communication device for an EOD and scouting mission is introduced in detail.

4.1 Configuration of the military version of ROBHAZ-DT3

Generally, for military missions, several special devices are required for a robot to satisfying the aims of each mission. In this paper, three kinds of an equipment installed to the ROBHAZ-DT3 for EOD and Scouting mission. The water disrupter with tilt mechanism is standard equipment for the EOD mission. The thermal scope is applied for ensuring a field of view in nighttime. It is very useful to detect an enemy soldier by measuring his/her body heat. Finally, to guarantee the stable communication, the long distance wireless communication device is installed. The communication device's maximum range is 24km with the specified antenna. Fig. 12 shows a military version of the ROBHAZ-DT3 with three kinds of the special devices.

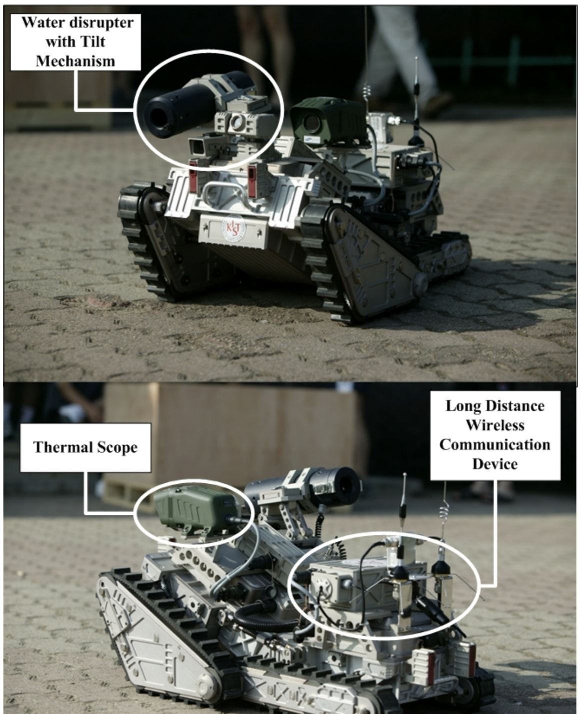


Fig. 12 Military version of the ROBHAZ-DT3

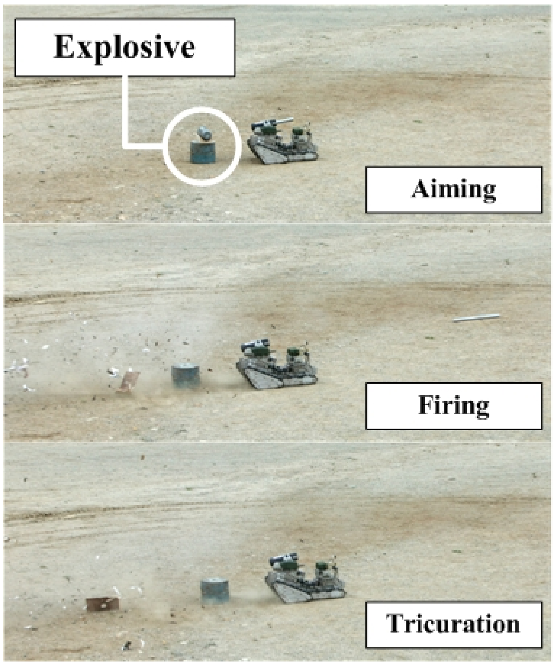


Fig. 13 Demonstration of shooting a water-bullet from a water disrupter

4.2 Demonstration and Practical Use

Fig. 13 shows a demonstration of shooting a water-bullet from a water disrupter mounted on the ROBHAZ-DT3. This demonstration was conducted in cooperation with the Korea Zaytun division for peace and reconstruction in Iraq in August 2004. Also the robot is applied to military tactics in Iraq and the feasibility of the ROBHAZ-DT3 is verified

5. CONCLUDING REMARKS

In this work, a passive double-track mechanism has been designed, analyzed and developed for rescue applications in hazardous environment. By means of dynamic analysis and simulation, significant design criteria are obtained as well as design parameters such as dimension of the track, minimum length of the whole body. The maximum driving torque for the spin motion of the vehicle is computed and is useful to choose driving motors with other criteria. A semi-automated mapping and localization method is developed for the rescue application. From the stair climbing experiments and participation in the RoboCup2004, it is verified that the ROBHAZ-DT3 is reliable in traveling rugged terrain and the proposed mapping method is effective in mapping and localization in the unstructured environment. Also the EOD version of ROBHAZ-DT3 is developed and we apply the robot system to the area of military tactics in Iraq. Consequently, the feasibility of the military version of the ROBHAZ-DT3 is verified.

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