The 2010 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 18-22, 2010, Taipei, Taiwan

# Improvement of the Remote Operability for the Arm-Equipped Tracked Vehicle HELIOS IX

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***Abstract*—This work presents the development of an arm-equipped tracked vehicle named HELIOS IX for search and rescue tasks in urban environments. HELIOS IX operator has to tele-operate several tasks such as opening of doors, negotiation of stairs and handling objects. However due to the complexity and kinematics of the system, these tasks are difficult to be carried out without some level of automation. This study proposes one of the shared autonomy type operator-supporting system for HELIOS IX. It is based on a laser range finder (LRF), finger-attached LED beam guiding systems and on a finger 3 axes force sensor interfaced by a novel reinforcing metal plate. Carrying out several experiments we could demonstrate that, tele-operation task can become easier by the introduction of the 3D space approaching assistance of the LRF, object grasping assistance of the LED beams attached on the fingers, and by the force following assistance of the force sensor attached to the wrist.**

## I. INTRODUCTION

Gathering information in a building polluted by BC terrorism is a very important task as well as the rescue and the urgent medical treatment for survivors. With the advance of technology and research, robots are expected to become a neuralgic supporting tools for responders. Mobile platforms are required to demonstrate the ability to open doors, negotiate stairs, handling suspicious objects while being remotely controlled. Various robots and system for this purpose have been developed and proposed. The robot introduced in [1] can move on stairs and open doors by using 2 robotic arms. However robot and controller are rather big and while they can be applied for tasks in nuclear plants, for search and rescue operations they would result in a bulky and difficult to be deployed solution. [2] proposes a platform capable of opening doors too. Though this robot cannot pass the door with the only operation of its arm, it can push or pull doors by a suction disk mounted on its front. The above systems have all a man in the loop, however fully autonomous systems on the other hand, have been studied and developed for home applications. For this kind of approaches, several issues must be addressed in order to have autonomous machines capable of interacting with the home environment. In the case of the robot presented in [3] it is assumed to know the position of the door and its knob. The robot can then open doors automatically. In [4], a laser range finder is utilized to recognize the door and its knob autonomously. The autonomous behavior of the above mobile platforms shows excellent capabilities, however, the recognition of doors, knobs, and the generation of the opening motion needs a lot of computational power due to the calculation complexity. Our research targets time-sensitive situations carried out with HELIOS IX platform:

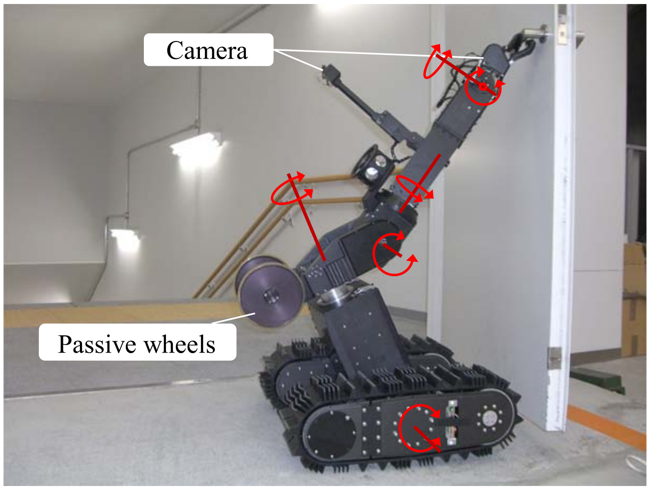

Fig. 1. Developed arm-equipped tracked vehicle HELIOS IX

1) The approach of object with the manipulator
2) Grasping objects
3) Rotating doorknobs or valves
4) Opening doors

Making use of camera images, the proposed system aims the support of rescue team. This study propose one of the shared autonomy[5] type operator-supporting system. In other words, we proposes object recognition and judgments in which normal human capability are embedded directly in the behavior of the robot to facilitate the rescue operation. The paper is organized as follows: HELIOS IX is firstly introduced. Next, the robot architecture is depicted in details. The remote operation assisting method is also introduced and it is verified through experiments carried out with the platform.

## II. HELIOS IX

HELIOS IX shown in Figure 1 is equipped with a 6-degree-of-freedom manipulator that can carry loads and open doors. The arm is installed in the center of a 2 tracks unit base that enables HELIOS IX to climb stairs and run at 7 km/h on flat surfaces as described in [6]. For the remote control, 2 cameras, an inertial motion unit sensor, a laser

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TABLE I

HELIOS IX SPECIFICATIONS

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

range finder, and a 3-axis force sensor are mounted on the vehicle. HELIOS IX specifications are shown in TABLE I.

Communication between the user and the robot can be by tether cable using a special reinforced optical fibers or wireless LAN. The operator can confirm the scenario by the camera images and the robot 3D model displayed on the graphic user interface (GUI). The robot sends to the user each joint angle, values of acceleration and gyro sensors and an estimated (by dead-reckoning) robot location on the ground plane. The robot 3D model reflects these information. The operator can control intuitively the 6 dof arm and tracks by a NINTENDO (R) Wii controller as introduced in [7]. The wrist position (x, y, z) in the space is utilized for the inverse kinematics control of the manipulator while the wrist orientation reflects the one of the operator wrist as the controller is equipped with attitude sensors.

## III. INTRODUCED TELE-OPERATION SUPPORTING SENSORS

In this section we introduce the type of sensors that were installed on HELIOS IX in order to improve the operations from a remote areas.

### A. Wrist mounted Laser Range Finder

A Laser Range Finder is installed on the top of the special wrist of the robot arm. In general when operating a robot from a remote area, it is difficult to get a correct understanding of the depth using camera images only. If a correct 3D relative position of a target with respect to the robot position is measured, we can expect to have an improvement of the remote operation with a consequent decrease of required time to carry out the operation. To acquire 3D information of environment, modern laser range finders and stereo-vision cameras are utilized. In general stereo vision cameras present a lower resolution in the measurement of 3D points coordinates, however the real-time performance and price are merits if compared to the one of a laser range finder. In this research, a compact 2D laser range finder (Hokuyo URG-04LX) easily-available on commerce is utilized. It is mounted on the top of the wrist. Local 3D environment maps can be generated by acquiring data readings while controlling the wrist. Coordinates in the absolute frame reference are calculated by solving the direct kinematics.

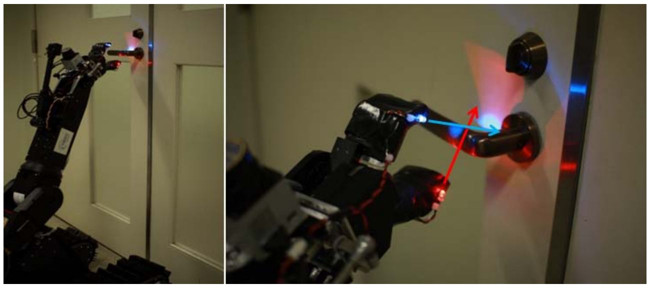


Fig. 2. Showing perspective by LED

Fig. 3. 3 Axes Force Sensor (Nitta PD3-32-10-80)

Fig. 4. Developed Elastic Plate

### B. Finger End Casting Structured Light

To provide on the GUI more understanding of the depth from camera images, we propose the use of LEDs directly installed on the gripper fingers as shown in Figure 2. In this way the intersection of the light beams can give an idea to the operator of the perspective in the camera images. For this tests we have utilized normal LEDs with 15 degree of directivity angle. However other types with different projection are under consideration.

### C. Reinforced 3 Axial Force Sensor

If the force acting on the end-effector can be measured when grasping objects or opening doors, it is possible to improve the maneuverability of the gripper and also preventing breaking the arm and/or doors. There is a great deal of research on systems making use of force sensors on the end-effector. Many of them use a 6 axis force sensor such as in [3] and in [8]. In [9] a 3 axis force sensor is instead utilized. By measuring 3 joint torques at same time it is possible to obtain the same result as in the case of a 6 axis force sensor. In this research, a 3 axis force sensor (Nitta PD3-32-10-80 as shown in Figure 3, TABLE II) was selected. This is an inexpensive sensor that offers in compact dimensions good sensibility. As with HELIOS IX the force acting point is located at the gripper fingers, moments are neglectable and not always applied.

We assume that the acting point of the force is located 10 mm ahead with respect to the position of the sensor. However, the actual acting point of the force is in the gripper, which is located about 130 mm ahead as the 3 axis force sensor is attached at the wrist as shown in Figure 5. Therefore, measurable range of x and y axis decreases greatly up to 6.2 N when using the sensor as it is. In order to amplify the range of measurable forces, it is possible to fix

TABLE II

NITTA PD3-32-10-80 SPECIFICATIONS

| | | | |
|---|---|---|---|
| Load Rating | x | 80 | Ncm |
| | y | 80 | Ncm |
| | z | 80 | N |
| Max.Static Load | x | 160 | Ncm |
| | y | 160 | Ncm |
| | z | 160 | N |
| Displacement of edge of stick | x | 0.1 | mm |
| | y | 0.1 | mm |
| | z | 0.05 | mm |

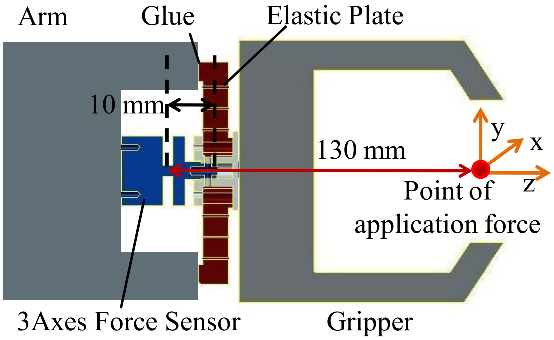


Fig. 5. Adding a elastic plate

an elastic plate as an interface between the force sensor and the robotic gripper. Thus, it is possible to measure forces acting on further location as well as near points relatively to the sensor position. The target force measurement range in the gripper was assumed to be of maximum 70 N for x and y axis. For the z axis(compression-tension) can be originally measured up to 80 N. Therefore the designed elastic plate should present friction to the motion range for x and y axis and less friction one in the z axis. Figure 4 shows the designed plate made of aluminum A2017. The particular shape was designed by using the structure analysis (Pro/MECANICA Wildfire4.0)

As what we want to measure is all the force applied, when fixing the elastic plate to the end of the forearm, it is necessary to avoid using screws that would preload the force sensor. In fact when the maximum force that is applied on the z axis on the sensor PD3-32-10-80, reaches the limit range of 80 N, the consequent displacement would be of only 0.05 mm. To leave this possible displacement available instead of using screws it was decided to glue the elastic plate to the frame of the forearm as shown in Figure 6; this can prevent causing preloads on the sensor.

While exerting a force on x, y, and z axis the output of the sensor was measured to confirm the measurable force range. Figure 7 shows the measurements with and without the elastic plate. Measurement range of x, y axis was successfully augmented by the corrections. The obtained characteristic that meets almost the desired specification is depicted in (TABLE III ).

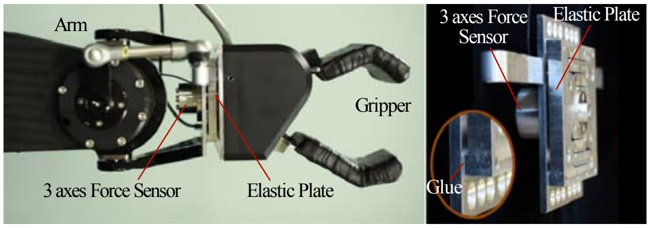


Fig. 6. Assembled force sensor and elastic plate

TABLE III

NEW MEASUREMENT RANGE

| | | Original range | New range |
|---|---|---|---|
| Load Rating | x | 6.15 N | 50.5 N |
| | y | 6.15 N | 58.9 N |
| | z | 80 N | 88 N |

## IV. ASSISTANCE METHODS AND EXPERIMENT

In this section, specific assistance methods by using sensor information presented in the previous section, are described.

### *A. Approaching an object using 3D Information*

User can retrieve information not only by the camera images (as shown in the right picture of Figure 8 ) but also from 3D local map reconstructions obtained by utilizing the data collected with Laser Range Finder. The left side of Figure 8 shows an example of a local 3D map. When the operator desires to place the end effector at a particular point in the environment it is possible to specify the coordinate of the desired point by selecting with the mouse its location on the 3D map. Consequentially by using the inverse kinematics the arm can autonomously approach the point. OpenGL is used for specifying the point coordinates. Operator, by using the joystick, can also select the approaching velocity in real-time.

### *B. Structured Light based Grasping*

As the accuracy of the laser range finder is limited, errors in reading the 3D information would remain after the approaching motion causing a slightly error between the target desired location and the real one. By installing a beam projection device in this case consisting of one LED on each finger of the gripper, it is possible to confirm by camera images, the projection of the beams over the object being approached by the gripper. In this way the GUI can give to the user, a more clear idea of the distance between fingers and object.

Figure 9 shows camera images with and without LEDs on each finger while approaching a door knob. It was confirmed that the reflection of such a light can give the possibility of improving the gripping operation as operator can see different reflections on the object. However, the optimal location of the two light beams, are currently under consideration. Eventually laser beams projecting a geometrical shape can be also utilized.

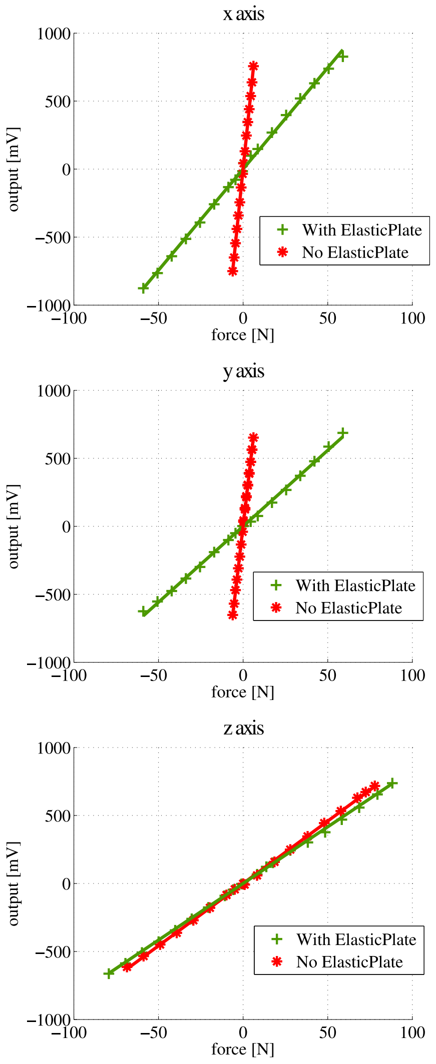


Fig. 7. Outputs of the force sensor while exerting a force on each axis

### C. *Force Based Grasping*

In this section, we introduce a simple control method that allows to control the arm end-effector position in order to cancel the force applied to the gripper.

Force vector with respect to the global coordinate reference frame $\boldsymbol{F}$ can be described as:

$$\boldsymbol{F} \quad = \quad R(\boldsymbol{\theta})\boldsymbol{F_l} \tag{1}$$

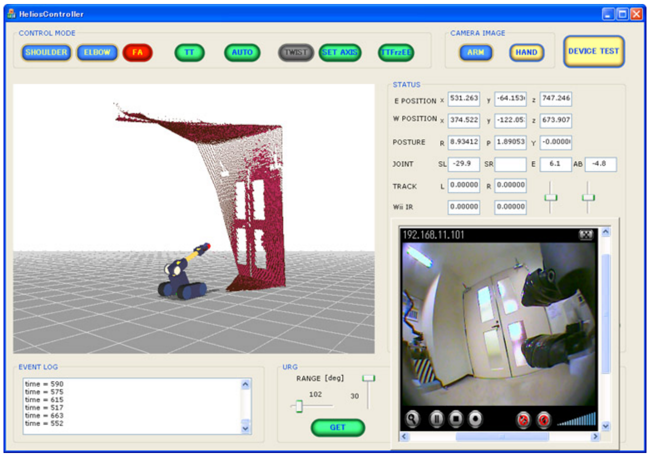
where $R$ is the rotation matrix of the force sensor reference frame from the global coordinate reference frame calculated taking into account each current joint angle $\boldsymbol{\theta}$, and $\boldsymbol{F_l}$ is the force vector composed by the 3 axis force sensor component outputs. The new reference wrist position $\boldsymbol{x_{ref}}$ is calculated using a proportional constant $\boldsymbol{k_f}$ and input from the operator $\boldsymbol{\Delta x_{operator}}$.

$$\boldsymbol{x_{ref}} \quad = \quad \sum(\boldsymbol{\Delta x_{operator}} + \boldsymbol{k_f F}) \tag{2}$$

The new joint angles to be applied for each motor, are calculated solving the inverse kinematics. Micro controllers inside the robot can complete this calculation in 30 ms. Figure 10 shows the position control loop.

On the computer graphic interface the measured force on the gripper is visually presented to operator. As shown in Figure 11, the force vector consisting of a red sphere and a vector line in the space connecting it to the end-effector is displayed on the robot 3D model.

Because of the particular mechanical configuration of the gripper (1 dof: the lower finger is fixed to the wrist while the upper one can be rotated and closed over an object) the gripper first strikes the object with the upper finger. Thus at the beginning the applied vector force is directed upward with respect to the lower finger plane. Figure 12-a shows an example of grasping without taking into account the exerted force on the wrist. The graph on the right shows the three force components. Clearly the x component as well as for the others, are overshooting due the difficulty in setting the position of the end-effector by only remote control and visual feedback. On the other hand, Figure 12-b presents the same type of experiments with using the force sensor output. By comparing the two graphs, it can be confirmed that the grasping operation is more comfortable and it causes less stress on the mechanical structure of the arm (all force components are contained between +/- 20 N) as well as on the grasped object. The position of the end effector command from the robot user, is corrected taking into account the force sensor feedback, thus the gripper positioning precision level



E POSITION x 531.263 y -64.153 z 747.246
W POSITION x 374.522 y -122.05 z 673.907
POSTURE R 8.93412 P 1.89053 Y -0.0000
JOINT SL -29.9 SR E 6.1 AB -4.8
TRACK L 0.00000 R 0.00000
Wii IR 0.00000 0.00000

time = 590
time = 575
time = 615
time = 517
time = 663
time = 552

RANGE [deg] 102 30

Fig. 8. Graphic user interface

Fig. 9. Gripper camera view without LED(left), with LED(right)

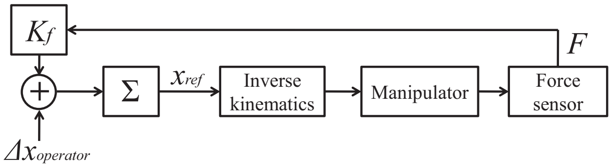


Fig. 10. Position control loop

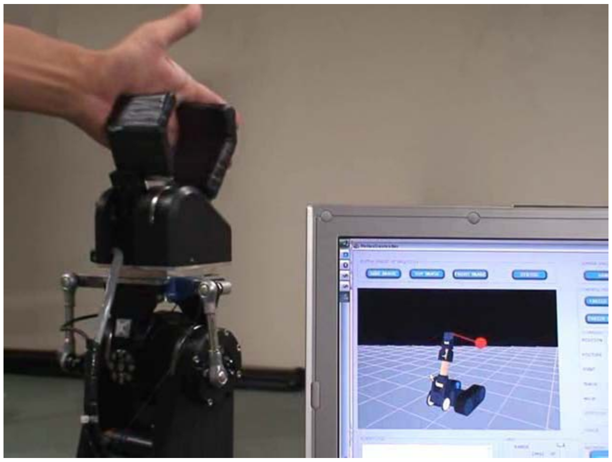
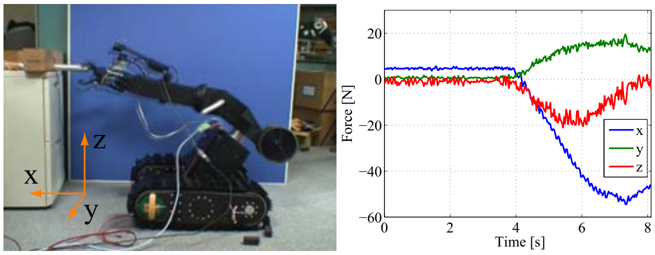


Fig. 11. Force vector displayed in GUI

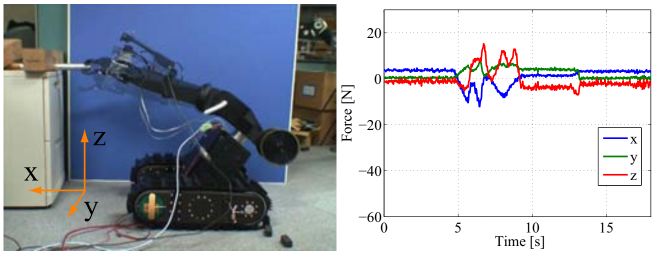
demanded to the operator is highly reduced.

### *D. Tele-operation Supported Rotation*

Many of the robots that can open doors arrange the roll degree of freedom at the end of the arm, in order to rotate the doorknob while grasping it [2][3]. In these cases it is not possible to take advantage of the use of the lever that would make the required torque smaller. HELIOS IX does not have the roll degree of freedom in end of the arm but placed before the wrist joint mechanism. In addition, when negotiating doors, it is necessary to grasp the doorknob from the bottom. In this situation, it can become difficult to rotate the doorknob with the conventional remote control because the total 6 dof of the arm are required to move simultaneously. For this reason we present the assisting system to make the doorknob rotation motion easier for the user operating from a remote area. The position and the direction of the rotation axis can be set by clicking on the 3D local map. At first a 3D local scan operation is carried out and all points are displayed on the 3D robot model image. Then operator needs to specify 3 points in order the clearly define the door plane. After this 3 points selection and after the doorknob has being grasped, the robot control mode switches to the rotation mode in which the configuration of gripper is automatically changed and set to match the rotation axis. At the same time, on the GUI, the vertical rotation axis with respect to the plane of the door is displayed between upper side of gripper and down one as depicted in Figure 13. If the doorknob is a cylinder-type one, the gripper is rotated in order to exert a rotation around the defined vector and the door is opened. In the case of lever-type doorknob, the rotational motion while grasping the lever can be easily generated by moving the rotation axis to the actual center of the handle rotation axis. then, the operator is required only to move the joystick to the right or the left.



(a) Without force feedback ($k_f = 0$ [mm/gf])



(b) With force feedback ($k_f = 0.002$ [mm/gf])

Fig. 12. Experiment of grasping objects

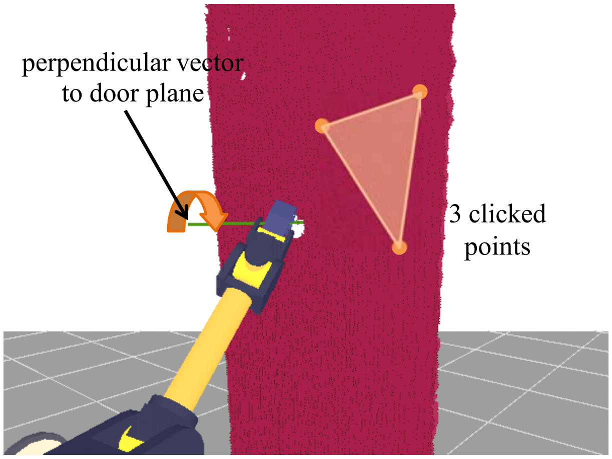


Fig. 13. Specifying the rotation axis

After several tests, the time required to carry out the operation was measured with and without respectively the force feedback and the setting of the rotation axis. Three examinee tried each combination two times. The result is depicted in Table IV. As it can be seen, on a four times trial, when neither the rotation axis is specified or force control is used, the operation was twice interrupted because of an over-current situation. When instead the rotation axis is set and the force control is utilized, the doorknob was successfully rotated in all the trials. Moreover when utilizing both the explained features, the total time for rotating the door-knob is minimized. Therefore, the effectiveness of the proposed technique was verified.

TABLE IV

AVERAGE TIME REQUIRED

| | with force feedback | without force feedback |
|---|---|---|
| with rotation axis | 77.6 s | 101.2 s |
| without rotation axis | 87.6 s | 112.5 s |

### E. Door Opening

To negotiate a door with a mobile platform, once the door-knob is successfully rotated, it is necessary to consider how to hold the door opened and how to move to the next room with only one mobile platform. To address this problem, we propose a particular procedure that makes use of the gripper and of the tracks simultaneously to fully control the position of the door once it has been opened. The motion is at the moment manually controlled. The operator sets the reference speed for the right and left track using the joystick. In general the reference speed of the gripper should be set in the opposite direction to the one of the tracks. The motion should be divided in two cases: when pushing and when pulling the door. While the end-effector keeps its posture and orientation with respect to the door-knob, the track base moves. This kind of motion can be seen as the end-effector is considered as a fixed base, while the tracks unit becomes the end-effector. When opening and passing the door by a push motion, the procedure to control the robot is set as follows:

1) opening the door a little by advancing with the tracked base after having rotated the doorknob. The goal is to advance until tracks can be utilized to hold the door and avoid it from closing after the release of the gripper. Advancing to Position in which door does not close by track even if gripper is released from knob.
2) Considering the workspace of HELIOS manipulator, start to push the door at a position that is lower than the knob location.
3) Finally, while avoiding the door and the base moves in the next room, the gripper is utilized to stop the door to avoid it from closing. Also in this case the end-effector holds the posture and orientation while the base moves.

When considering the pulling motion, the whole procedure clearly gets more complex as the mobile base must first pull, then it should move backwards in order to open the door and then again forward to enter in the adjacent room. As shown in Figure 14, to facilitate this motion we propose the use of the tracks for holding the door in between the right and left track units. Moreover making a small pivot rotation of the base it is possible to further open the door.

The proposed procedure has the following steps:

1) Pulling the door after rotating the doorknob. Then, the gripper is rotated around the orbit of the door using the same force control as explained in section IV-C (Figure 14-a, 14-b, 15-2 and 15-3).
2) While holding the door knob with gripper, set the door between the right and left track, so that the door does not close even if gripper is released from knob. (Figure 14-c and 15-4). In this case the gripper keeps the posture and orientation while the base moves.
3) the gripper is released from knob and utilized to hold the door once it is opened. (Figure 15-5 and 15-6)
4) Change the motion direction for the tracked base and passing the door with holding it with the gripper so that it does not close by using the operation mode described above. (Figure 15-7 and 15-8)

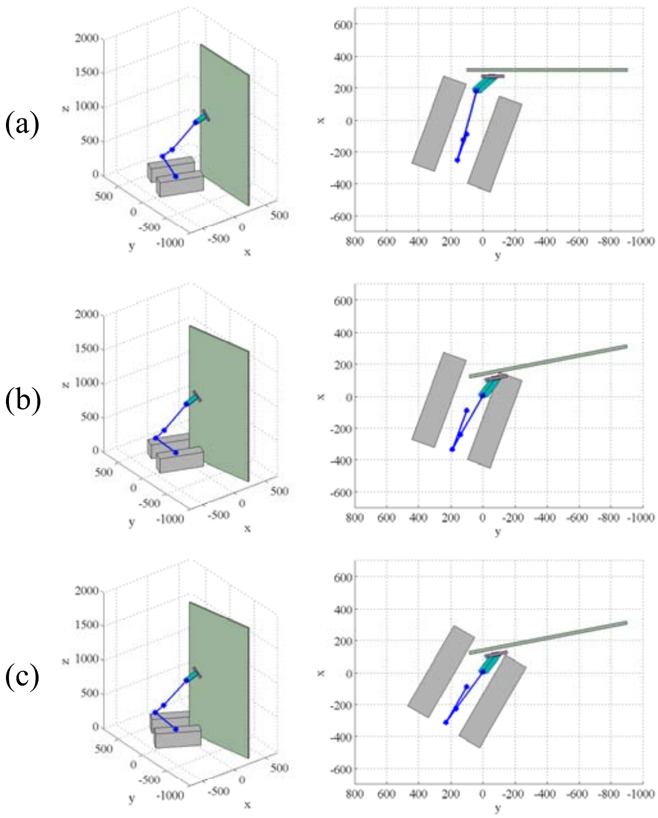


Fig. 14. Pull-type door opening flow

## V. CONCLUSIONS AND FUTURE WORKS

A new system for assisting rescue team operations from remote areas has been proposed. We first introduced the use of sensors for the robotic platform HELIOS IX. Laser range finder has been utilized to give to the robot operator 3D information of the scenario, while a 3 axis force sensor is utilized to measure forces applied on the end-effector. To absorb eventual extra force and to amplify the force measurable range a special elastic plate has been designed and mounted as an interface between the sensor and the wrist. By using these sensor information, specific assistance methods for approaching and grasping of objects, rotating doorknobs or valves and opening doors were proposed and verified throughout practical tests. By making use of the sensors installed on board and of the proposed methods the total required operation time to carry out each motion has been reduced. We will make the system that assists the operation further advanced, and try shorten the operation

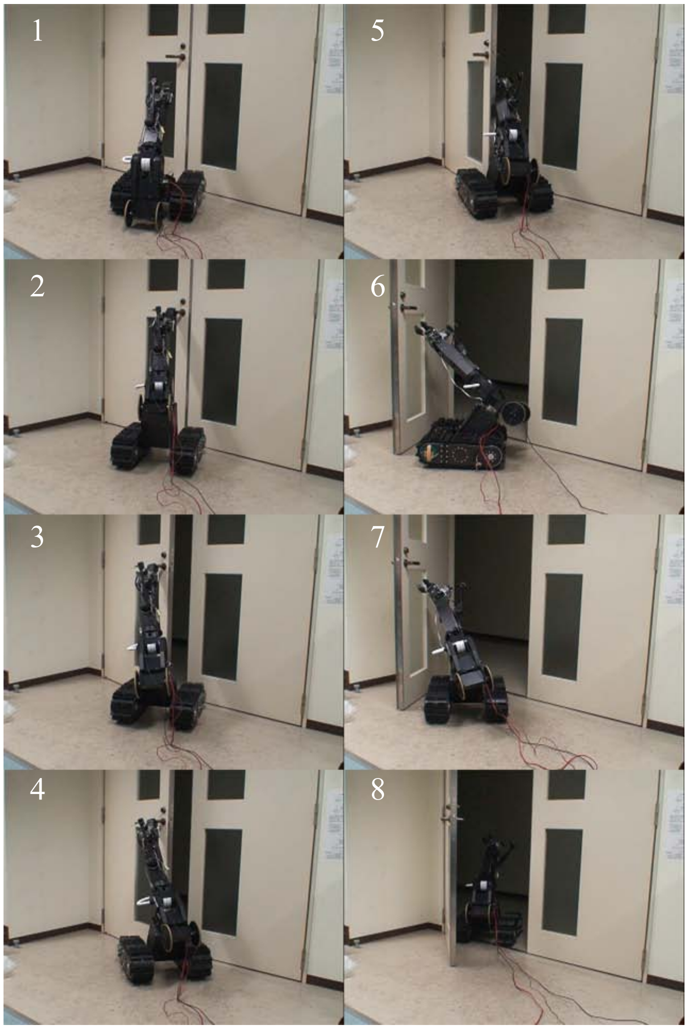


Fig. 15. Pull-type door opening experiment

time. In addition, as the robot is being under tests in a special field area, authors will collect feedbacks from first responders to further confirm the capability of the proposed shared autonomy.

## REFERENCES

[1] K. Oka and K. Shibanuma, "Development of radiation-proof robot," in *Advanced Robotics*, vol. 16(6), pp. 493–496, 2002.

[2] S. Kobayashi, Y. Kobayashi, Y. Yamamoto, T. Watasue, Y. Ohtsubo, T. Inoue, M. Yasuda, and T. Takamori, "Development of a door opening system on rescue robot for search "UMRS-2007"," in *SICE Annual Conference, 2008*, pp. 2062–2065, 2008.

[3] K. Nagatani and S. Yuta, "Designing a behavior of a mobile robot equipped with a manipulator to open and pass through a door," *Robotics and autonomous systems*, vol. 17, no. 1-2, pp. 53–64, 1996.

[4] R. Rusu, W. Meeussen, S. Chitta, and M. Beetz, "Laser-based perception for door and handle identification," in *Proceedings of International Conference on Advanced Robotics*, 2009.

[5] S. Hirai, "A theoretical view of shared autonomy," *Journal of Robotics Society of Japan*, vol. 11, no. 6, pp. 788–793, 1993.

[6] M. Guarnieri, I. Takao, P. Debenest, K. Takita, E. Fukushima, and S. Hirose, "HELIOS IX tracked vehicle for urban search and rescue operations: Mechanical design and first tests," in *IEEE/RSJ International Conference on Intelligent Robots and Systems, 2008. IROS 2008*, pp. 1612–1617, 2008.

[7] M. Guarnieri, R. Kurazume, H. Masuda, T. Inoh, K. Takita, P. Debenest, R. Hodoshima, E. Fukushima, and S. Hirose, "HELIOS system: A team of tracked robots for special urban search and rescue operations," in *IEEE/RSJ International Conference on Intelligent Robots and Systems, 2009. IROS 2009*, pp. 2795–2800, 2009.

[8] L. Petersson, D. Austin, and D. Kragic, "High-level control of a mobile manipulator for door opening," in *Proc. of IROS*, 2000.

[9] J. Kang, C. Hwang, and G. Park, "A Simple Control Method for Opening a Door with Mobile Manipulator," in *ICCAS*, vol. 2003, pp. 1593–1597, Citeseer, 2003.