1-1-2013

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Abstract

It is well known that haptic feedback can facilitate the tele-operation of a remotely controlled robot by providing the user with intuitive tactile and/or force sensations from the robot's interactions with the environment. However, such mechanical haptic feedback systems can be complex, cumbersome, costly and application specific. This paper presents a novel tele-operation haptic feedback system that overcomes many of these limitations by providing electro-tactile feedback to the operator via wireless electrodes placed on the operator's skin. We show that this form feedback can provide a viable substitute for force and tactile feedback systems without the need for mechanical linkages or actuators. Experimental results are provided showing how electro-tactile feedback can facilitate the tele-operation of a mobile robot by improving the user's.

Keywords

mobile, operation, tele, robot, feedback, electro, tactile

Disciplines

Engineering | Science and Technology Studies

Publication Details

Pamungkas, D. & Ward, K. (2013). Electro-tactile feedback for tele-operation of a mobile robot. 2013 Australasian Conference on Robotics and Automation (pp. 1-7). Australia: Australian Robotics & Automatioin Association.

Proceedings of Australasian Conference on Robotics and Automation, 2-4 Dec 2013, University of New South Wales, Sydney Australia

Electro-Tactile Feedback for Tele-operation of a Mobile Robot

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Abstract

It is well known that haptic feedback can facilitate the tele-operation of a remotely controlled robot by providing the user with intuitive tactile and/or force sensations from the robot's interactions with the environment. However, such mechanical haptic feedback systems can be complex, cumbersome, costly and application specific. This paper presents a novel tele-operation haptic feedback system that overcomes many of these limitations by providing electro-tactile feedback to the operator via wireless electrodes placed on the operator's skin. We show that this form feedback can provide a viable substitute for force and tactile feedback systems without the need for mechanical linkages or actuators. Experimental results are provided showing how electro-tactile feedback can facilitate the tele-operation of a mobile robot by improving the user's perception and interaction with the environment.

1 Introduction

Despite recent advances in autonomous control systems many tasks performed by robots or machinery still cannot be done autonomously. This is mainly due to human skills or judgment being required to perform such tasks. Consequently, the tele-operation of robots and equipment is finding increased applications in research and industry. Typical applications include mining machinery [Sungsik, *et al.*, 2011], underwater maintenance [Boyle, *et al.*, 1995], bomb disposal [Kron et al., 2004], hazardous waste removal [S. Hirche and Buss, 2003], space missions [Sheridan, 1993] and tele-surgery [King, *et al*, 2009].

Tele-operation requires careful monitoring (or feedback) of the remote work area and appropriate remote control of the robot via some sort of user interface (e.g. joystick, control panel or data glove.). Remote cameras and video monitors typically form the most common type of feedback systems used for tele-operation, e.g. [Zhang and Ostrowski, 2002; Kai-Tai. and Wen-Hui, 1996]. However, video feedback alone is often not sufficient to convey the "reality" of the robot's world or the "sensations" produced from the robot's interactions with the environment. [Klein, 1977].

To enable the operator to perceive a more realistic view of the robot's world and experience sensations felt by the robot from its interactions with the environment, researchers have been experimenting with various types of haptic feedback systems [Tsetseruko, *et al.*, 2009].

"Haptic" comes from Greece word, "Haptesthai" which means "of" or "relating to" the sense of touch [El, 2007]. Most haptic feedback systems are aimed at reproducing tactile or force sensations so that the operator can better interpret the remote environment or interact with it more appropriately [Paterson, 2007].

Furthermore, haptic feedback, in the form of tactile and/or force sensing combined with immersive video feedback, via a VR headset, can give the operator a sense of being present in the remote environment (tele-presence) which can further improve the ability of the operator to perform the required task [Paterson, 2007].

Most force and tactile haptic feedback systems are comprised of various mechanical linkages and actuators for delivering the force or tactile sensations to the operators hands or other parts of the body. This can make such systems rather complicated to construct, awkward to setup, cumbersome to wear and costly. They can also be somewhat time consuming to restructure or reconfigure for different applications.

To overcome many of these drawbacks we have been experimenting with electro-tactile feedback. This involves attaching adhesive electrodes to the operators skin and applying a mild electric current to stimulate nerves within the skin. Although electro-tactile feedback cannot replicate "force" feedback directly, it can be used to deliver a wide variety of sensations, by modulating both the intensity and frequency of the electrical stimulus making it suitable for providing feedback from a variety of environment sensors.

Previously, we have shown how electro-tactile feedback can be used to facilitate manipulating a robot arm and performing certain tasks like placing a peg in hole via tele-operation [Pamungkas and Ward, 2013]. In this paper we provide details of how electro-tactile feedback can be used to facilitate the tele-operation of a mobile robot.

In Section II we outline previous research on the tele-operation of mobile robots with haptic feedback. Section III provides details of our electro-tactile feedback system applied to controlling a mobile robot. Section IV provides experimental results which demonstrates the potential of our electro-tactile feedback system at assisting the operator to avoid obstacles and relocate objects with a tele-operated mobile robot. In section V we provide concluding remarks and further work.

2 Background

Researchers have been using haptic feedback to facilitate the tele-operation of mobile robots for some time. The two most common forms of haptic-feedback used to facilitate the tele-operation of mobile robots are force feedback and vibro-tactile feedback.

Force feedback involves the use of a haptic feedback device that typically gives positive feedback to a hand or fingers when the mobile robot detects an obstacle with its sensors and obstacle avoidance is required to prevent a collision.

Some researchers have utilized commercial haptic force feedback interfaces for the tele-operation of a mobile robot such as Phantom [Geomagic, 2013]**,** e.g. [Nadrag, *et al.*, 2011]. In this work seven ultrasonic sensors mounted on a mobile robot provide range information of the surrounding environment. This information is then processed into resistive forces applied to a control lever to assist the user with avoiding obstacles. Similarly, [Seung Keun, *et al.*, 2010], used a force feedback joystick implemented with a rotating magnetic field to tele-operate a mobile robot for avoiding obstacles.

In [Ba-Hai and Jee-Hwan, 2010], a force feedback system was implemented by using dc motors to apply forces to a joystick for the teleoperation of wheeled and tracked vehicles. This arrangement allowed sensor information on the surface conditions to be processed and converted into force feedback for providing proportional speed control of the vehicle based on the steering angle. Force feedback joysticks have also been deployed on powered wheelchairs to assist with avoiding collisions with walls and objects, e.g. [Fattouh, *et al.* 2004].

Although these haptic force feedback systems have shown promise in facilitating the control of mobile platforms, they are limited to restricting the control actions the user can apply to the platform and do not provide any additional perception of the environment via the haptic interface.

To provide additional perception of the environment using haptic feedback, for the tele-operation of mobile robots, researchers have devised various vibro-tactile interfaces. For example, [Tsetserukou, *et al.* 2011] devised a belt tactile interface which is fitted to the operator's waist. Data from a laser range finder mounted on a robot is sent to the vibro-tactile belt so that the user can “feel” the environment and be more aware of any obstacles that may not be visible on the video feed.

This device has been shown to be able to resolve the profile of obstacles surrounding the robot, however, wearing a belt full of vibro-tactile actuators is somewhat awkward, cumbersome and limited in application.

To provide a more versatile haptic interface for tele-operating robots we have been experimenting with electro-tactile feedback. This has been shown to be capable of providing the user with a wide range of sensations almost anywhere on the skin and can be configured to avoid the skin from becoming desensitized to prolonged electrical stimuli. [Peruzzini, 2012; Meers, and.Ward, 2004]. Other advantages are that electro-tactile feedback is relatively cheap to construct. It can deliver a wider information bandwidth than vibro-tactile feedback and can be used to deliver feedback from a variety of sensors for different applications. The following sections provide details of our electro-tactile feedback system applied to the tele-operation of a mobile robot.

3 Controlling Mobile robot with Electro Tactile Feedback

To test the effectiveness of our electro-tactile feedback system we equipped a mobile robot with a camera, distance sensors and a gripper limit switch, as shown in Figure 1. Information from these sensing devices is transmitted wirelessly to the receiver station connected to the operator's computer, as shown in Figure 2.

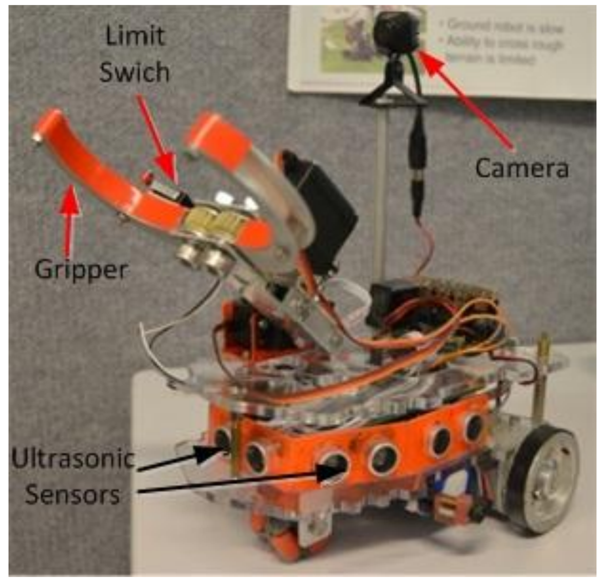

Figure 1. Mobile robot.

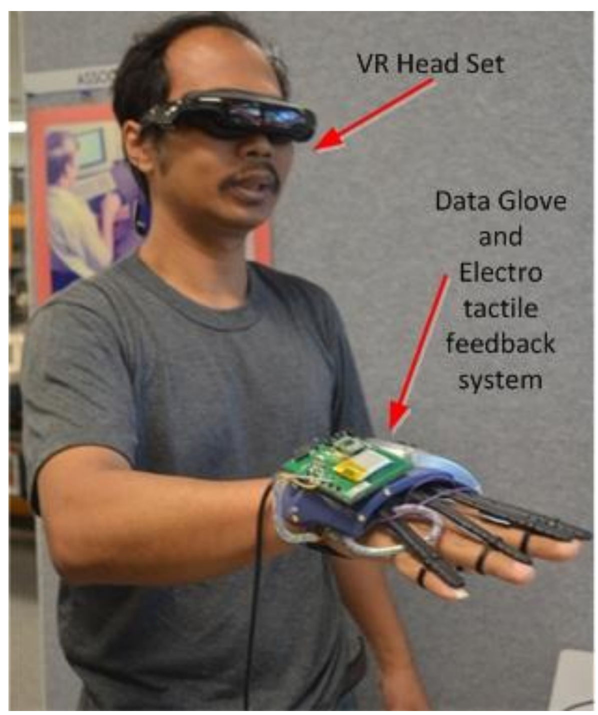

Figure 2. User with data glove and the feedback system

The camera enables the user to view the immediate environment in front of the robot via the VR headset shown in Fig. 2. Information from the robot's range sensors and gripper limit switch is delivered to the user's skin via TENS electrodes fitted to a data glove, as shown in Fig. 2. This enables the user to feel the presence of obstacles in the near vicinity of the robot via electro-tactile feedback. The data glove also has finger bend sensors and a tracking system which enables it to convert hand gestures into control commands to the robot. This control-feedback system is intended to make the user's hand feel as if it is "immersed" or "gloved" into the mobile robot and capable "feeling" its sensor stimulus and directing its motion.

Figure 3 shows an overview of the electro-tactile tele-operation systems. This control feedback loop communicates with the robot wirelessly and operates at a frequency of 5 cycles per second.

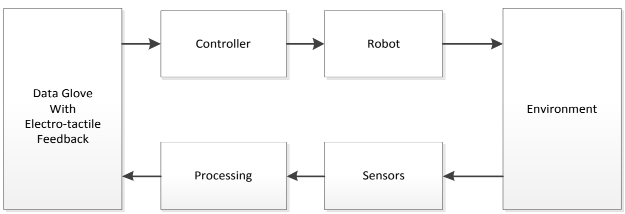

Figure 3. Block diagram of electro-tactile tele-operation system

The implementation details of the electro tactile feedback system, robot, sensors and the data glove are provided in the following sections.

3.1 Mobile Robot and Feedback System

The mobile robot measures approximately 20 cm x 13 cm x 20 cm (L x W x H), as shown in Figure 4. It has two drive wheels, one idler wheel and a gripper which is suitable for picking up drink cans. The robot has a maximum speed of 20 cm/s in the forward and reverse directions and is equipped with an xbee wireless modem for communications between its main processor and the host computer. The robot is also equipped with a wireless video camera mounted on a turret for monitoring in the forward direction. This camera is wirelessly connected to the VR headset shown in Figure 6. Six SRF05 ultrasonic sensors and one limit switch are used for sensing obstacles in the environment as well as the presence or absence of an object in the gripper.

Figure 4 and 5 show a photo of the robot in its environment and a snapshot of the settings window of the electro-tactile feedback system, respectively. The settings window (Fig. 5) allows the user to view the values of the feedback signals returned from the robot and the live video feed from the camera. Sliders are also provided for setting the maximum speed of the robot as well as the maximum and minimum intensity and frequency of the electro-tactile feedback signals. The VR head set, shown in Figure 6, also receives the video feed from the robot's camera and is for providing the user with an immersive First Person View (FPV) of the robot's environment.

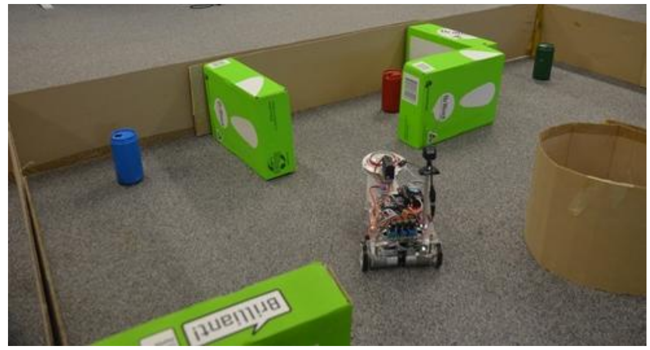

Figure 4. Robot and environment

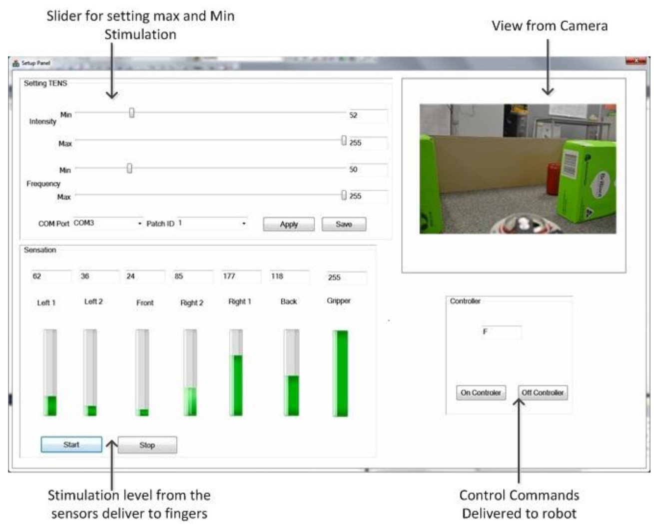

Figure 5. Electro-tactile feedback settings window.

Figure 6. VR head set.

The ultrasonic range sensors are mounted on the body of the mobile robot and are for detecting objects in the near vicinity of the robot. One sensor is facing the forward direction (or 0^0). Two sensors are aimed right and left (90^0 and -90^0) and the other two sensors are aimed at $+45^0$ and -45^0 off-set from the front of the robot. Another distance sensor is facing the reverse direction of the robot. For this experiment, we set the maximum and minimum range the ultrasonic sensors to 75 cm, and 4 cm respectively.

To avoid crosstalk between ultrasonic sensors, the front, rear and side sensors are fired and read first, followed by the two 45^0 sensors. To retain the sensor readings a local occupancy grid is used with a cell size 10 cm and a minimum side length of 1.5 m. A local occupancy grid is an occupancy grid where the grid remains fixed relative to the robot position, as shown in Figure 7. An inverse sensor model algorithm is used for updating the occupancy grid elements [Thrun, *et al*, 2005]. To obtain the four feedback signals from the sonar sensors (i.e. front, back, left & right), we divide the region surrounding the robot into four overlapping sectors. These sectors are further divided into four regions defined by concentric circles which decide the intensity of the feedback signals (i.e. very close, close & near). The closest occupied elements of the occupancy grid are used to determine the appropriate feedback signals.

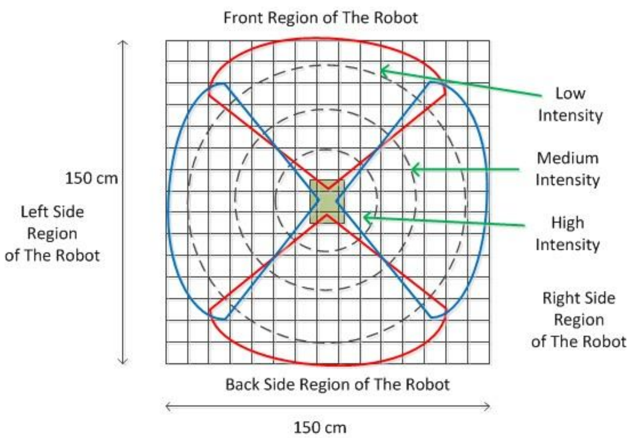

Figure 7. Occupancy grid and feedback signals

A fifth feedback signal is derived from a limit switch fitted to the robot's gripper to indicate if an object is present in the gripper. This feedback allows the camera to be aimed higher as it is not necessary for the camera to be aimed at the gripper when it is picking up a can.

3.2 Data Glove

We use a P5 Virtual Reality Glove to control the movement of the mobile robot, as shown in Figure 8 and 9. This data glove can give coordinates x, y, z of the glove's position as well as the roll, pitch and yaw orientation of the glove. The glove can also provide information on the bend position of all five fingers. There are also three buttons mounted on the back shell for providing additional signals from the glove. To read the data glove's position and state, the glove is placed in front of the receptor tower shown in Figure 8. A custom built five channel electro-tactile feedback unit is mounted on the glove's back shell, as shown in Figure 8. Each output is attached to electrodes mounted on the bend sensors, as shown in Figure 9. To facilitate conduction the user applies a small amount of conductive gel to the back of the fingers prior to fitting the glove.

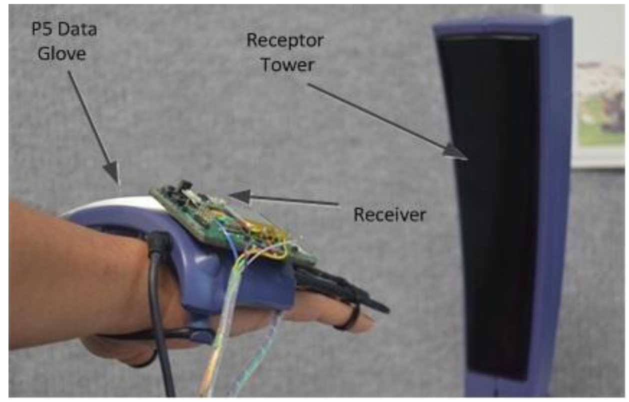

Figure 8. Data Glove with feedback unit and receptor tower.

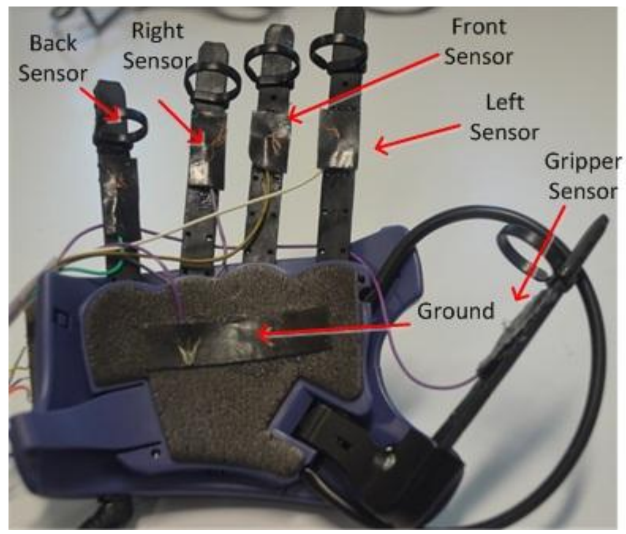

Figure 9. TENS electrodes fitted to data glove.

The mobile robot has two speeds and has commands to move forward, backward, pivot, and arc. To map hand gestures to the robot's control signals we use the glove's pitch to control the forward/reverse direction and roll to control the left/right motion. Bending the middle finger raises and lowers the gripper. The thumb is used to open and close the gripper. This protocol was found to be sufficiently intuitive for the user to be able to control robot within its workspace without much practice being required.

3.3 Electro Tactile Feedback

A custom built five channel wireless TENS system is used to deliver sensor information from the robot to the user, as shown in Figure 10. This system is gives five channels of TENS stimulus to the user’s skin with both controlled frequency and intensity. The electro tactile system is comprised of a USB transmitter, shown in Figure 10a, and the self contained receiver unit shown in Figure 10b. The receiver unit receives its data wirelessly and converts this information into 5 channels of electrical pulses, as shown in Figure 12. These pulses are then delivered to the electrodes to provide variable stimulus to the user's fingers.

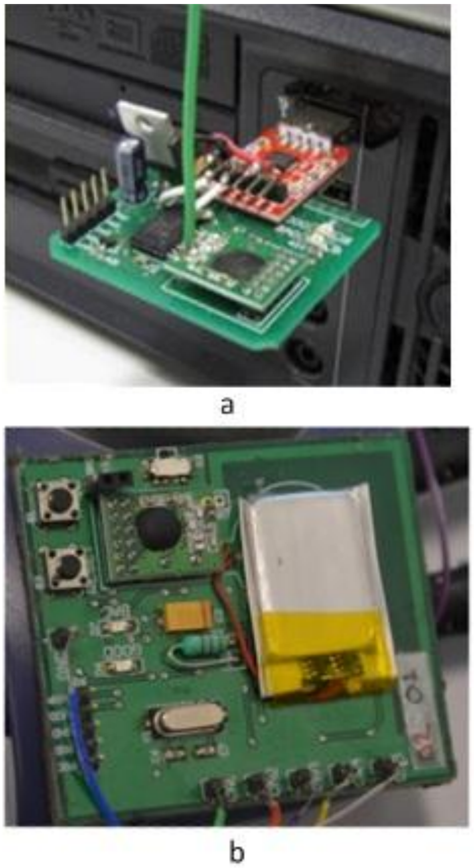

Figure 10. a. TENS transmitter. b. USB receiver

The feedback electrodes are placed on the data glove so that they make contact with the back of the users fingers, as shown in Figure 11. The ground of the receiver is connected to the electrode which placed in the centre of the back of the hand. This arrangement allows the user to receive five channels of stimulus information via the fingers as explained in Section 3.2. As the electrodes are not directly stimulating mussels they do not cause the hand to contract. In fact, for this experiment the stimulus is mild and completely painless.

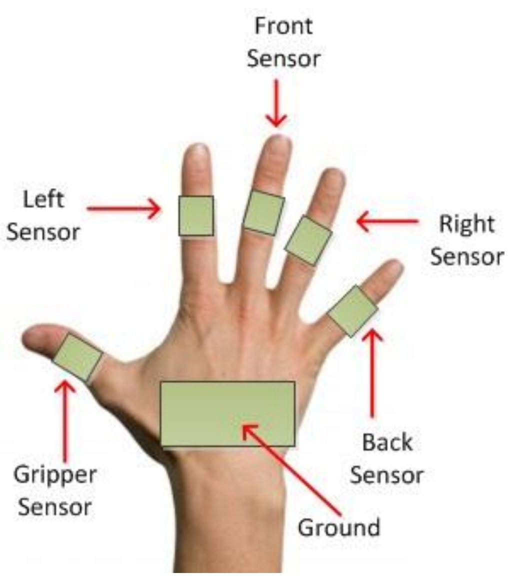

Figure 11. Position of the feedback electrodes

The feedback stimulus is delivered via pulses with the frequency set at 20Hz, as shown in Figure 12. The amplitude of the pulses are set within the range 40V to 80V depending on user comfort. To control the intensity, the pulse width of the signal is varied between 10 to 100μs, depending on the signal from the robot's sensors.

Figure 12. TENS output waveform

4 Experimental Methods

This section addresses to demonstrate the effectiveness of electro-tactile feedback system. The tele-operation experiment is conducted with a mobile robot fitted with the sensors as described in the previous section. The experiment is to control the mobile robot to transport cans and avoiding obstacles in a cluttered workspace.

In these experiments, the data glove is used to control the mobile robot while the user is monitoring the movement of the robot from the VR Headset. At the same time the user can feel the environment from the intensity of the signals which are delivered by the TENS electrodes on the skin of the user. The intensity from the TENS electrodes depends on the readings from the robot's sensors. For example, low stimulus from a specific electrode, linked to a specific distance sensor on the robot, indicates that an object has been detected far to the corresponding sensor and vise-versa.

Figure 13(a) and 13(b) shows the environment the mobile robot is to negotiate. This environment is setup to test the ability of our electro-tactile feedback system at improving a tele-operation task which involves relocating cans while avoiding obstacles. Some places in this environment require the user to rely on the electro-tactile feedback because the visual feedback cannot be used to see all obstacles in the path of the robot, especially when the robot reverses. The task involves placing the mobile robot in the environment near position A and then relocating the can at position A to position F. The can at position B is then moved to position A. This is repeated until all 5 cans have been relocated to their preceding position.

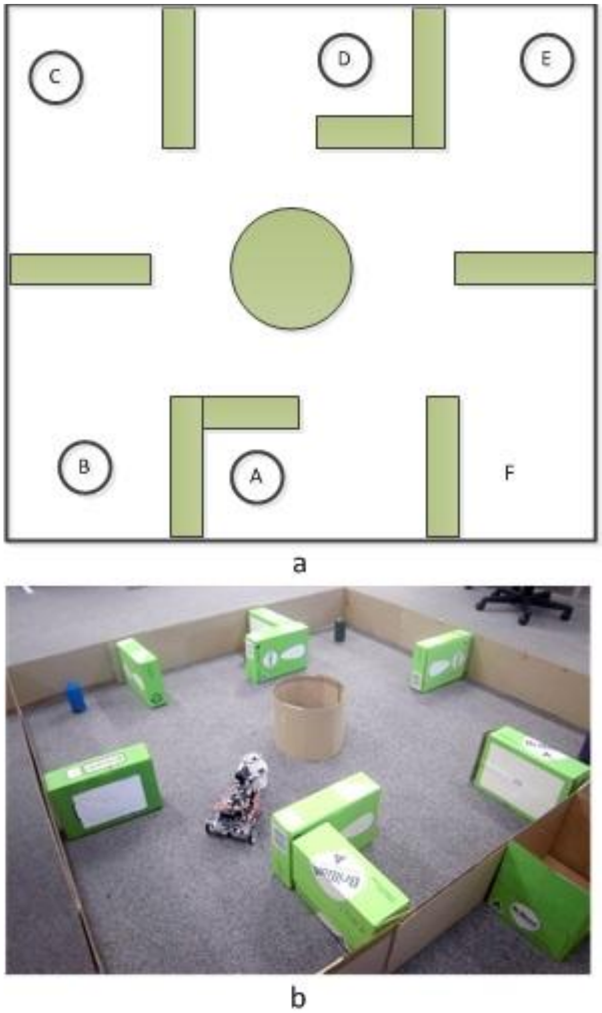

Figure 13. Obstacle avoidance obstacles experiment setup

To test the potential of the feedback system, different users were asked to conduct trials. All of the users have no experience at performing this task. Before controlling the robot, the users are fitted with the data glove and asked to adjust the level of intensity of the TENS electrical signals to appropriately feel sensation according to the distance between the robot and obstacles. The user feels the strongest sensation if obstacles are in the minimum range (3 cm), on the contrary, the user feels a light sensation if the robot is in the middle of the path (25 cm or greater from obstacles).). Each user was given ten minutes to practice controlling the mobile robot using a data glove both with and without electro-tactile feedback. This was to enable each user to familiarize themselves with the control of the robot and the distance sensations so that they can estimate the approximate distance between the robot and the obstacles. Stimulation from the force sensor associated with gripping an object was calibrated to range from zero (indicating gripper held nothing) to mild intensity (indicating a cylinder is held by the gripper

We compared the time it took for each user to accomplish the task using only visual feedback and with visual feedback enriched with electro-tactile feedback. All users reported that the electro-tactile feedback enable this task to be completed considerably faster and with less collisions with obstacles.

5 Result and Discussion

The experimental results show that users have difficulty controlling the robot using only visual feedback because of the amount of obstacles in the environment and the limited visual field provided by the camera. Enhancing the visual feedback with electro-tactile feedback showed that the users could operate the robot more competently, because with electro tactile feedback, the operator can “feel” the surrounding obstacles and steer the robot to avoid them. The results also show that the users are able to learn to interpret the information sent via the electro-tactile feedback relatively quickly and use this information to control the robot more effectively. Users also reported that the electro-tactile feedback system can make the hand feel immersed in the robot and capable of "feeling" what the robot experiences. Furthermore, this tactile feedback system is simpler than other haptic feedback techniques because it requires no cumbersome electro-mechanical actuators and linkages to provide the tactile feedback.

6 Conclusion and Future Work

This paper has presented a novel mobile robot tele-operation system involving a data glove, for controlling the robot, and an electro-tactile feedback system for assisting the user to perceive the environment. The electro-tactile feedback is comprised of distances range sensors and a limit sensor, which is mounted on the robot, and wireless electrodes placed on the back of the glove for providing the feedback. The experimental results show how this system can help the user achieve immersive control of a mobile robot for collecting and placing cans in a cluttered environment.

In future work, we intend using electro-tactile feedback for other tele-operated robotic applications which involve more complicated and delicate tasks. We also intend exploring the possibility of using electro-tactile feedback for providing touch sensations to amputees with prosthetic limbs.

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