Haptic teleoperation of mobile robots for augmentation of operator perception in environments with low-wireless signal

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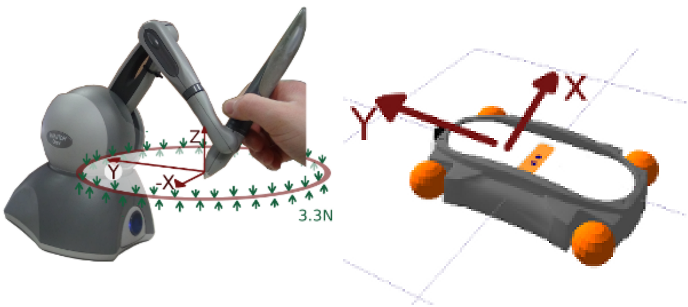
***Abstract*—Wireless teleoperation of field robots for maintenance, inspection and rescue missions is often performed in environments with low wireless connectivity, caused by signal losses from the environment and distance from the wireless transmitters. Various studies from the literature have addressed these problems with time-delay robust control systems and multi-hop wireless relay networks. However, such approaches do not solve the issue of how to present wireless data to the operator to avoid losing control of the robot. Despite the fact that teleoperation for maintenance often already involves haptic devices, no studies look at the possibility of using this existing feedback to aid operators in navigating within areas of variable wireless connectivity. We propose a method to incorporate haptic information into the velocity control of an omnidirectional robot to augment the operator's perception of wireless signal strength in the remote environment. In this paper we introduce a mapping between wireless signal strength from multiple receivers to the force feedback of a 6 Degree of Freedom haptic master and evaluate the proposed approach using experimental data and randomly generated wireless maps.**

I. INTRODUCTION

The issues of low wireless connectivity in teleoperation of field robots become increasingly important in large, unstructured environments, such as in maintenance of large scientific facilities and rescue situations [1], [2]. Several previous studies have aimed to solve the problems of high latency and areas of wireless coverage loss by increasing autonomy [3], [4]. While this autonomy can be advantageous in some robotic applications, there is still a demand for teleoperation. Unknown and unpredictable environments and operating conditions mean that operators must maintain some control over the robot in order to avoid disaster, as human operators are inherently more versatile than autonomous systems [5], [6]. One well established way of utilising this human versatility is through haptic teleoperation [7], [8], [9], [10] However, enabling teleoperation comes at the cost of higher bandwidth to provide continuous feedback to the user, which can be difficult in areas of low wireless signal. One effective way to boost wireless coverage is to implement ad-hoc wireless relay systems utilizing multiple mobile wireless transmitters [11]. As the resulting wireless coverage is unknown, human teloperators must then be supplied with information on the wireless system to avoid driving the robot into an area of low coverage. As teleoperation interfaces often already include haptic devices it may be advantageous to extend this to give the user a perception of the wireless signal. To the authors' knowledge, no previous studies have not looked at the possibility of extending this existing haptic feedback available to the teleoperator to allow them to move more naturally in these environments with unknown wireless connectivity.



(a) z-restricted haptic plane (b) Simulated youBot in Rviz.

Fig. 1: Haptic operation of Youbot mobile robot with a 6 DoF PHANToM OMNI slave with 3DoF haptic feedback in (x, y, z) direction

In this paper we propose the use of haptic feedback to give the operator of a teleoperated mobile robot a perception of the wireless signal in the remote environment to allow them to intuitively travel in areas of high wireless signal.

Maintenance tasks often involve haptic feedback to the operator anyway, to improve telemanipulation [12]. We simply propose to utilize this existing feedback to allow the operator to perceive the received wireless signal strength (RSS) through haptic feedback. We propose that this approach will be useful to allow the operator to make better decisions when driving a mobile robot. For example, if the operator feel that the mobile robot is entering an area with lower wireless signal they may choose to activate an autonomous mode, gracefully degrade the video feedback or take a different route.

This is useful when the mobile robot have to be operated in a very low radio signal region and the properties of the wireless network and the environment may not be fully known previously, due to the unknown reflection and absorption by the environment. It is important to note that our method is not designed to remove control from the operator, as automatic systems do. Instead, our method allows the operator to make better decisions of the robotic intervention with the man-in-the-loop control model.

Although four sensors are used in this study, the proposed algorithm can be extended to as many or as few sensors are available, making it very flexible - the more wireless receivers,

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the better the feedback to the operator. However, even only two sensors are available, in a left-right configuration, this will provide the operator enough feedback to naturally steer the mobile robot towards the area with better signal.

This paper is organised as follows: Section 2 describes the methodology for wireless communication modelling and the haptic control architecture for the master-slave system; Section 3 describes the experimental set-up in a simulated remote environment and Section 4 describes the results.

II. METHODOLOGY

This study uses a mobile robot and haptic master and a randomly generated environment of wireless signals, implemented in the RViz and Gazebo simulator of Robot Operating System (ROS) framework [13]. This simulated environment both allowed a larger complex environments and the possibility to create multiple, unknown wireless environments to ensure that the operator was only relying on haptic feedback for their perception of the wireless signal. For these reasons the simulated environment was preferable over the limited available physical environment.

The hardware used was an KUKA YouBot [14] (omni-directional mobile platform) as the slave robot and a PHANToM OMNI haptic pen [15] with 6 DoF as a master device, shown in Figure 1.

A. Wireless communication model

In a typical wireless network, when the connectivity worsens because of movement of the wireless receiver and/or the transmitter or change in antenna orientation, for instance, the data-rate is automatically adjusted downward to maintain the reliability in connection. However, when the radio signal power is not enough to maintain the link quality, there is a possibility of losing the communication link for some time depending on conditions such as interferences and obstructions.

According to Shannon's capacity theorem [16], the wireless communication channel capacity C is related to the signal's received signal strength (RSS) as follows:

$$C = B \cdot log_2(1 + \frac{P_r}{P_n}) \qquad [\text{Mbit/s}] \tag{1}$$

where, B is the Bandwidth of the channel and P_n is the power of the noise in the channel. This indicates that the data throughput in the wireless network, which is a measure of the channel capacity C, depends on the received signal power P_r.

The RSS P_r is equal to the difference in the transmitted power P_t and the path loss PL_d over a distance d,

$$P_R = P_T - PL_d \qquad [\text{dBm}] \tag{2}$$

The path loss PL is the attenuation in the power of the radio signal from the transmitter to the receiver and is caused by many factors such as distance (free space loss), penetration losses through walls, objects and multi-path propagation effects [17]. In particular, all walls, ceilings, and other objects that affect the propagation of radio waves will directly impact the signal strength and the directions from which radio signals are received. The path loss can be modelled as a log-normal distribution [17]:

$$PL_d = PL_{d_0} + 10n\log(\frac{d}{d_0}) + \mathcal{X}_\sigma \qquad [\text{dBm}] \tag{3}$$

where, PL_{d_0} is the path loss at a reference distance d_0, n is the environment specific propagation constant, and χ_σ is a zero mean Gaussian distribution with variance σ_x and represents the large scale fading because of shadowing effects [18]. n and σ_x define the environment together with χ_σ.

Prior to this work, we conducted an experiment to empirically determine the environmental parameters n and σ_x specific to complex environments. A wireless access point was used as a transmitter and was stationed at a point. Several wireless adapters were mounted on the Youbot mobile robot and were used as receivers. The details of wireless transmitter/receivers used in this study are shown in Table I.

	Access Point	Wireless Tranceivers
Make and Model	ProSafe, WNDAP350	ZyXEL, NWD2105
Protocol	IEEE 802.11n	IEEE 802.11n
Frequency (f)	2.4 GHz	2.4 GHz
Transmit Power (P_t)	20 dBm	15.5 dBm
Receive Sensitivity (R_t)	-	-64 dBm
Antenna Gain (G)	3 dBi	0 dBi

TABLE I: Wireless transceiver details used in this study

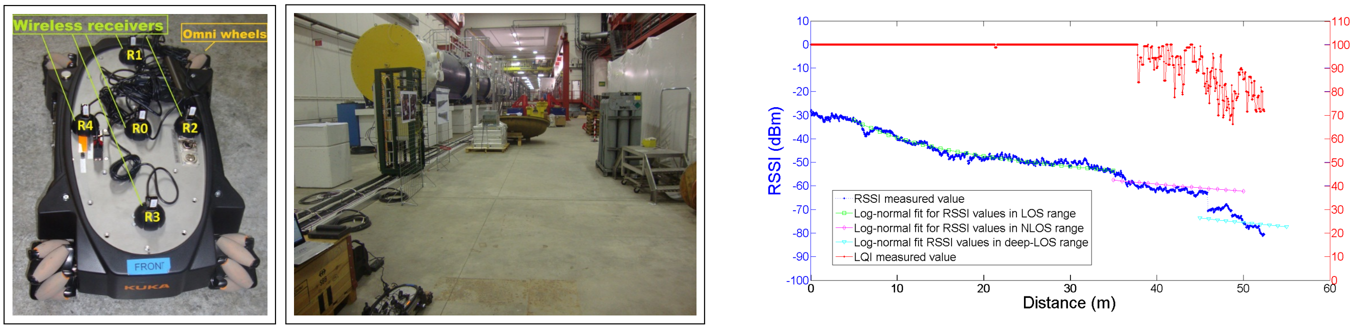
Figure 2a shows the Youbot with five wireless receivers arranged in a diamond-like configuration where the receivers were placed one on each side and one at the center. The robot was autonomously driven in an underground tunnel facility called ECN3 in a scientific facility at CERN shown in figure 2b. The values of RSS and the quality of link is recorded using the $RSSI$ (Received Signal Strength Indicator) and LQI (Link Quality Indicator) metrics [19], [20].

Up to 35 m distance from the static transmitter, the robot travelled in Line of Sight (LOS) condition. After that, the robot was moving in non-LOS (NLOS) condition until 45 m. Then the robot was moved in a deep NLOS condition. The resultant average of $RSSI$ and LQI of the five receivers with respect to distance are shown in Figure 2c. From the $RSSI$ values, the the calculated values are $n = 3.02$ and $\sigma_x = 1.52\text{dBm}$ for NLOS conditions using the log-normal fit in the equation 3.

B. Velocity control on fixed haptic plane

As the YouBot can only move in xy plane 1b, the 3 dimensional workspace was restricted in the z-axis by a hard haptic plane of 3.3N, as shown in Figure 1a, which is the maximum executable force of the PHANToM OMNI. The x and y components of the radial distance from the centre of the workspace were used to control the translational velocity $\dot{v}$ of the mobile robot. Torsional velocity of Youbot was not considered in this study.

The position of the OMNI tip is used to control the velocity of the YouBot using the relationship shown in equation 4.



(a) Youbot mobile robot

(b) ECN3 tunnel at CERN

(c) RSSI and LQI versus distance in ECN3 tunnel

Fig. 2: Experiments conducted in the ECN3 tunnel at CERN for determining the radio propagation parameters

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \alpha_x & 0 & 0 \\ 0 & \alpha_y & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} c_x - p_x \\ c_y - p_y \\ c_z - p_z \end{bmatrix} \tag{4}$$

where $\vec{c}$ is the centre of the haptic workspace and $\vec{p}$ is the position of the tip of haptic device relative to this centre. α_x and α_y.

Fig. 3: PHANToM OMNI slave controller is used to control the youbot simulated using ROS

C. *Wireless signal to force mapping*

The wireless signal strength $RSSI$ is converted into a haptic feedback profile which can be perceived by the operator at the tip of the OMNI device in all the directions on xy plane. Before using the $RSSI$ values, it is first filtered using an averaging function of $\overline{RSSI} = \frac{1}{100} \cdot \sum_{i=1}^{100} RSSI_i$ with 100 samples at a sampling rate of 100 Hz.

The position of the wireless receivers x, y was converted to polar coordinates r, θ. The $RSSI$ values from four outer receivers on the Youbot represents the signal strength in four directions $0°, 90°, 180°, 270°$ from the center of the robot in xy plane as the receivers were configured in such manner (figure 2a). A spline cubic smoothing polynomial function was used to interpolate the $RSSI$ values in all the directions between 0 to 2π radians.

The use of four wireless receivers on the robot was useful for calculating the two dimensional feedback to the operator in perceiving the signal strength in all the directions. The higher the number of wireless receivers, the better the resolution of interpolation, with a minimum of 2 sensors as previously discussed. In fact, even with only one wireless receiver, haptic feedback to the operator is possible with vibration which occurs when the robot enters low wireless signal region. However, such feedback cannot let the operator determine the direction to move the robot in order to avoid the low signal region.

To translate arbitrary $RSSI$ signal values into a force which is intuitive to the user, it was required to choose signal levels which correspond to normal operating signal levels for teleoperation of the robot. The conversion of $RSSI$ to force vector for haptic force feedback is made using equation 5.

$$\vec{F} = \begin{bmatrix} \beta_x \left|\cos\theta_p\right| & 0 & 0 \\ 0 & \beta_y \left|\sin\theta_p\right| & 0 \\ 0 & 0 & \beta_z \end{bmatrix} \begin{bmatrix} \Theta_x \\ \Theta_y \\ \Theta_z \end{bmatrix} \tag{5}$$

where

$$\begin{aligned} \vec{\Theta} &= \vec{c} - \vec{p} \\ \theta_p &= atan2(\frac{p_x}{|\vec{p}|}, \frac{-p_y}{|\vec{p}|}) \\ F_i &: \mathbb{R}\left\{0 > F_i > 3.3N\right\} i = x, y, z \end{aligned}$$

$$\beta_x = \beta_y$$

θ_p is the heading of the tip of the haptic device relative to the centre of the haptic plane described. A spring force is applied to the tip of the master device towards the centre of the plane and is calculated instantaneously at each polar coordinate.

The factor $\beta_z = 0.2$ was used to give a haptic plane lying on c_z, described by the spring equation:

$$F_z = 0.2(c_z - p_z) \tag{6}$$

giving a maximum force of $3.3N$ at:

$$(c_z - p_z) = \frac{3.3}{0.2} = 16.5mm \tag{7}$$

The value of β_z has been chosen to eliminate the noise which occurs at higher gains in feedback. The values for β_x

and β_y were derived empirically, represented by the following function:

$$\beta_x = \beta_y = \begin{cases} F_{max} & when\ P_r \leq -55\text{dBm} \\ \Upsilon_{P_r} \cdot P_r & when - 55\text{dBm} < P_r \leq -42\text{dBm} \\ F_{min} & when\ P_r > -42\text{dBm} \end{cases} \tag{8}$$

According to [21], the Packet Reception Ratio PRR which is equivalent to LQI, should be at least 85% to consider the link as being of a good quality. Applying the threshold of 85% LQI in figure 2c, for a good connection, the $RSSI$ value should be greater than -55 dBm. Therefore, a minimum $RSSI$ value of -55 dBm is required to operate the YouBot, and thus the highest force is applied below this signal.

Table II shows the signals which were chosen and the corresponding force levels which were applied. These were chosen to give a natural force profile that would allow the operator to perceive the direction of better wireless signal region and move within areas of good signal with ease, naturally guiding them towards areas with higher RSSI and only restricting them from areas where the signal was too low to operate the robot ($-55\,\text{dBm}$). As the aim of this system is not to remove the control from the operator, operating to these low $RSSI$ level areas was still possible, but gave sluggish control.

	Signal Strength (RSSI)	Centring Force (per mm)
Minimum Signal	-55dBm	0.1500 N
Low Signal	-53dBm	0.0340 N
Preferred Signal	-50dBm	0.0195 N
Good Signal	-47dBm	0.0123 N
Great Signal	-42dBm	0.0050 N
Best Signal	-20dBm	0.0050 N

TABLE II: The signal levels used in this study and the force exerted by the haptic master towards the centre of its workspace, corresponding to a speed command of zero to the mobile robot in all directions.

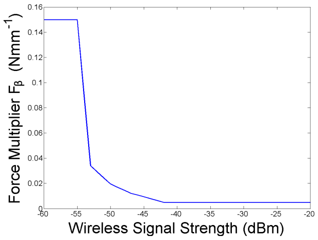


Fig. 4: The force multiplier derived for the usable range of $RSSI$ signal values.

Figure 4 show the force profile with respect to $RSSI$ values. The applied force to the operator is piecewise linear with the received signal strength, P_r with the linearity factor Υ_{P_r} depends on the $RSSI$ which is necessary for various levels of reliability of the wireless communication with the robot, as shown in Table II.

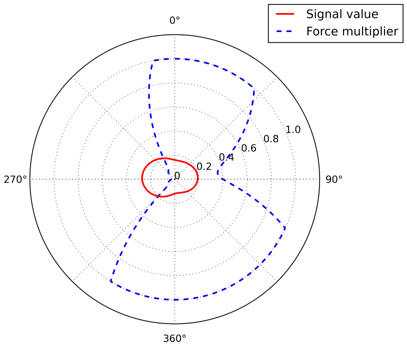


Fig. 5: The RSSI and resultant force profiles scaled to between $[0, 1]$ with 0.0 being Minimum RSSI (-55 dBm) and minimum force (0.005 N) and 1.0 being maximum RSSI (-20 dBm) and maximum force (0.15 N).

The force values and the $RSSI$ values are scaled between $[0, 1]$ and figure 5 shows the measured $RSSI$ at one position of the robot and the applied force vector to the operator in each direction. Figure 5 is displayed in real-time while the operator is driving the robot. Therefore the operator can visualise the wireless signal levels in different directions and can move the robot in the direction of better signal strength.

III. EXPERIMENTAL SETUP

Since real environments were unavailable to use at the time of this study, we simulated the environments using equation 3 with the propagation parameters obtained empirically ($n = 3.02$ and $\sigma_x = 1.52\text{dBm}$). Therefore we used simulated Youbot robot on the virtual environment controlled by a real haptic master device. Using simulated wireless environment maps was advantageous as it both allowed the creation of unknown landscapes of wireless signal, as would be the case in a real situation, and allowed a larger working area than was available in the physical space.

Also, it is notable that in real environments the wireless signal would be less radial, with reflections and distortions of the signal by various surfaces and materials in the environment. However, the mapping of a perfect simulation of such properties is beyond the scope of this paper, which is to demonstrate the effectiveness of the haptic feedback.

A. Simulated environment

A virtual rescue environment was created in the Gazebo simulator. A fixed course of obstacles was placed to add some realism to the scenario as shown in Figures 6 and 8(a).

In each experiment, the operator was instructed to drive the mobile robot in unknown wireless environment from a predefined start point to an end point. One operator was used, who was adept with the haptic device but not an expert on wireless distribution. A subjective evaluation is made with multiple trials and multiple operators with and without haptic force feedback. While driving the robot, the operator saw two windows on-screen. In one window, the operator view the Youbot located in the simulated environment in gazebo as in

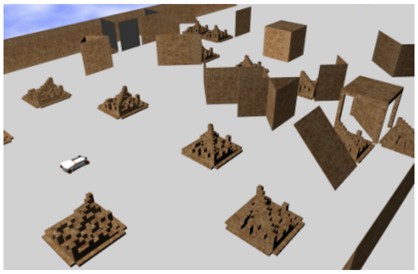


Fig. 6: Gazebo simulation of a rescue scenario.

figure 6. In another window (only when haptic feedback is used), the force and signal profile at the center of the robot as in figure 5 is displayed so that the operator can decide the change in direction of the robot to avoid bad wireless signal region.

B. *Map Generation*

A selection of 6 manually generated maps of wireless coverage were chosen at random using a MATLAB script. The path loss equation (equation 3) was used for create random maps of wireless signal coverage. To make the map more realistic, we added additive white gaussian noises (AWGN) in both time and space dimension with zero mean ($\mu = 0$) and std. deviation $\sigma = 2\,\mathrm{dBm}$ as shown in figure 7. Therefore, we simulate both the temporal and spatial fluctuations in $RSSI$. In addition, we placed randomly generated black spots (where $RSSI = 0$) on the map in difference sizes and at different places to simulated the loss of wireless communication at certain places.

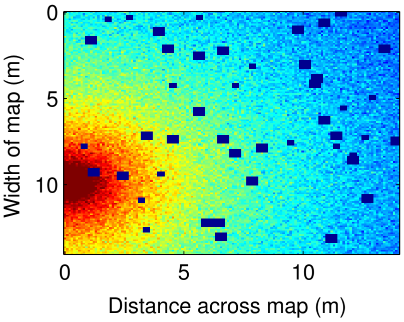


Fig. 7: Plot of the wireless map with randomly placed black spots and transmitter.

Figure 8 shows the Rviz visualisation of the wireless map and its corresponding environment. The spatial resolution of the map is set to $0.1\,\mathrm{m}$ which is greater than $0.38\lambda_c = 12.5\,\mathrm{cm}$ at $2.4\,\mathrm{GHz}$. Therefore, uncorrelated and independent $RSSI$ samples were obtained at each point in space [22].

Since the wireless environmental properties are considered unknown to the operator, the wireless signal map is hidden from the operator during the experiments.

IV. RESULTS AND DISCUSSION

A. *Reaching the goal*

30 automatically generated maps were created, each with three, randomly placed wireless transmitters. To avoid the situation where transmitters were all placed in the same place, the width was sectioned into thirds. The goal of the operator is to start the robot at $(0,0)$ and reach the goal at $(13,-2)$ and the trajectory is recorded. Figure 9 shows one such map.

The results for all 10 trials are shown in Table III.

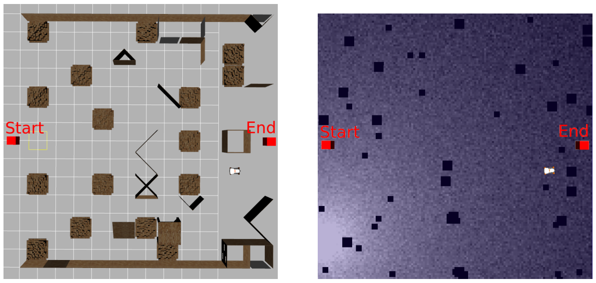
	With Haptic Feedback		Without Haptic Feedback	
Trial Number	Distance (m)	Success?	Distance (m)	Success?
1	12.9	Y	5.7	N
2	12.9	Y	8	N
3	12.9	Y	13.5	Y
4	12.9	Y	8.1	N
5	13	Y	7.4	N
6	12.9	Y	8	N
7	12.9	Y	7.9	N
8	13	Y	13.5	Y
9	12.9	Y	8.5	N
10	12.9	Y	5.7	N

TABLE III: Distance travelled and success of each trial with and without haptic feedback enabled.

It can be seen that with force feedback, the operator can achieve the goal but not without haptic feedback as the operator enters into bad wireless signal coverage and loses communication link. In Figure 10, the Manhattan distance travelled by the operator in different trail is shown. The success ratio with haptic feedback is increased to the order of five when the haptic feedback is used. This demonstrates the use of haptic feedback to perceive wireless signal strength.

B. *Avoiding blackspots*

To further test the effectiveness of our approach, the operator was instructed to drive the robot with and without haptic feedback from start point $(1,7)$ to end point $(14,7)$ across multiple black spots that were randomly generated. The trajectory along with the number of black spots across the way and the $RSSI$ values were recorded during the test. When haptic feedback is used, the operator was able to avoid all the black spots except in one place where the robot entered a



(a) Operator's view in Gazebo

(b) Wireless map and robot in Rviz

Fig. 8: Views of the test setup in both Gazebo and RViz.

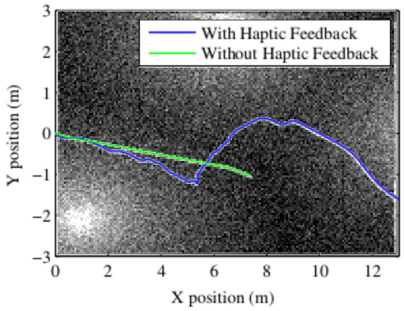


Fig. 9: The path of the robot along with the $RSSI$ map is shown with and without haptic feedback enabled

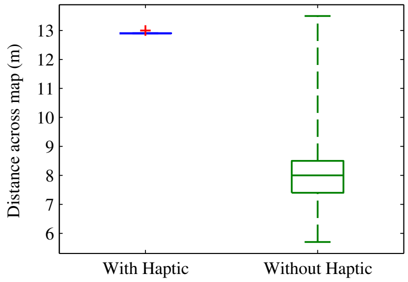


Fig. 10: Completed distances along the test track for test runs

black spot but was able to return back to operation because of effective haptic feedback. When the haptic feedback was not used, the operator drove the robot through 3 black spots, which, in a real-world situation, means that the robot would have lost the communication with the operator whenever the robot had passed through the black spots.

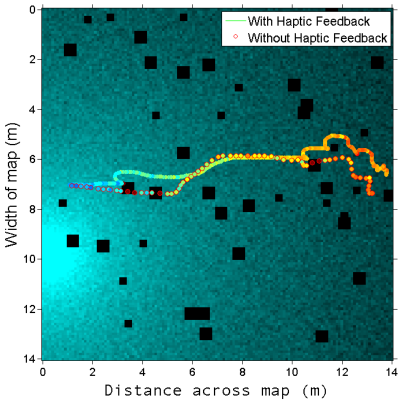


Fig. 11: Map of RSSI values overlaid with paths for a trial with and without Haptic Feedback. With Feedback the robot completes the track (13m) in all trials, while Without Haptic the robots loses communication at an average of 8m.

Figures 11 shows the path taken by the operator with and without haptic feedback and the corresponding RSSI is shown in 12. It can be observed that, with haptic feedback the operator avoided the area where the wireless signal level falls below the minimum required (-55 dBm) to operate the robot.

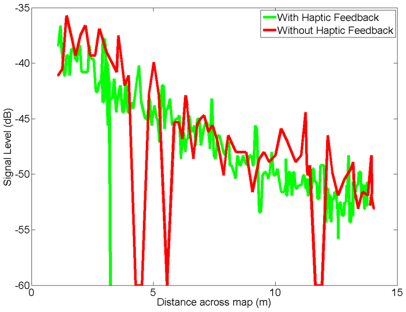


Fig. 12: The $RSSI$ values recorded over distance

V. CONCLUSIONS AND FUTURE WORK

Rescue scenarios often exhibit environmental properties which is complicated for radio signal propagation. We have proposed and demonstrated with simulated experiments a method which uses haptic feedback to allow operators to perceive wireless signal strength when driving a field robot during rescue robot missions so as to avoid low wireless signal regions. We have shown that this type of feedback is a natural and intuitive way to guide operators into areas with higher wireless signal strength and carried out a series of tests on environments with randomly generated wireless signal strength maps to demonstrate the effectiveness of this approach. The haptic feedback helps the robot in avoiding the communication loses and avoids the manual recovery of the robot in case the robot loses communication link. As the mapping is highly customisable, the work performed in this study can be extended to use other types of sensors such as laser scan readings to avoid obstacles.

In our further work, we plan to conduct the experiments in the real environments in complex environments such as at CERN when the facility becomes available. We also have plans to investigate the burden of cognitive load to the operator when haptic feedback is used for perceiving wireless signal strength.

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