Standard Radio Communication Test Method for Mobile Ground Robots

Galen Koepke*. David Hooper, John M. Andrews**, and Kate A. Remley***

**National Institute of Standards and Technology, Boulder, CO 80305*
USA (Tel: 303-497-5766; e-mail: koepke, remley@ boulder.nist.gov).
***Unmanned Systems Branch of the Space and Naval Warfare Systems Center Pacific, San Diego, CA 92152, USA (e-mail: dhooper@spawar. navy.mil, john.andrews@navy.mil)*

Abstract: This paper describes a proposed standard test method for evaluating the performance of wireless communications links used for control and telemetry in mobile ground robots. Range performance metrics are determined under open line-of-sight (LOS) and simple obstructed non-line-of-sight (NLOS) conditions. The method was demonstrated as part of the annual Response Robot Evaluation Exercise at the Texas A&M University Riverside Campus during November 2008, where it was used to compare range performance of several advanced radio systems.

Keywords: Radio communication, robots, standards, teleoperation, testing, wireless.

1. INTRODUCTION

Teleoperated robotic vehicles are rapidly emerging as an invaluable tool for the military as well as civil emergency response organizations. Remote operation offers clear advantages in applications such as hazardous materials response, mine safety, urban search and rescue, and reconnaissance. The stand-off provided by telerobotics can serve to reduce human exposure to dangerous situations and environments while also providing opportunities to extend the users' tactical reach into otherwise inaccessible spaces.

A critical performance parameter influencing, if not determining, overall system capability is the communication link between the user and the robot. This link is typically duplex, serving as the means of issuing remote commands to the robot while also providing one or more channels for transmitting sensor data, usually including live video images, back to the controlling user. The communication link may be wired but is more commonly wireless to facilitate enhanced mobility; *i.e.*, movement without the encumbrance of a tether. Range performance of wireless teleoperated robots varies between systems as a function of several design parameters including: radio frequency, power, antenna gain, antenna height, etc. Environmental conditions strongly affect range performance as well, because wireless systems are subject to operational range limitations due to path attenuation, latency, and interference arising from other wireless users, ambient noise, and multipath effects. Depending on system specifications and environmental conditions, the maximum effective range of commercially available teleoperated ground robots generally varies from tens of meters to several kilometers.

Currently there are no standard test methods for obtaining and evaluating performance metrics for the wireless telemetry and control systems of ground robots. The U.S. Department of Homeland Security has tasked the National Institute of Standards and Technology (NIST) to address this need as part of its comprehensive effort to develop standards related to the testing, evaluation, and certification of robotic technologies [1]-[3]. NIST is actively working to develop standards for mobility, perception, navigation, endurance, and human factors, as well as communications. The NIST program places specific emphasis on standards appropriate for urban search-and-rescue (US&R) scenarios, but its practices are widely applicable to other operational domains employing mobile robots.

This paper describes two of the preliminary standard test methods for communications and their recent use to evaluate and compare range performance metrics for several radio technology alternatives on a small ground robot. The two methods include a line-of-sight range test and a non-line-of-sight range test.

2. PERFORMANCE TEST METHODS

Test methods to ensure that a given robot will meet the needs of a given response agency must be repeatable, reproducible, and must isolate various characteristics of robot performance. When a number of potential impediments to robot performance are present simultaneously, it is impossible to assess a specific characteristic of the wireless system. This was illustrated clearly in [2], which described initial field tests where various robots were exposed to preliminary test methods. In [2], robots were unable to complete line-of-sight and non-line-of-sight tests because of radio interference from other robots nearby. As a result, the test methods discussed below were developed to test specific characteristics of robot performance, in isolation from other effects. These methods are intended to test only the specific attributes of (1) loss of radio communication in a line-of-sight condition as the robot moves down range and (2) loss of radio communication as the robot moves behind an obstacle.

In order to isolate these attributes, the performance test methods are necessarily abstract, because no real-world environment will present such isolated conditions. It is also necessary to conduct these tests in a facility where they may be repeated and reproduced as often as necessary. The test facility chosen to meet the above criteria of isolation and reproducibility is an airstrip at the Texas A&M University Riverside Campus. The preliminary exercise of [2] and other response robot field exercises has led to the standardized test methods described below. These test methods are the first two in a series of tests that will be needed to fully characterize robot performance. Such methods could be useful in characterizing other types of robots, as well as other types of field-deployable wireless communication equipment.

2.1 Line-of-sight (LOS) range test method

This test effectively replicates the simplest propagation environment likely to be encountered by radio-linked robotic systems on the ground. The test scenario is intended to evaluate system communication range under conditions of unobstructed visual line-of-sight between the robotic vehicle and the base-station antenna. This will typically involve two antennas separated by a distance (d), though the scenario could accommodate multiple nodes, such as in the case of a robot that carries and deploys repeaters to extend its communication range [4].

Radio propagation under these conditions can be described by the two-ray model over plane earth [5]. This model assumes only two signals arriving at the receive antenna: the direct (shortest line-of-sight path) signal between the two antennas, and one signal that reflects (bounces) off the earth before it arrives at the receiving antenna. The reflected signal typically has a different amplitude and phase compared to those of the direct signal. The method assumes relatively short separation distances ($d < 2.0$ km), hence the curvature of the earth can be ignored. A minimum of 50 meters on each side of the test path (100 meters total) must be clear of any obstacles or reflecting objects in order to minimize multipath effects.

Test points are established at regular intervals (Fig.1). The reference location is at 50 m. The second location is at 100 m, with subsequent locations at every 100 meters. Test locations at shorter intervals (*e.g.*, 50 m) may also be used if needed.

Test procedures: At each test point the mobile robot is made to perform a full system evaluation while facing in each of the four compass directions relative to the direction of travel. This is accomplished while maneuvering through a tight figure-eight course and selecting four test stations such that the robot is facing in each direction (Fig 2). Performance testing at each test point serves to validate function of both the control and data (video) links while removing orientation bias in cases where either the radiation pattern of the on-board antenna system is not perfectly omnidirectional or the antenna is obstructed by an asymmetric part of the robot platform, for example, a manipulator arm.

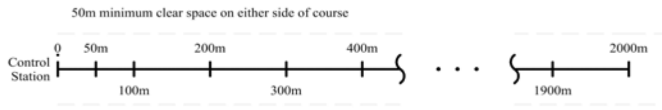

Fig. 1. Line-of-sight course layout showing spacing between test points

The LOS range test sequence is as follows:

Step 1: Perform a full system(s) evaluation in each of four directions (*e.g.*, read visual charts, read on-board sensors, operate manipulator, etc.) at a reference point 50 meters from the control point. This is the reference test and is used to determine the best-case performance for the communications systems.

Step 2: Proceed to the next test point location (*e.g.*, 100 m, 200 m, etc.) and perform a full system(s) evaluation in each of four directions.

Step 3: Repeat step 2 until any system operation becomes unacceptable (as defined for the particular system) or the end of the course is reached at 2000 meters.

2.2 Non-line-of-sight (NLOS) range test method

The NLOS test is intended to evaluate the effectiveness of the robotic system's radio communication link under conditions where the visual line-of-sight between the robot and base station is completely occluded by a physical object. In this case, neither the base station nor the robot's onboard antenna receives a direct signal but instead they receive one or more significantly attenuated signals due to diffraction around the obstacle. The course is located at least 50 m from any other obstacles in order to minimize reflection and/or scattering from a nearby object.

This is intended to serve as a simplified replication of a scenario where the robot is used to explore an object or incident beyond or out of the visual field of the operator. The test studies path loss that is due to attenuation rather than scattering.

The NLOS test includes two sections: a 500 meter line-of-sight portion with characteristics similar to the LOS test, after which the robot makes a 90 degree turn behind a tall, broad obstruction such as a building and continues the test (Fig. 3). Both tests are executed in a manner identical to the LOS test in that the robot is made to maneuver through a figure-eight while confirming visual acuity four times at regularly spaced test points. However the test point spacing is shortened for the non-line-of-sight portion of the test.

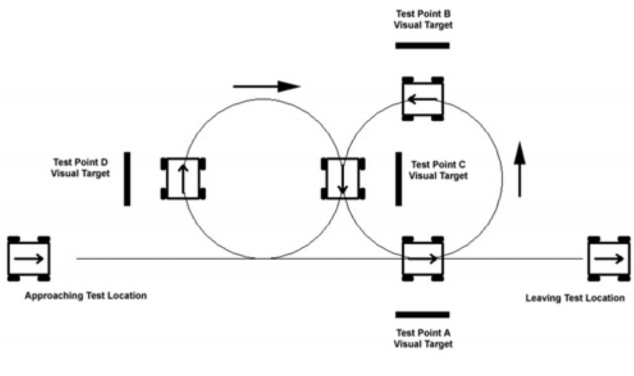

Fig. 2. Position sequence at each test point. Robot traverses a figure-eight and executes four visual acuity tests while halted in front of visual targets. The test ensures that the robot will operate in all four compass directions by requiring it to face the pre-oriented targets.

Obstacle (building) requirements: The building or obstacle should provide complete shadowing of the radio-frequency signal for the path taken by the robot. It should be constructed of materials that prevent easy penetration of the signal and should be both tall and broad enough to prevent signals from reaching the reverse side of the structure, for example, a metallic wall. The standard test course may be assembled from 12.2 meter long (40 foot) International Organization for Standardization (ISO) shipping containers stacked three high and at least two wide such that the resulting obstacle measures 7.8 meters (25.5 feet) tall by 24.4 meters (80 feet) wide. The electrically conductive steel construction of shipping containers makes for an excellent radio-wave barrier for most frequencies of operation currently used by robotics manufacturers. To ensure no energy leakage, metal foil and tape should be used to cover any gaps between containers.

Similar test courses may be used to provide an estimate of robot performance for this test method. For instance, a large commercial multi-story concrete and steel structure covering a large portion of a city block would be acceptable, while a wood-frame single family home is unlikely to provide adequate attenuation or shadowing. The results may be complicated by an obstruction that is too small to sufficiently block the direct path signal, or a highly reflective environment, such as an urban canyon, where signals are channeled along side streets by tall structures; such conditions should be avoided.

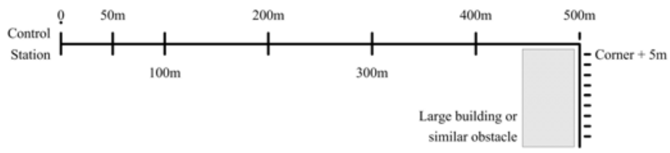

Fig. 3. Non-line-of-sight test course configuration showing LOS portion leading to a 90 degree turn behind an obstacle that blocks the direct radio propagation path. Test points are set up at regular intervals.

There are two separate and distinct propagation profiles that result from the two parts of the test path. The LOS portion is expected to follow the two-ray model, as before. The signal attenuation associated with the NLOS section will increase rapidly after the mobile robot moves behind the obstacle. The weakened NLOS signal can be attributed to a combination of indirect paths, including diffraction around the obstacle as well as small amounts of scattering and reflection from nearby objects, although care is taken to minimize the latter.

Test procedures: At each test point the mobile robot is made to maneuver through a figure-eight and perform a full system evaluation while facing in each of the four compass directions, just as in the LOS test. Some robot systems may not have the ability to communicate over the full length of the 500 meter LOS portion of the test course, making it impossible to reach the NLOS part of the course. In this case the system start point should be set at a distance from the obstruction equal to not more than one half of the maximum achievable LOS range, as determined by the LOS range test described above.

The NLOS range test sequence is as follows:

Step 1: Initiate the LOS section, conducting full system(s) evaluation (*e.g.*, read visual charts, read on-board sensors, operate manipulator, etc.) at 50 meters from control point.

Step 2: Proceed to the next test locations iteratively (100, 200, 300, 400, and 500 m) and perform a full system(s) evaluation.

Step 3: Repeat (2) until any system operation becomes unacceptable (as defined for a particular system) or until the system reaches the far corner of the obstacle at 500 meters.

Step 4: Maneuver the robot 90 degrees so that it is behind the obstacle. This is the start of the NLOS section. The first test station is located 5 m from the corner of the obstacle (building). The test station and the robot path should be positioned as close as possible to the obstacle, with one of the test charts directly on the surface of the structure. Perform a full system(s) evaluation (*e.g.*, read visual charts, read on-board sensors, operate manipulator, etc) at the 5 m test location.

Step 5: Proceed to next test point location (at 5 m or 10 m intervals from the corner).

Step 6: Perform a full system(s) evaluation.

Step 7: Repeat Step 6 until any system operation becomes unacceptable (as defined for a particular system) or until reaching the far corner of the obstacle.

Fig. 4. Line-of-sight course set up over a 1 km distance on an airstrip with orange safety cones marking test points.

3. CONDUCTING THE TESTS

NLOS and LOS range performance tests, using the standard methods described above, were conducted as part of the NIST sponsored Response Robot Evaluation Exercise held 17-20 November 2008 in College Station, Texas. The communication test portion of the event was conducted at the Texas A&M University Riverside Campus, just west of Bryan, Texas. The event was facilitated by the Texas A&M Texas Engineering Extension Service (TEEX).

The Riverside Campus location was originally built as an Army Airfield. The former airfield's runways, no longer in use, serve as an excellent location to conduct radio range testing. The hard concrete surfaces of the airstrips provide a uniform reproducible environment, the terrain is flat, and the facility provides kilometers of maneuvering space that is relatively free of existing obstructions. The LOS test course was established on one runway, the NLOS course on an adjoining runway.

Fig. 5. Example test station for both the LOS and NLOS methods. Three visual acuity charts are set up around the figure-eight maneuver path.

Fig. 6. Example of a visual acuity chart used at each test station for both the LOS and NLOS methods

The set-up for LOS testing is shown in Fig. 4. Orange safety cones were used to mark test stations along the course (Fig. 5), visual acuity charts were mounted in orange safety triangles, as shown in Fig. 6. The length of the LOS course was limited to one kilometer, rather than two, with a reference point established at 50 m and subsequent test points starting at 100 m and continuing at 100 m intervals as per the method guidelines.

The NLOS course layout is shown in Figs. 7-8. Six steel ISO shipping containers were set up to serve as the obstruction. TEEX employees used a crane to stack the boxes two wide (24 m) and three high (7.8 m). The container stack was located at a 500 m distance from the start (control) point of the NLOS course. A reference point was set at a 50 m distance, with subsequent test points emplaced starting at the 100 m mark and continuing at 100 m intervals up to 500 m, collinear with the near edge of the obstacle.

Fig. 7. NLOS test course as viewed from near the start point looking toward the container stack 500 m away.

Fig. 8. The far side of the container stack showing placement of the final (500 m) figure-eight LOS test station and subsequent NLOS test points located along the back wall.

Prior to the start of each test run, a spectrum analyzer was used to identify and document ambient radio-frequency noise and establish baseline noise conditions. These provided a means of recognizing environmental changes that could influence performance. As the tests were conducted in a populated, albeit semirural area, some level of background activity was expected with the potential for interference within commercial and unlicensed portions of the spectrum.

The LOS and NLOS test courses were used to evaluate range performance on six unique radio systems. Frequencies ranged from 225 MHz to 5.9 GHz. Each radio system was integrated onto an iRobot PackBot EOD robot [6, 7] which served as the mobile platform for each test. Each PackBot mounted radio was maneuvered through both the LOS and NLOS test lanes to determine the maximum effective communication range for the system. Each run was replicated at least twice as an initial means of validating reproducibility.

Specific details on the radio systems tested and a comparative evaluation of their performance based in part on the methods described in this paper are to be published separately.

4. DISCUSSION

4.1 Precision and Bias

The communication test methods should be evaluated for reproducibility each time they are used. During the Response Robot Evaluation test event, the maximum achievable range determined for a given system varied somewhat from run to run. For example, two of the six tested systems were able to successfully complete the full length of the NLOS test course on one run, but failed at a point significantly short of the final test point during their next run.

Several factors can lead to variance in testing. One variable that was found to introduce bias is radio interference arising from outside transmissions in the vicinity of the test site. Ambient radio interference and noise levels are often beyond the control of the test manager. To mitigate this bias, a survey of background spectral emissions using a spectrum analyzer should be carried out prior to, or preferably, during each test. This is particularly important to help ensure accurate comparison when evaluating systems operating at different frequencies, as they may be unequally affected depending on the spectral characteristics of the interfering noise.

During the Response Robot Evaluation event, measurement and analysis of background noise led to the discovery of significant 400 MHz noise that may have limited the performance of some of the tested radio systems. Knowledge of the background noise characteristics will also allow for more informed comparisons when evaluating performance measurements gathered from different locations or at different times. Nevertheless, if a wireless system passes the test method in the presence of interference, it should not affect the rating of that system.

Other variables that may introduce bias into the wireless communication test methods are related to the environmental condition under which the tests were carried out. Atmospheric conditions, solar activity, precipitation, temperature, and humidity can all affect the results. The composition of the soil and ground at a given site can be expected to influence performance results as well. We suspect that the environmental conditions produce test results outside the standard deviation of the reproducibility of the method, so that the operator may return to the test site for additional testing when the conditions more closely match those specified in the reproducibility test.

4.2 Use of Additional Indicators

The test methods have been developed with the end user in mind; they are specifically designed to provide a go/no-go performance evaluation for a given system in a simulated environment. The method may find additional utility among developers by introducing the continuous measurement of key performance indicators such as latency, data error rate, bandwidth loss, etc. This could be used to identify specific failure mechanisms and lead to engineering changes resulting in extended range performance.

5. CONCLUSION

The development of application-specific robot standards and repeatable performance testing methods with objective metrics will accelerate the development and deployment of mobile robotic tools for the user community. Improved understanding of specific robotic capabilities and limitations will enhance the effectiveness of operator teams while serving to reduce the risks and uncertainty associated with operational use.

Adequate performance using these test methods will not ensure successful operation in all operational environments, due to possible unforeseen extreme or unusual communications difficulties present in some radio environments. Rather, these tests are intended to provide a common ground for comparison of technologies against a reasonable simulation of relevant environments and to provide quantitative performance data to user organizations to aid in choosing appropriate systems.

The practice described in this paper provides a method for quantifying the maximum effective range performance for on-the-ground communications systems of mobile robots. NIST and its partners, including the U.S. Department of Homeland Security (DHS) and the American Society for Testing Materials (ASTM), will continue to utilize the results and lessons learned from ongoing use of the test methods, as described here, to improve and refine the protocol. This will ultimately lead to recognized and accepted standards that provide a consistent way of evaluating and comparing system performance within the growing field of available robotic platforms.

ACKNOWLEDGEMENT

The authors thank the staff of Texas A and M University of Texas Engineering Extension Service (TEEX) for their support in setting-up and facilitating test scenarios during the 2008 Response Robot Evaluation Event. The U.S. Department of Homeland Security Office of Standards supplied funding for this work.

REFERENCES

[1] Elena Messina, Adam Jacoff, Jean Scholtz, Craig Schlenoff, Hui-Min Huang, Alan Lytle, and John Blitch, Preliminary Report: “Statement of Requirements for Urban Search and Rescue Robot Performance Standards”, [Online]. Available: http://www.isd.mel.nist.gov

[2] Kate A. Remley, Galen Koepke, Elena Messina, Adam Jacoff, and George Hough, Standards Development for Wireless Communications for Urban Search and Rescue Robots, Proc. ISART 2007, Boulder, CO, March 2007, pp. 79-82, [Online] Available: http://www.boulder.nist.gov/div818/81802/MetrologyForWirelessSys/pubs/R11_ISART07_Remley.pdf

[3] Elena Messina and Adam Jacoff, Performance Standards for Urban Search and Rescue Robots, Proceedings of the SPIE Defense and Security Symposium, Orlando, FL, April 17-21, 2006, [Online] Available: http://www.isd.mel.nist.gov/documents/messina/6230-77.pdf

[4] Narek Pezeshkian, Hoa G. Nguyen, and Aaron Burmeister, Unmanned Ground Vehicle Radio Relay Deployment System for Non-Line-of-Sight Operations, 13th IASTED International Conference on Robotics & Applications, Würzburg, Germany, August 29-31, 2007, [Online] Available: http://www.spawar.navy.mil/robots/pubs/IASTED_ADCR_2007.pdf

[5] Ramakrishna Janaswamy, “Radio Propagation and Smart Antennas for Wireless Communications,” Kluwer Academic Publishers, 2001, eq. 2.60, pg 36.

[6] Identification of commercial products does not imply endorsement by the National Institute of Standards and Technology. Other products may work as well or better.

[7] Information available at: http://irobot.com