A Technical Review of MANET Testbed Using Mobile Robot Technology

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Abstract. Recently, MANET (Mobile Ad Hoc Network) researchers have shown increased interest in using mobile robot technology for their testbed platforms. Despite the existence of review papers that discuss the usage of mobile robot technology pertaining to a MANET testbed from the perspective of a MANET researcher, said findings are rather lacklustre as it is not the sole purpose of said reviews. Hence, this review aims to comprehensively discuss the technical aspects that were facilitated with mobile robot technology for previous undertaken research. Only selected MANET testbed relevant to this review are compiled, namely Mobile Emulab, MiNT-m, MiNT-2, Proteus, w-ilab.t, ARUM, Sensei-UU, Kansei, CONET-IT, CONE, Roomba MADNet, Explorebots, SCORPION, MOTEL, iRobotSense, IoT-Lab, and NITOS. The discussions in this article are divided into three parts, namely hardware, software as well as mobile robot positioning and localization. The technical content of this review is expected to be a source of reference for other MANET researchers who are interested to use mobile robots for real mobility in their MANET testbeds.

1. Introduction
MANET (Mobile Ad Hoc Network) researchers have shown increased interest in using mobile robot technology for their testbed platforms. This paper therefore extends the discussions of our previous paper titled “Mobile Ad hoc Network Testbed Using Mobile Robot Technology” [1] by scrutinizing it as a technical review.

This paper is organized as follows. In section 2, the relevancy of selected MANET testbed facilities in this article is detail out. Section 3 describes three aspect of this paper, namely software, hardware and mobile robot positioning as well as localisation of robot technology used in MANET testbed. Finally, section IV provide some concluding remark.
2. Related Work

It is to be noted that most previous discussions on MANET testbed facilities did not reveal technical aspects of mobile node facilities used in MANET testbed laboratories, especially those that are conducted in public testbed laboratories. Testbed facilities that do provide technical information are mostly from private and community testbed facilities and this is most likely due to the need to publish articles and technical reports as it is part of their requirement. However, the remaining testbed facilities merely states some technical specifications of mobile nodes in the testbed facilities without elaborating much details. Thus, the aim of this article is to comprehensively discuss these technical aspects of mobile robot usage in MANET testbeds which includes exploring the trends and advancements of robot technology usage chosen by robot-based MANET testbeds. These conditions are very much needed to deduce suitable construction of a good robot-based MANET testbed facilities that can be applied in the future.

The selection of robot-based MANET testbeds that were chosen in this review was purely based from the perception of MANET researchers and not from a robotic expertise perspective as was reported in most review articles. The focus and perspectives of the selected surveys were determined based on the discussion of the types of suitable, non-suitable and irrelevant robot-based MANET testbeds that were specific to this review.

In this article it was decided that MSNs, opportunistic networks and DTNs were a subset of MANETs because all of the mentioned wireless ad-hoc networks had mobility criteria and most importantly, wireless multi-hop ad-hoc communication. Therefore, 17 identified types of MANET platform mobile robot will be discussed in this article, namely, Mobile Emulab, MiNT-m, MiNT-2, Proteus, w-ilab.t, ARUM, Sensei-UU, Kansei, CONET-IT, CONE, Roomba MADNet, Explorebots, SCORPION, MOTEL, iRobotSense, IoT-Lab, NITOS.

On the other hand, testbed facilities devoted to research of multiple mobile robots using MANET-based communication were dismissed in this article. Examples of research in MANET-based multiple robot communication are CENTIBOTS [2], Robomote [3] and Mobile Multirobot Systems [4]. Based on a review of the aforementioned research articles, it was deduced that the testbed facilities that they developed were more focused towards research on multiple robot communication through MANETs with very limited discussion on the MANET research itself. Hence, the testbed facilities devoted to research of multiple mobile robots using MANET-based communication were dismissed.

3. Technical Review

In this section, the discussion is divided into three parts, namely (i) hardware platform (ii) software platform and (iii) mobile robot positioning and localization.

3.1. Hardware Platform

3.1.1. Robot Platforms and Chassis.

Much of our review is centred on testbed platforms using readymade robot platforms such as iRobot Roomba/Create and LEGO Mindstorms. iRobot Roomba and Create are one of the most popular robot platforms due to several factors including the ability to carry loads up to 2 kg, presence of basic sensors for mobile robots such as bump sensors, obstacle avoidance sensors and wheel encoders, ease of controllability via iRobot Roomba Open Interface (ROI), large rechargeable li-ion battery (44000 I) capacity, and a self-recharging docking station as well as their competitive prices as compared to other platforms [5].

iRobot Roomba was introduced in 2002 and became among the earliest household robots made available to the public. It functioned as an autonomous robotic vacuum cleaner while at the same time it became a favourite robot for robotics researchers and hobbyists that used it to be the main platform for mobile robots. iRobot Create was later introduced in 2007 and was based on the iRobot platform due to the popularity of iRobot Roomba among robotics researchers and hobbyists. iRobot Create was sold at a lower prices because it did not have some of the components attached to
iRobot Roomba such as vacuum cleaning (although the component could be added separately) [5].

iRobot Roomba and Create are usually controlled with a robot controller (usually a combination of an embedded PC and microcontroller) through the iRobot Roomba Open Interface (ROI) protocol whereby communication is enabled via a serial port on iRobot Roomba/Create are MINT-m [6], MINT-2 [7], Proteus Roomba [7], w-ila.t [8], Roomba MADNet [9], SCORPION [10] and iRobotSense [11].

Apart from the iRobot Roomba and Create, LEGO Mindstorms is another preferred choice as robot platforms for mobile robots in the MANET testbeds. Examples of MANET testbeds that used LEGO Mindstorms robot platform are Sensei-UU [12] and Cone Testbed [13].

The Acroname Garcia robot platform also was a popular choice in several MANET testbeds such as the Emulab Mobile (TrueMobile) [14] and Kansei Testbed [15].

There are also other readymade robot platforms that were utilised, such as e-puck that was used in the MOTEL testbed [16], the Pioneer 3AT robot platform used in CONET-IT [17], the Lynxmotion 4WD rover robot platform used in ARUM [18] and the Rogue ATV robot platform used in Explorebot [19].

3.1.2. Robot Controllers. The selection of robot controllers used for mobile robots in previous MANET testbeds varies. Most have used a combination of an embedded PC board, microcontroller and motor controller. Examples of testbeds that combined an embedded PC board and microcontroller are MINT-m, MiNT2, Proteus, CONET (custom version), Kansei as well as NITOS.

There were testbeds that used smartphones as their robot controller such as Sensei-UU [12], custom made circuit boards such as w-ila.t [8] while others utilised ready-made robot controllers like the LEGO NXT robot controller, a robot controller for LEGO Mindstorms that was used in the Cone testbed [13] and also Atom Bot Board Lynxmotion [18], a robot controller for the Lynxmotion based robot platform used in the ARUM testbed.

Some isolated cases like Roomba MADNet used an openwrt-based wireless router as a robot controller [7], a solution that was quite rare in mobile robot design.

Some mobile robots have used laptops/netbooks as their robot controller, e.g. ARUM [18], CONET-IT (Pioneer 3AT platform) [17] and IoT-lab (turtlebot2 platform) [20] where they were capable of carrying laptop loads weighing between 1.5 kg to 2 kg.

3.1.3. Supporting Components and Sensors. Apart from main robot platform/chassis and robot controllers, mobile robots for MANET testbed also required other components such as for mobile robot localisations, obstacles and collision avoidance, testbed miniaturization and mobile devices such as sensor nodes to carry out MANET experiments.

i. Sensors and Other Components for Robot Localisation

There are many methods of robot localisation used in robot-based MANET testbeds that have been reviewed in this work and is the main factor for the selection of sensors and components used. Robot-based MANET testbeds that chose centralized visual localisation methods used ceiling-mounted video cameras with some opting for IR cameras such as ARUM [18] or fish eye cameras such as in the MOTEL testbed [21] to track the location and movement of mobile robots. Most testbeds used colour pattern recognition to identify different mobile robots identities such as Mobile Emulab [22], MINT-m [23] and MOTEL [21], where each mobile robot was equipped with a board with different colour patterns from one another. ARUM on the other hand, selected a different method that used motion capture-based localisation that used reflective balls arranged in different pattern for each mobile robot. Aside from centralized visual localisation, there have been mobile robots in MANET testbeds that used local visual localisation methods such as NITOS [24] that utilised webcams fixed to the mobile robot and at predetermined locations, black and white image pattern boards were placed that acted as location marks.
There have been some robot-based MANET testbed facilities such as Sensei-UU [12] and ARUM [18] that used fixed circuit-based mobility and they were usually equipped with infrared sensors to detect black lines placed on the floor to guide their movements.

For testbeds that used the iRobot Roomba and iRobot Create, wheel encoders that were available on Roomba or Create were fully utilised as an aid in determining the distance, speed and direction of their movements using the odometry method to support the localisation mechanism as used in the MINT-2 mobile robot [7], w-iLab.t [25] and Explorebot [19].

Robot-based MANET testbeds that used the Acroname Garcia robot platform for mobile robots such as Mobile Emulab (TrueMobile) [14] and Kansei Testbed [26], were equipped with ultrasonic sensors and IR sensors that could be used in obstacle and collision avoidance mechanisms. The Proteus mobile robot in Pharos testbed facilities had a variety of different settings to suit the experiments that were to be conducted. For experiments conducted outdoors, a combination of GPS and a magnetometer sensor were used, and for indoor experiments, a combination of visual localisation and IMU were chosen to be the components for robot localisation [27].

Mobile robots in the CONET-IT laboratory were equipped with laser range finders (LiDAR), Microsoft Kinect 3D camera sensors, GPS and IMU sensors to enable accurate robot localisation to be done independently on each mobile robot unit [28].

ii. Radio Signal Attenuators
Other than sensors and components used for robot localisation, obstacles and collisions, there were other supporting components such as radio signal attenuators that were used for testbed miniaturization such as the ones used in Mobile Emulab [22], MiNT-m [23], MINT-2 [7], ARUM [18], Kansei [26] and Sensei-UU [12]. The original purpose of the radio signal attenuators were to reduce the noise and interference of the radio signals. However, for testbed miniaturization, radio signal attenuators could also be used to reduce the wireless signal range that enabled the multiple hop ad hoc network to occur in a small testbed area. All the testbeds mentioned used fixed radio signal attenuators.

iii. Mobile Devices
The final component to be viewed in the MANET testbed is the type of components that are used as mobile devices. The selection of a mobile device carried piggyback by the mobile robot in the testbed is dependent on the purpose and scope of the testbed facilities. For example, the MANET testbed dedicated to WSN research or IoT with mobility used sensor nodes (or mote), the Mobile Emulab used Mica2 sensor nodes for mobile device, Sensei-UU used TelosB sensor node, CONET-IT used several different sensor nodes like TelosB, Iris, MicaZ, Mica2, CM5000 and CM5000-SMA, Explorebots used Mica2 sensor nodes, MOTEL testbeds used TelosB, MicaZ and Scatterweb sensor nodes while IoT-Lab used WSN430, M3 and A8 sensor nodes.

Some parts of the MANET testbeds used embedded computer boards such as MiNT-m that used the Routerboard RN-230, MINT-2 that used the Soekris net5501 board, Pharos/Proteus and SCORPION testbeds that used a mini-ITX x86 computer, ARUM that used a laptop or Macbook, Roomba MADNet that used a Linksys WRTSL54GS wireless router and NITOS that used an Alix motherboard. All of the above used low power consumption computer boards to represent the mobile devices. The CONE testbed was a bit unique as it used a Nokia mobile phone to represent the mobile device, specifically,
the Nokia mobile phone models: Nokia N97 mini, Nokia N97 and Nokia 5800 XpressMusic that had the same firmware and capabilities.

Additionally, some robot-based MANET testbeds combined sensor nodes and embedded computer board as the mobile device such as the w-lab.t lab testbed that combined eZ430 sensor nodes and an embedded board computer powered with an Intel Atom processor chip and the Kansei testbed that used Extreme Scale Mote (XSM) sensor nodes and a Stargate board as the mobile device in the MANET testbed.

3.2. Software Platforms

3.2.1. Robotic Software. Much of the earlier generations of the MANET testbeds with real mobility facilities like MINT and Mobile Emulab used in-house robotic software platforms as open source robot frameworks did not exist at that time. Later generation testbeds such as Pharos/Proteus, ARUM and Kansei combined in-house software and an open source software robot framework Player/Stage or ROS (Robot Operating System).

The latest trend in testbed platforms such as the w-ilab.t, NITOS and CONET robots combined an open source framework with ROS with the network testbed platform such as the GENI interface and the OMF-OML framework with some additional customization that were suitable to their needs.

3.2.2. Testbed Management and Monitoring Platforms. Testbed platforms from earlier generations of MANET testbeds that used mobile robots had their own custom made testbed management and monitoring platforms. This was because, at their time of development, a standard network testbed framework had not existed as the development of wireless network testbeds was still considered new.

Normally, the components to control the experiment process and the components that control the mobile robots are isolated but are integrated through the testbed core management component. Modular architecture enables the implementation of two different components separately using different technologies and tools. Some testbed platforms used different programming languages for the experiment control process components and mobile robot control components.

Some MANET testbed platforms integrated simulator and testbed platforms to compare data obtained from the simulator with data obtained from the testbed, such as MINT that used a hybrid simulator that was modified from the ns-2 simulator [23], libAra that used a DES-testbed platform [29] and Pharos testbed that used a combination of an OMNeT ++ simulator and a click modular router [30]

The Emulab testbed in its early phases of development, used its own version of testbed practice management that included mobile emulab facilities. On a similar note, the MINT testbed used MOVIE, an in-house testbed GUI based management and monitoring platform that was developed based on the NAM toolkit (GUI component of ns-2 network simulator).

3.3. Mobile Robot Positioning and Localisation

It has been observed that a majority of MANET testbed facilities that used mobile robots utilised mobile robot localisation technology to monitor the current location of the mobile robots and guide the mobile robots’ positioning. Earlier generations of MANET testbed however, used visual based localisation methods where several cameras were mounted on the overhead ceiling within the testbed area. The cameras served to recognize different mobile nodes and identified their positions and movements. Among the testbeds that used visual based localisation methods were MINT and Mobile Emulab.

Proteus on the other hand, used several different methods as mobile robots in Proteus were used in many different fields including robotics research. The combination of GPS and compass sensors were an option for Proteus outdoor testbed localisation. For indoor testbeds however, various
localisation methods were chosen such as ultrasound scan localisations, IR bacon RSSI based localisations as well as visual localisations.

It was found that only a few testbeds did not utilise the robot localisation method to control mobile robot positioning and navigation. In fact, there were some that used only random movement approaches that excluded the monitoring of the location and movement of each mobile robot used in the testbed. The CONE testbed is one of the examples of a testbed that did not utilise a localisation method to control the mobility of the mobile robots in the testbed. In the CONE testbed, the movement of mobile robots were limited to green lines that acted as boundaries in the testbed area and the mobile robots were equipped with ultrasound sensors that provides avoidance abilities during their run.

To facilitate the readers understanding and flow of our discussion for the topic abovementioned, we presents it in tabular form as shown in Table 1. Table 2 on the other hand provide pictures of the type of robot used in MANET-Testbed.

**Table 1. Technical Summary of Robot-Based MANET Testbed**

| Testbed | Robot Platform | Robot Controller | Sensor and Other Components | Robot Software | Testbed Management System | Mobility and Localisation User Defined Mobility |
|---------|----------------|------------------|-----------------------------|----------------|---------------------------|---------------------------------------------|
| Mobile Emulab | Acroname Garcia | Intel Stargates Board (X-Scale 400MHz CPU) | • Ceiling Mounted Cameras • Colour Pattern Board • IR Sensors • Ultrasonic Sensors | Inhouse | Emulab Framework | Centralised visual localisation |
| MiNT-m | iRobot Roomba | Routerboard RN-230 | • Ceiling Mounted Cameras • Colour Pattern board | Inhouse | MoVIE | Centralised visual localisation |
| MiNT-2 | iRobot Create | Net5501 Board | • RFID Reader • Wheel Encoder • IMU | Inhouse | Desktop GUI interface | RFID based localisation |
| Proteus | Traxxas Stampede RC Car Chassis | Mini-ITX x86 Board and Arduino | • GPS • Compass Sensor • Player • ROS | Inhouse | Command Line Interface | Random waypoint mobility • User defined mobility |
| w-ilab.t | iRobot Roomba | In-House Board | • Wheel encoder sensors • IR sensors • Wi-Fi interface | Inhouse | ROS | Emulab Framework • GENI Framework • OMF/OML Framework • Random mobility with position logging • User controlled mobility • Odometry • RSSI based localisation |
| ARUM | Lynxmotion Atom Bot Board | Lynxmotion 4WD Rover | • IR Cameras • Reflective Ball as Marker | Inhouse | Inhouse | Fixed circuit-based mobility • Motion capture based monitoring |
| Sensei-UU | LEGO Mindstorms | Smartphone | • IR Sensors | Inhouse | Inhouse | Fixed circuit-based mobility • RSSI based monitoring |
| Institution  | Acronym  | Sensors | OSP | Framework | Mobility |
|-------------|----------|---------|-----|-----------|----------|
| Kansei      | Garcia   | Ceiling Mounted Cameras, IR sensors, Ultrasonic Sensors | Inhouse | GENI Framework | Centralised visual localisation |
| CONET-IT    | Pioneer 3AT | LIDAR, Microsoft Kinect, GPS, IMU Sensors | ROS | CONET Framework, GENI Framework | Random waypoint mobility, User control mobility |
| CONE        | LEGO Mindstorms | Ultrasonic Sensors, Colour Sensors | Inhouse | Inhouse | No localisation, Random move in fixed area |
| Roomba MADNet | iRobot Roomba/ Create | LIDAR, Microsoft Kinect, GPS, IMU Sensors | Inhouse | Inhouse | No localisation, Random move based on wireless signal RSSI |
| Explorebots | Rogue ATV | 1-axis Gyrometer, Bumper Sensors, Cliff Sensors, Wheel Drop Sensors | Inhouse | Inhouse | No localisation, Movement controlled by user |
| SCORPION    | iRobot Create | Microsoft Kinect, IR Sensors | Inhouse | Inhouse | No localisation, Random move in fixed area |
| MOTEL       | e-puck | Compass Sensor (HMC 6352), Wheel Encoder | Inhouse | Inhouse | Centralised Visual Localisation |
| iRobotSense | iRobot Create | Microsoft Kinect, IR Sensors, 1-axis Gyrometer, Bumper Sensors, Cliff Sensors, Wheel Drop Sensors | Inhouse | Inhouse | No localisation, Random move |
| IoT-Lab     | Turtlebot2 | Microsoft Kinect, IR Sensors | ROS | GENI Framework | Fixed circuit-based mobility |
| Wilfbot     | Intel Atom Based SBC | Microsoft Kinect, IR Sensors | Inhouse | GENI Framework | Fixed waypoint mobility |
| NITOS       | iRobot Create | Wheel Odometry, Webcam, Black and White Pattern Boards | Inhouse | GENI Framework | Fixed waypoint mobility |
Table 2. Robot Used in MANET Testbed

| Picture of Robot Used in MANET Testbed |
|----------------------------------------|
| Explorebots                           | MiNT-m     |
| CONET-IT                              | CONET-IT   |
| ARUM                                  | Kansei     |
| NITOS                                 | Roomba MADNet |
| MiNT-2                                | iRobotSense |
| w-ilab.t                              | Motel      |
| CONE                                  | Sensei-UU  |
| Mobile Emulab                         | IoT-lab    |
| IoT-lab                               | Proteus    |

4. Conclusion
The targeted objective of this work was achieved, that is to comprehensively discuss on the technical aspects of mobile robot usage in MANET testbeds. Further extension of this paper can be referred to in our paper entitled “A Critical Review of MANET Testbed Using Mobile Robot Technology” [30].

Armed with the wealth of relevant information provided in this paper, the content of this paper is expected to be a source of reference for MANET researchers who are at a crossroad when selecting the preferred mobile robot technology and approach to suit their own specific needs.

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