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Farkhana Muchtar, Abdul Hanan Abdullah

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Mobility in Mobile Ad-Hoc Network Testbed Using Robot: Technical and Critical Review

Farkhana Muchtar[a,b,1,*], Abdul Hanan Abdullah[a,2]

[a] *Faculty of Computing, Universiti Teknologi Malaysia, Skudai, 81310, Johor, Malaysia*
[b] *School of Computer Science, Universiti Sains Malaysia, 11800, Pulau Pinang, Malaysia*

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 and analyse MANET testbeds that were facilitated with mobile robot technology for previous undertaken research. To enable readers to keep abreast with mobile robot technology used in previous research, whilst presenting the advantages and disadvantages of said methods, this review will first superficially discuss prior robot based MANET testbed facilities, before presenting technical analysis overview and critical analysis. Additionally, suggestions to heighten mobility mechanisms by using mobile robots to be more practical, easy and inexpensive are also included in this paper. The technical and critical content of this review is expected to be a source of reference for other MANET researchers interested in the most suitable mobile robots to ensure real mobility in their MANET testbeds.

Keywords: MANET Testbed, Mobile Robot, Real Mobility

1. Introduction

Most research that involves mobile ad-hoc network (MANET) evaluation utilise simulation methods. Recently, it has become increasingly clear that the current practice of utilizing network simulators could only provide summarized assumptions in modeling the characteristics of the real systems. As the researcher needs to observe the effect and influence of the MAC and the physical network layer due to mobility and topology changes against the links and communication quality of the MANET, a MANET testbed with real mobility is therefore vital. In terms of accuracy, the results obtained from this approach are not available using methods such as network simulation and emulation. As of now, only a few experiments have been conducted in the MANET testbeds as compared to simulation based MANET experiments [1–21]. There are various methods of mobility implementation that are used in MANET testbeds, which can be divided into two main types, namely real mobility and emulated mobility (sometimes called virtual mobility). Both methods have their own advantages and disadvantages.

The distinctive feature of emulated mobility is its non-physical node mobility. In other words, although the real implementation of the MANET testbed is performed on the data-link layer and the application layer above, the node mobility is not conducted physically. Physical node movement and topology changes are

*Corresponding author
Email addresses: farkhana@gmail.com (Farkhana Muchtar), hanan@utm.my (Abdul Hanan Abdullah)
[1]Currently a Ph.D. candidate at Faculty of Computing, UTM, Malaysia.
[2]Currently is a Senior Professor at Faculty of Computing, UTM, Malaysia.

carried out through the use of emulation [22]. There are several different methods of emulated mobility such as instance migration [23], on connections [22], RF matrix switches [7, 24–27] and the use of virtual machine technology and virtual networks [28].

Among the wireless testbed platforms that have used emulated mobility methods Open-Access Research Testbed for Next-Generation Wireless Networks (ORBIT)[3] [23], Ad-hoc Protocol Evaluation (APE) testbed with emulated mobility[4] [29–31], the Carnegie Mellon University Wireless Emulator (CMUWE)[5] [32–40], Castadiva[6] [41–43], Mobi-emu[7] [44], Emulab[8] [45, 46], MOBNET [47, 48], MobiNet [49], the Resilience Evaluation Framework for Ad Hoc Networks (REFRAHN) [50, 51], MeshTest[9] [7, 24–27] and WISEBED[10] [52].

Emulated mobility methods have the advantage of being repeatable and reproducible that are almost the same as the network simulators. Mobility mechanisms that are conducted are therefore more manageable and predictable. However, emulated mobility methods are unable to represent the actual MAC layer and physical layer and hence the result obtained using emulated mobility are less accurate than the use of real mobility [22, 44].

Real mobility in MANET testbed experiments is vital in order to obtain accurate and realistic result. However, implementing real mobility in the testbeds is a difficult task. If this is done correctly, real mobility is able to provide very accurate experimental result on the impact of mobility on MANETs [1, 10, 53].

Previous research on MANETs have reported the use of various approaches to provide real mobility mechanisms in their MANET testbeds. Some of the methods included the use of cars [54–59], taxis [60], trains [61], [52, 62–66], bicycles [67, 68], humans [1, 8–12, 69–81], remote control cars [82], and multiple mobile robots (to be discussed in the next section).

Although there have been some reported reviews on robot-based MANET testbeds, it has been observed that the reviews mainly discussed only general aspects and surface level discussions on the use of mobile robots in MANET testbeds. Other review articles have discussed robot-based MANET testbeds from robotic perspectives while interrelating them with testbeds in other areas that utilise mobile robot technology.

In this review, the main focus was the MANET testbeds that utilised mobile robot technology to provide real mobility. The use of mobile robot technology to provide real mobility in MANET testbeds is an interesting approach as mobile robots provide the highest controllability of node movements as compared to other methods. Furthermore, as mobile robots allow high controllability of the MANETs for the real mobility of the researchers in their experiments, this also meant that mobile robots have great potential in improving the repeatability and reproducibility of the MANET experiments conducted.

Hence, this review article aims to comprehensively discuss and analyze robot-based MANET testbeds that have been developed in previously reported research. Furthermore, this analysis is based on the perspectives of a MANET researcher. Previous robot-based MANET testbed facilities will be discussed superficially before a technical analysis overview and a critical analysis is presented. This will allow readers to observe how mobile technology robots have been used to create well-designed MANET testbeds while at the same time providing readers with information on the advantages and disadvantages of each of the methods.

[3] http://www.orbit-lab.org
[4] http://apetestbed.sourceforge.net
[5] http://www.cs.cmu.edu/~emulator
[6] http://castadiva.sourceforge.net
[7] https://code.google.com/archive/p/mobiemu/
[8] http://emulab.net
[9] https://wiki.umiacs.umd.edu/VirtualMeshTest/index.php/Main_Page
[10] http://www.wisebed.eu

2. Related Work

In this section, readers can obtain information related to mobility execution in MANET testbeds. Some successful examples on the use of robots for mobility testbeds are outlined. Also, the surveys found in the bibliography on MANET testbeds using robotic mobility are critically analyzed.

2.1. Discussion from Other Surveys

Prior to this, several review articles have reported MANET testbeds with real mobility as part of their review. Some of the reviews have only slightly discussed the use of multiple mobile robots in providing real mobility in the testbeds. Most of the reviews that discussed the use of mobile robots in testbeds have focused on testbeds for mobile sensor networks. The remaining reviews have discussed the general use of mobile robots in testbeds with no specific focus on MANET testbed.

Kropff et al. [83], Blywis et al. [84] and Kulla et al. [53] are among the first pioneering surveys on the implementation of MANET testbeds. However, they only conducted a review on the MANET testbed mobility with mobile robots for the Truemobile (Mobile Emulab) testbeds [85] and MINT testbed [86–88] only. This was because Truemobile and MiNT were among the earliest MANET testbed platforms that used mobile robot technology to provide real mobility within their testbeds.

Kropff et al. [83] mainly discussed the advantages of using the testbed miniaturization method in Truemobile [85] and MiNT [86–88] towards a wireless multi-hop network of mobile nodes that allowed experiments to be conducted repeatedly in indoor testbeds without being affected by environmental conditions. There was not much discussion on MANET testbeds with real mobility in his report.

Blywis et al. [84] stated that the number of experiments using MANET testbeds was very low in number when compared to simulation method experiments. This was due to the fact that technology at that time was still constrained in terms of cost, effort and complexity of implementation for developing MANET testbeds with real mobility. Blywis et al. [84] also emphasized on the need and importance of a software framework that facilitated researchers to perform algorithms that were developed in their study into testbed platforms that were as easy as the implementation in simulation facilities.

Kulla et al. [53] reported that mobile robot technology was capable of being a tool to help testbeds with real mobility to be more repeatable and reproducible similar to using simulation methods. According to their findings, if the development cost and complexity of implementing mobile technology in MANET testbed robots could be reduced, the use of mobile robots as real mobility in MANET testbeds would allow researchers to observe and report unpredictable effects in their experiments and use those findings as a reference in the future.

A review by Jiménez- González et al. [89–91] was one of the most comprehensive reviews that was identified. Although the review was conducted from the perspective of ubiquitous robotics, their review allowed an easy understanding of robotics without a need for prior technical robotics knowledge. Jiménez-González et al. [89–91] divided all the testbeds they reviewed into three main types that were, non-integrated testbeds, partially-integrated testbeds and highly-integrated testbeds. This testbed categorization distinguished between the testbeds used for multiple mobile robots for MANET experiments and testbeds that were used for multiple mobile robots that communicated as MANETs. The categorization facilitated an understanding of these differences for those with little or no background in the robotics field.

Most MANET testbeds reported that used mobile robots to provide real mobility were mobile sensor networks (MSN). Some testbeds combined mobile sensor networks with generic MANETs (ad hoc network of mobile devices, not mobile sensor nodes) and only a few testbeds were dedicated for generic MANET testbeds. Therefore, most of the reviews were conducted on mobile sensor network testbeds [92–96].

Osman Khalid and Muhammad Sualeh [92] conducted a simple review of four testbeds that used mobile robot technology for MSN testbeds namely MINT [88], Mobile Emulab (Truemobile) [97], Pharos [98], Scorpion [67] and Sensei-UU [99]. Each testbed was analyzed from various angles such as scalability, automaticity, repeatability and others. Based on their work [92], they stated that a good WSN testbed should be scalable and reliable in its characteristics and if it involved mobile robots, cost was a critical factor in determining the size of the testbed to be developed. Testbeds should also be autonomous in their characteristics that included the self-charge ability of the mobile robots to enable 24x7 operation plus the inclusion of web based interface testbeds to enable the researcher to use the testbed facilities remotely.

A survey conducted by Horneber & Hergenroder [93] was based on the WSN testbed implementation trends, and comparisons between previous and current WSN testbeds at that time. The latest trend in the development of WSN testbeds at that time was the creation of mobile node facilities in the testbeds that used mobile robotic technology. Horneber & Hergenroder [93] observed that in order to allow WSN testbeds that had mobile nodes to generate repeatable and reproducible experiments (especially on mobile nodes locations and trajectory), accurate mobile robot localisation techniques needed to be used. Apart from the need to provide real mobility in the testbeds, mobile nodes were also developed in WSN testbeds as nomadic testbed facilities whereby the testbeds could be remounted and restored at any location as per the requirements.

Wichmann et al. [94] noted that the use of mobile robots in WSN testbeds was a growing trend and the level of autonominity of mobile robots varied depending on different WSN testbeds. Some were fully autonomous and some required human intervention. Wichmann et al. [94] was more inclined towards the integration of mobile robots with WSN testbeds as compared to the use of mobile robots for piggyback sensor nodes to provide mobility in the testbeds.

Akkaya et al. [94] compared WSN testbeds that used mobile robots for mobility based on two perspectives that were; comparisons that were based on robot platforms and comparisons that were based on based testbed platforms. Akkaya et al. [95] concluded that most of the testbeds focused on navigation and localisation issues of the mobile robots for MSN testbeds and not much effort was given to the MSN testbeds themselves. Furthermore, most of the testbeds used an IEEE 802.11 based wireless network and very little was reported on sensor node communication based on IEEE 802.15.4. There was a lack of focus on the overall design of the MSN testbeds including the lack of detail on interference issues, sensing, routing and sensor node energy consumption in the MSN. Often, the testbed hardware and software used were not specified and described in detail. The omission of this information made it difficult for other researchers to learn and expand their knowledge of the developed testbeds.

Tonneau et al. [96, 100] categorizes mobility in testbeds into two categories that were; undergone and controlled mobility. Most of the mobile robot based mobility in WSN testbeds fell into the controlled mobility category. Self-charging and localisation was given emphasis to create autonomous testbeds with little human intervention. In addition, Tonneau et al. [96, 100] emphasized the use of practical and user friendly software and tools so that testbed users could conduct their experiments in a simple and seamless manner.

2.2. Prior Research That Utilised Robots for Mobility in MANET Testbeds

The selection of robot-based MANET testbeds that were chosen in this review was purely based on the perception of MANET researchers and not from a robotic perspective as was reported in several 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 addition, some new testbed facilities that were not elaborated in previous review articles are outlined.

During the early stages of compiling this review, the choice of suitable robot-based MANET testbeds that were appropriate for discussion was difficult due to the fact that the definition on the scope of MANET-based research itself was rather vague. For example are mobile sensor networks (MSNs), opportunistic networks and delay tolerant networks (DTNs) subsets of MANETs? There has yet to be one existing and agreeable reference that discusses and defines these vague but bordering and closely knitted definitions of MANETs. It was then decided that MSNs, opportunistic networks and DTNs were a subset of MANETs because all the mentioned wireless ad-hoc networks had the mobility criteria and most importantly, wireless multi-hop ad-hoc communication.

There has been also some reported research on MANET technology that was used as a backbone to a communication network of multiple mobile robots. Examples of research in MANET-based multiple robot communication are CENTIBOTS[11] [101–105], Robomote[12] [106–110] and Mobile Multirobot Systems[13] [111, 112]. 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.

Only selected articles that were relevant to this review have been compiled. Instead of discussing all the existing MANET testbeds, the primary focus is on robot-based MANET testbeds that can be highlighted as a source of reference for other MANET researchers who are interested on the use of mobile robots for real mobility in their MANET testbeds.

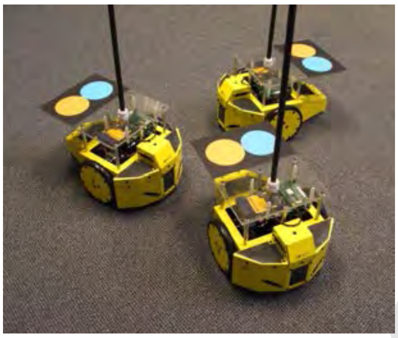
2.2.1. Mobile Emulab Testbed (Also Known as TrueMobile)

Mobile Emulab, otherwise known as TrueMobile was developed and run by Flux Group, part of the School of Computing at the University of Utah. It was one of the first mobile sensor node network testbed facilities that provide registered users public access to mobile sensor network testbeds with real mobility using robots. Mobile Emulab was a continuation of the Netbed testbed, a testbed platform that used an emulation method especially for wired network testbeds [113]. Mobile Emulab was among the most popular public WSN testbeds until its discontinuation in 2008 [91].

The L-shaped testbed was conducted indoors in an area that covered $60m^2$. There were 25 static sensor nodes Mica2 installed in the testbed arena and for the Mobile Emulab setup, 6 units of mobile robots based on the Acroname Garcia robot platform were developed and each mobile node was accompanied with a unit of 900 MHz Mica2 sensor node and Intel Stargates computer board with an X -Scale 400MH CPU (running Linux) as a robot and mobile node controller. Each mobile node had two Wi-Fi interfaces, one with a wifi interface for the sensor node (WSN) and the other WiFi interface was for the testbed control network. Wi-Fi antenna for the sensor nodes were placed on top of a 1 meter pole to represent the height of humans that carried mobile devices [85, 97, 114–116].

[11] `http://www.ai.sri.com/centibots/`
[12] `http://www-robotics.usc.edu/~robomote/`
[13] `http://webuser.unicas.it/lai/robotica/`

Figure 1: Mobile Emulab Wireless Node Robot



Visual based localisation was used by placing 6 units of ceiling-mounted cameras to trace the position of each mobile node in the testbed area. Each mobile node was placed with a colored card that had different pattern to represent different mobile nodes. The sensors on the Acroname Garcia robot platform were used for collision and obstacle avoidances during the testbed [85, 97, 114–116]. Mobile Emulab used a standard Emulab API and Interface that enabled the Mobile Emulab GUI to display the current status of the mobile nodes in the testbed using images when the testbed used was in progress.

The main drawback of the Mobile Emulab was that the developed mobile node did not have a self-recharging mechanism. As a result, the testbed operations were often a painstaking effort that limited the number of times and the duration that the testbeds could be operated [117].

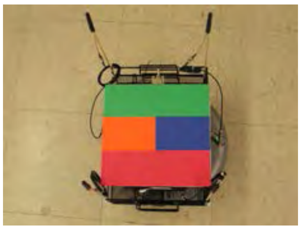
2.2.2. MiNT, MiNT-m and MiNT-2

MINT (miniaturized mobile multi-hop wireless network testbed)[14], developed by Stony Brook University, was an indoor MANET testbed that emphasized on the miniaturization of testbeds where a real multihop wireless network could be conducted in a small testbed area. The MINT testbed was used as an experimental platform in research that were related to mobile ad-hoc network testbeds [117–123].

12 units of MINT-m (mobile) were developed to replace the initial prototype of a mobile node that originally used a LEGO Mindstorm based robot platform [87]. Mint-m was equipped with iRobot Roomba as its robot platform and Routerboard RN-230 as its robot controller and mobile node. At the same time, the Mint-m was a self-recharging mobile node that fully utilised self-charging docking facilities that were available on the iRobot Roomba [86, 88, 117]. Each unit of the MINT-m Wi-Fi was installed with 4 Wi-Fi interfaces where 3 of the Wi-Fi interfaces were used for the multi-channel ad hoc network testbed and the other Wi-Fi interface was used for the testbed control network. Robot localisation was conducted in a centralized manner using visual localisation where the tracker software received input from 4 overhead cameras to determine the position of each mobile node [117].

[14] `http://www.ecsl.cs.sunysb.edu/mint/`

Figure 2: MiNT-m Mobile Node



TrueMobile

Top View

To enable users to control the operation of the testbed, the MOVIE (Mint Control and Visualization Interface) software was developed. MOVIE functioned as the 'eyes' and 'hands' for the user to regulate and manage existing resources in the MINT. MOVIE also enabled the MiNT testbed to be accessed remotely by outside users [117].

Each of the MINT-m mobile nodes were equipped with a hybrid simulator, which was a modified ns simulator where the simulation model of the link layer, the MAC layer and the physical layer of the simulator were replaced with wireless card drivers, firmware, and real wireless channels respectively. In addition, MINT also suggested a distribution solution that was easy to deploy and test with the availability of the Fault Injection and Analysis Tool (FIAT) component [117].

A few years later, MINT-215 was developed as a continuation to the MINT project in collaboration between the University of Binghamton and SunnyBrook University. The main goal of the MINT-2 project was to reproduce the MINT testbed for research purposes on wireless networking in Binghamton University using methods and technologies that were more effective and up to date [124–126].

Figure 3: MiNT-2 Mobile Node

There were three notable and significant improvements to the MiNT-2 testbed when compared to the original MINT testbed namely:

i. The first improvement was in the use of iRobot Create instead of iRobot Roomba that was cheaper and more developer friendly. The iRobot Create was coupled with the Roomba Serial Console User Interface (SCI) to allow manipulation [124–126].

ii. The second visible improvement was the replacement of the visual based localisation with an RFID based localisation that was more robust, simple and cheap. The MINT-2 mobile node navigation system was a combination of an RFID based localisation and wheel odometry from a wheel encoder found on iRobot Create [124–126].

iii. The third improvement was the replacement of the Routerboard RB-230 to a Soekris net5501 board, a x86 processor -based computer board. The net5501 board was easier to use and could share a power source with the iRobot Create as compared with the old MINT-m, where the Routerboard RB-230 used a separate laptop battery [124–126].

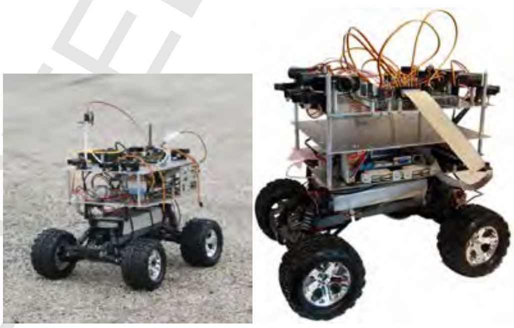
2.2.3. Proteus Mobile Node in PHAROS Testbed

PHAROS Testbed was a project developed by a team of researchers from the Department of Electrical and Computer Engineering in collaboration with research teams from the Mobile and Pervasive Computing Group, the Laboratory for Informatics, Networks, and Communication (LINC) and the Wireless Network and Communications Group (WNCG). The Proteus mobile node on the other hand, was developed to meet the need for creating multiple mobile robots in PHAROS testbed facilities that were often used in other multidisciplinary research namely; robotics, MANETs, VANETs, WSNs, mobile networks and wireless networks [127].

There are several design versions of the Proteus robots developed by PHAROS Testbed developers as shown in Figure 4. Most of the testbeds involved pervasive computing and mobile networks that utilised the Proteus robot that used a Traxxas Stampede RC Car Chassis as shown in Figure 5 [98, 127].

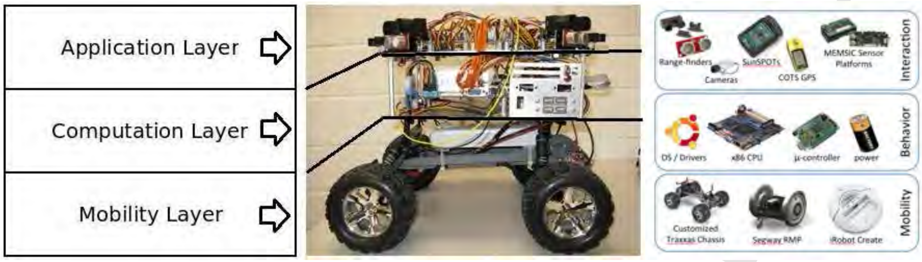
Figure 4: Three Different Types of Proteus Mobile Nodes

Figure 5: Proteus Mobile Node using Traxxas Stampede Chassis



The design layout of the Proteus robot components was arranged modularly where each component was placed in a staggered manner and the components were divided separately in different platform panels according to their respective functions. In general, the components of the Proteus robot consisted of three layers namely; the mobility plane, the computation plane and the application plane (Figure 6).

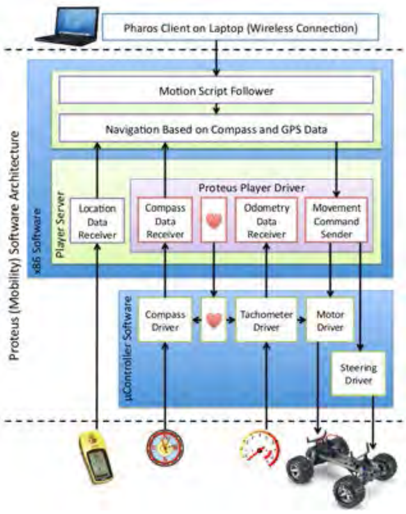
Figure 6: Proteus Seperation of Modular Hardware



In Proteus, the combination of a x86 embedded computer and microcontroller was used as the robot control module. The microcontroller was used for tasks that were related to real-time processing such as motor control and sensor data processing. The x86 computer on the other hand, was used to perform high-end and complex processes such as the robot control logic [98].

A player framework (in the latest version, an ROS framework[15]) was selected as the main software platform to control the Proteus robot mobility when the testbed was running while several other software such as Jbot were used for the path coordination of the Proteus robot when the testbed was in use [127].

Figure 7: Proteus Software Architecture



The Pharos testbed platform was used to experiment in various fields such as MANET [128] VANET [129], DTN [130–132], mobile cyber-physical systems [133] and Autonomous Intersection Management Policies [134].

2.2.4. An Approach for the Resilience of Ubiquitous Mobile Systems (ARUM) Mobility Platform.

An Approach for the Resilience of Ubiquitous Mobile Systems (ARUM) Mobility 17 is a testbed platform that was developed in collaboration with The Mosaic project[16], The Hidenets (highly dependable IP-based

[15] http://pharos.ece.utexas.edu/wiki/index.php/Controlling_the_Proteus_III_Traxxas_using_ROS_Hydro
[16] http://webhost.laas.fr/TSF/mosaic/

Networks and Services) project[17] and The ReSIST organization[18]. Mobile robot technology was chosen as the mobility platform for the ARUM testbed to enable the testbed to be carried out using a repeatable real mobility. The Lynxmotion 4WD Rover was the main robot platform as this particular robot chassis had the capacity and ability to carry loads weighing 2 kg at speeds of 1 m/s for several hours while it was in duration. This was a required feature for this particular experiment as it was similar to a person carrying a laptop. Robot control and localisation were implemented using the Lynxmotion Atom Bot Board, a robot control module that also included the Lynxmotion 4WD Rover. The robot control module communicated with the localisation server that also interacted with motion capture based facilities to ensure that each of the mobile robots knew their time and position exactly [135, 136].

Figure 8: The ARUM Platform

Each mobile robot in the ARUM testbed moved according to the line track that was drawn on the floor surface while robot localisation and positioning used motion capture technology. Previously, researchers in the ARUM project used several localisation methods such as an ultrasound beacon-based localisation and a Cricket Solution developed by MIT. However, noises captured from the ultrasound sensors severely reduced its accuracy. Ultimately, they resorted to the solution of motion capture based on localisation utilizing 3 different products for a motion capture solution, namely The Cortex system, the Hagisonic Stargazer technology and the Ultra-Wide- Band-based localisation system (UWB) by Ubisense [135–137].

The ARUM testbed also utilised a miniaturization approach by reducing the Wi-Fi transmit power and at the same time, used a radio signal attenuator to reduce the radius signal range between each mobile node up to 4 meters in radius to enable the multihop wireless network to be conducted in a small space testbed [138].

2.2.5. Robotic Mobile Nodes in w-iLab.t Testbed Laboratory

w-iLab.t Zwijnaarde testbed laboratory[19] in iMinds Research Institute[20] is one of the GENI based wireless testbeds that has mobile nodes as part of their testbed assets. It is located in Zwijnaarde, Ghent, Belgium where it provides 20 units of mobile robots along with 60 other static sensor nodes. Mobile robots for the wireless network testbed were deployed in a second w-iLab.t (Zwijnaarde lab) in 2013 [139] as an extended mobility facility in the w-iLab.t testbed [139–142].

w-iLab.t is a heterogeneous wireless network testbed that supports IEEE 802.11 a/b/g for Wi-Fi, IEEE 802.15.4 (e.g. ZigBee) for WSN, IEEE802.15.1 for Bluetooth and cellular networks such as GSM, HSDPA

[17] `http://web.archive.org/web/20150217155501/http://www.hidenets.aau.dk`
[18] `http://www.resist-noe.org`
[19] `http://wilab2.ilabt.iminds.be`
[20] `http://ilabt.iminds.be`

and LTE platforms by using a software-defined radio platform (USRP) technology. W-iLab.t also allows the testbed to be conducted in a centralized mode (or infrastructured network) or in an ad hoc multihop wireless network (e.g. mesh network and MANET). A spectrum sensing component is also attached to conduct studies that included wireless signal spectrum analysis in their testbeds [139–142].

Mobile robots in the w-iLab.t Zwignaarde used iRobot Roomba as the robot platform and a Roomba Serial Console Interface (SCI) to control and utilise sensors available in the Roomba. Each mobile robot was also equipped with the same facilities such as a fixed node that consisted of 1 unit of a sensor node (eZ430), 1 unit of powered embedded PC with an Intel Atom processor chip that was used as a mobile node, 1 unit of an emulator environment. In addition, an extra battery pack was required to supply power to the PC and the embedded in-house custom made board to control a mobile robot and to recharge both the iRobot Roomba and the mobile node (embedded PC) [140, 141, 143].

The integration between the control and coordination of the mobile robots with the testbed management system was based on an OMF framework whereby users used the OMF format testbed configuration file to determine the coordination of the mobile robots and how they were used in the testbed. The use of the OMF framework for the testbed configuration simplified the process in cases where users needed or were required to repeat their experiment repeatedly using mobile nodes [140].

Similar to other testbeds that used iRobot Roomba as their main robot platform for mobile nodes, w iLab.t also used a self-charging docking station that was available on Roomba to be part of its autonomous features in mobile nodes for the w-iLab.t testbed lab. Every time the mobile node spent one cycle of an experimental task, the mobile node then will return to the docking station for self-charging while at the same time connecting itself back to testbed control network [140, 141].

Figure 9: w-iLab.t GENI Mobile Node

In the early stage of testbed development, w-iLab.t used a dead reckoning approach for mobile robot localisation and positioning. This method was based on the assumption that the current position of the mobile robot was known and accurate. The current position of the mobile robot while moving was detected through a method known as odometry using a wheel encoder that was already available on the iRobot Roomba. To improve the position accuracy, the testbed area floor was marked with black and white lines both vertically and horizontally to allow mobile robots to recheck their current positions using cliff sensors that were also available on the iRobot Roomba each time it passed through the white and black line on the floor of testbed area [140].

However, it was found that the robot localisation approach also created many flaws and had many disadvantages particularly when the exact location of the mobile robot was missed. The accuracy of the mobile robot localisation greatly affects the quality of the experiments conducted and therefore new robot localisation methods needed to be developed to overcome robot localisation accuracy issues [141]. Hence, the latest method developed for mobile robots in the w-iLab.t was an RF-based indoor localisation system where Wi-Fi RSSI signals were processed using an RSS-based multi-lateration algorithm to determine the exact current position of the mobile robot [143, 144].

w-iLab.t mobile node facilities can be used remotely via the web based testbed interface[21] by authorized users only. w-iLab.t is integrated with other testbed laboratories under the ed4fire federation and uses a GENI interface to allow integration on the experiment [140, 145].

One of the MANET experiments that utilised mobile node facilities in the w-iLab.t laboratory was a research conducted by Neumann et al. [146] that compared performance and resource consumption of three open source mesh routing protocols which were olsrd, babeld and bmx6 with real mobility on each of the MANET nodes. The facilities available in the w-iLab.t allowed Neuman et al. to carry out the experiment with ease on a testbed setup using real mobility as compared to their previously reported experiments [21, 147] which were conducted using only emulation-based node mobility. They found that the use of the testbed facilities that provided real mobility in the testbeds enabled results that were more accurate and realistic, most notably on issues related to interference and CPU consumption [146].

2.2.6. Sensei-UU

Sensei-UU is a WSN testbed that uses a group of small mobile robots for repeatable real mobility. It was developed by the Uppsala Vinn Excellence Center for Wireless Sensor Networks[22] and was partly supported by VINNOVA. This testbed was run indoor and was integrated with static nodes and a central site manager of an existing WSN testbed lab [17, 99, 148–150].

Mobile nodes were built using LEGO NXT robots as their main platform and each mobile node was equipped with 1 unit of TelosB WSN nodes and 1 unit of a smartphone. TelosB was used as the sensor node for testbed purposes and the smartphone functioned as a testbed robot controller with Wi-Fi communication and as the central site manager. Therefore, there were two wireless network in the Sensei-UU, namely ZigBee WSN testbed for the network (IEEE 802.15.4) that was available in the TelosB sensor node and a Wi-Fi network for the testbed control network (IEEE 80.211b/g) that was available on a smartphone [17, 149, 150].

Figure 10: Sensei-UU Mobile Sensor Node

[21] `http://robotcontrol.wilab2.ilabt.iminds.be`
[22] `http://www.wisenet.uu.se`

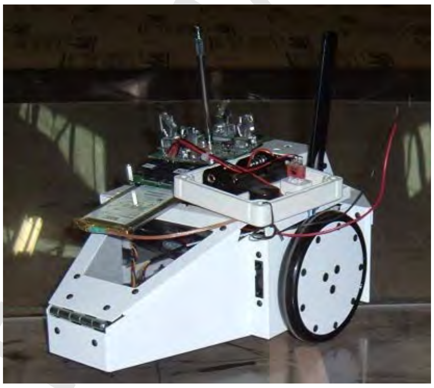
Sensei-UU utilised a simple robot positioning technique that used a tracks and markers approach where each mobile robot would move according to track lines on the floor inside the testbed area. For mobile robot localisation, the TelosB sensor node would share the RSSI reading with the smartphone to estimate the individual mobile robot location through an RSSI based localisation approach. The usage of line tracking and positioning and the RSSI based localisation ensured that the same simple mobile node localisation could be easily adapted by various different types of mobile robots. The whole Sensei-UU testbed architecture used a centralized approach that provides modularity and flexibility in its design to fulfill the requirements from internal developers [17, 149, 150].

2.2.7. Kansei Testbed

The Kansei testbed is a testbed facility that was used as a research platform related to networked sensing applications that was conducted on a large scale. The Kansei testbed was designed to support a variety of WSN related research that would cover indoor or outdoor environments.

The testbed facilities developed consisted of one WSN with 210 static sensor nodes and multiple Acroname-based mobile robots. Each node in the WSN on the other hand, were combinations of Extreme Scale Mote (XSM) and Stargate board. Mobile nodes that used the Acroname robot were equipped with XSM to represent the mobile sensor nodes in the Kansei testbed and interacted with static sensor nodes available in the Kansei testbed [151, 152].

Figure 11: Kansei Mobile Node



To ensure that the testbed was properly managed, the Kansei Director was developed as a centralized modular testbed management system that allowed customization and integration to be carried out according to the requirements of an experiment. The Kansei Director is a software component developed to manage complex multi- tier experiments. The Kansei testbed could be accessed remotely (open to public in 2005) and hybrid simulation method(s) could be performed simultaneously in both a simulator and the real hardware [151, 152].

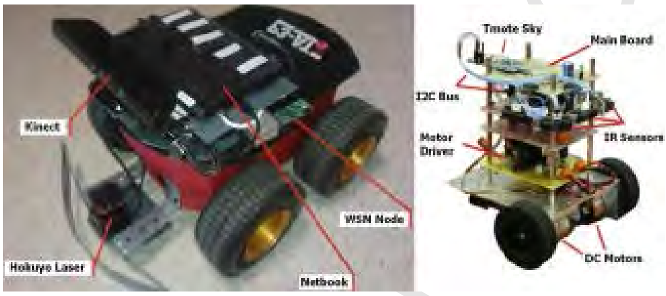
The use of a mobile robot in the Kansei testbed was merely for the mobility of the sensor node purposes as robot localisation was centrally controlled through the Kansei Director. Interactions of the mobile robots did not fully occur on the sensor nodes carried in the mobile node but the interactions that took place were simply testbed instructions sent by the Kansei Director via the mobile robot controller [151, 152]. The same approach was also used in other testbeds such as that developed by Rahimi et al. [153], Giordano et al. [154], Jayasingha et al. [155] and Forster et al. [156].

2.2.8. Mobile Robots in CONET-IT (Cooperating Objects Network of Excellence Integrated Testbed)

The Cooperating Object Network of Excellence (CONET)[23] testbed is a generic remote testbed that supports various forms of experimentation and it provides a variety of applications for research purposes related to wireless networking. It was developed at the University of Seville under the Cooperating Objects Network of Excellence fund [89, 90, 157].

Two types of mobile robots were developed using two different robot platforms known as Pioneer 3AT and another custom robot platform that used a RC car chassis. Each mobile robot unit was equipped with a laser range finder, Microsoft Kinect, GPS and IMU sensor nodes [158, 159].

Figure 12: CONET Mobile Node



The mobile robot operations were controlled via a Player/Stage modular software with commands from the testbed control center. Mobile nodes in CONET-IT could be accessed via an interactive web-based interface and it provided some basic functions such as user-controlled mobility for experiments in various fields such as mobile sensor networks and ubiquitous robotics [89–91, 158].

CONET-IT facilities have been used in several experimental fields including mobile robots, WSNs, and integrations between WSNs and mobile robots. Some of the experiments conducted in CONET testbed facilities were RSSI based WSN localisations, simultaneous multiple robot localisations, mobile robots and WSN cooperation for data collection, as well as robot guiding using WSNs [91, 159].

CONET-IT facilities were designed in a flexible manner to enable new experiments that could be conducted whenever the need for new equipment and technology arose in the future. The main strength of CONET testbed facilities was that peer to peer integration of mobile nodes could be enabled without full intervention of the controller from the main testbed [159].

2.2.9. Mobile Nodes in Cooperation and Network Coding (CONE) Testbed

Mobile MANET testbeds were developed by the Cooperation and Network Coding (CONE) as a research project under Aalborg University to address issues related to network coding implementation in mesh networks of mobile devices. In particular, CONE researchers realized that data dissemination processes performed differently in dynamic networks as agile protocol was required to enable mobile nodes to interact with each other when they were within communication range [160].

CONE researchers used the LEGO Mainstorms NXT as their robot platform for mobile nodes and Nokia Mobile Phones (7 units Nokia N97 mini, 1 unit of Nokia 97 and 2 units Nokia 5800 XpressMusic) as mobile devices for the MANET testbeds with real mobility purpose(s). Previously, CONE researchers tried to reuse testbeds with a mobile robot method proposed by Reich [161] for the Roomba MADNet that utilised the

[23] `http://www.cooperating-objects.eu`

Robot Create robot platform. However iRobot Create did not meet the criteria that they required in terms of speed and steering abilities and at the same time, it was also less suitable for outdoor testbeds [160, 162].

The CONE testbed design did not utilise robot localisation and merely provided simple logic to the LEGO NXT to perform random movements within the testbed arena. All the 10 units of mobile robots involved were placed in a circular formation in the middle of testbed arena as in Figure 13 before the testbed was performed. The Standard LEGO Mindstorms ultrasonic and color sensors used equipped each mobile node with the ability for obstacle and collision avoidance and it moved inside the testbed area that was bordered and marked with green lines [160, 162].

Figure 13: LEGO Robots with Nokia Mobile Phone

LEGO NXT and the Nokia mobile phone on each mobile node had no direct interaction with each other. The robot platform served only to provide real mobility in the testbed. All the testbed processes and collection of testbed results were conducted in the Nokia mobile phones. Testbed autonomy was achieved by setting a coordinator node among the 10 mobile nodes in the testbed that would determine the start and stop of the testbed and at the same time, determine which testbed should be running. The coordinator node also monitored the status of each mobile node to ensure that the testbed performed effectively. During the testbed run time, some human intervention was required when the mobile robot stopped moving, after it failed to overcome a particular obstacle in the testbed area [162].

During the testbed operation, the results obtained were collected on each of the Nokia mobile phones and was then analyzed based on several metrics such as bandwidth, throughput, completion time and energy consumption, each at different data dissemination strategies [162].

2.2.10. Roomba MADNet in SCAN (Spreadable Connected Autonomic Network) Research

MADNet (mobile, ad-hoc, delay tolerant network testbed) is a testbed setup with real mobility and it was developed as a testbed platform for Spreadable Connected Autonomic Network (SCAN) Research at Columbia University. The objective of SCAN research was to study ad hoc network connectivity and data collection. MADNet was designed to be a platform to implement mobile SCAN network designs.

iRobot Create robots were selected as the main platform, although Reich et al. [161, 163, 164] named the mobile node platform of the testbed as Roomba MADNet and the Linksys WRTSL54GS wireless router (installed with OpenWRT Linux OS) was chosen as the mobile wireless device. Roomba MADNet was equipped with multi peripherals such as a webcam for generating image data in the network testbed and USB storage to save testbed log files. The Roomba MADNet setup is displayed in Figure 14. The router and the peripherals were supplied with power from the iRobot Create battery through a modified serial port connection to the iRobot Create serial interface.

Figure 14: Roomba MADNet Mobile Node

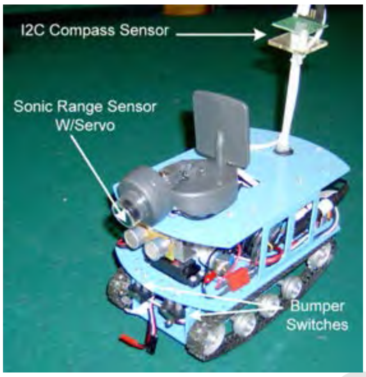
The focus of SCAN research was on network connections and therefore, researchers have excluded the robot localisation method on Roomba MADNet. Simple algorithms were used to operate Roomba MADNet that prescribed each of the mobile nodes to move forward until an obstacle(s) was detected, then the Roomba MADNet moved towards the opposite direction, away from the detected obstacles. To ensure the formation of a random network topology, each Roomba MADNet would change the polarity of its direction of rotation at random before it moved forward again [165].

Figure 15: Roomba MADNet in Action

2.2.11. Explorebots

Explorebots is an indoor based mobile robot testbed designed for mobile multi-hop network research. It was constructed using Rogue ATV as its robot chassis, a Rabbit 3000 microprocessor as its main controller and Mica2 as its wireless communication module. In addition, Explorebots was also equipped with multi sensors such as the ultrasonic range sensor, a magnetometer for heading and direction sensors, tactile sensors for obstacle avoidance and custom-made wheel encoders for odometry measurements. The combination of the ultrasonic range sensor, magnetometer and wheel encoder functioned as its robot localisation. In addition to the robot controller board, sensor nodes and various other sensors, Explorebots was also equipped with a wireless webcam for remote monitoring purposes on the GUI-based testbed controller [165].

Figure 16: Explorebot with Sensors



2.2.12. SCORPION, Heterogeneous Wireless Networking Testbed

SCORPION (Santa Cruz Mobile Radio Platform for Indoor and Outdoor Networks) is a heterogeneous multihop wireless network testbed run by the Inter-Networking Research Group (i-NRG) at UC Santa Cruz University of California. The SCORPION project was created to study heterogeneous wireless networking environments that included MANET. The SCORPION testbed has many types of mobile nodes namely, airplane node, bus node, briefcase node (carried by people to reflect human mobility) and iRobot Create mobile node [67].

There were 4 units of airplane nodes, 40 mobile nodes installed on the bus, 20 nodes in the form of briefcase nodes and 20 nodes in the form of mobile robots. Each mobile node was equipped with a mini-ITX computer and used the Wi-Fi network for wireless communication. The iRobot based mobile node was used as the indoor mobile node where every movement of the mobile robot used a random waypoint mobility model [67].

2.2.13. MOTEL: Mobile Wireless Sensor Network Testbed

MOTEL testbed is a mobile sensor network testbed platform developed by the Networking Laboratory, ISIN-DTI, University of Applied Sciences of Southern Switzerland. The MOTEL testbed platform consisted of two main components namely, the MuRobA (MultiRobot Architecture for Coordinated Mobility) as its first component that was related to localisation and navigation of multiple mobile robots which allowed real mobility to be performed in mobile sensor network and a second component named FLEXOR (flexible sensor network architecture for enabling backchannel-free WSN experiments) that controlled and managed mobile sensor network experiments performed in the MOTEL testbed [156, 166, 167].

e-puck is chosen as the main robot platform for the MOTEL testbed and it did not interact with the piggybacked sensor node. Mobile robot (epuck) positioning and localisation was controlled through a MuRobA system via Bluetooth wireless communication. Testbed processes towards sensor nodes carried by each mobile robot was controlled by FLEXOR via IEEE 802.15.4 wireless communication. MOTEL used a visual localisation approach utilizing one fisheye camera unit that was mounted on the ceiling to recognize the position and movement of each mobile node and the information obtained was sent to MuRobA. After that, MuRobA would provide further instructions to each of the mobile nodes regarding the direction of movement and destination of each random waypoint from the information that was generated [166].

Figure 17: MOTEL Mobile Robot

2.2.14. iRobotSense : A Mobile Sensing Platform Based on iRobot Create

iRobotSense is a mobile node for mobile sensor network testbeds that use iRobot Create as its robot platform. The main goal for the development of iRobotSense was to test the effectiveness of routing algorithms in the sensor node when it reconnected a disconnected wireless connection due to sensor node mobility [168].

iRobotSense mobility did not use a robot localisation method as the movement distance and destination was already known and fixed. The combination of compass sensors (HMC6352) and a wheel encoder on iRobot Create was used to help iRobotSense identify the direction and distance of movement according to the given movement instructions [168, 169].

Figure 18: iRobot with Sensors

The simplistic design of the Simple iRobotSense was intended to ensure that the cost of iRobotSense was kept low with the use of a simple mobility mechanism and straightforward operation as well as a simple mechanism of robot localisation [168, 169].

Among the experiments conducted using iRobotSense testbed was a research conducted by Senturk et al. [170], which involved real implementation of MSN connectivity based on a partition approach.

2.2.15. Mobile Nodes in FIT IoT Laboratory (IoT-Lab)

FIT (Future Internet of Things) IOT-lab[24] is the largest IOT laboratory ever built to date and was developed by the Future Internet of Things (FIT) Consortium[25] [96, 100, 171]. IOT-lab was a continuation to the SensLAB project [172, 173] (operated from 2010 to 2013) [174]. It consisted of 2728 wireless sensor nodes placed in 4 different lab facilities namely, Inria Grenoble (928 nodes), Inria Lille (640 nodes), ICube

[24] `https://www.iot-lab.info`
[25] `https://www.fit-equipex.fr`

Strasbourg (400 nodes), Inria Rocquencourt (344 nodes), Inria Rennes (256 nodes) and Institut Mines-Télécom Paris (160 nodes) which included several mobile nodes in each lab facility.

IoT-Lab has two types of mobile robots, turtlebot2 and wifibot. IOT-lab turtlebot2 used a turtlebot 2 robot platform[26], and a low cost open source robotic platform that was powered by a Kobuki mobile robot. It was equipped with an Asus X200CA netbook as the robot controller and/with Microsoft Kinect, a gyroscope and a 4 hall encoder for robot localisation. IOT lab wifibot was a mobile robot that uses a 4x4 wheel RC car chassis. It was equipped with a dual core Intel Atom based single board computer (SBC) as its robot controller, Microsoft Kinect and a gyroscope for robot localisation [174].

IOT-Lab turtlebot2 was a COTS robot platform that was equipped with a self-recharging docking station. IOT-lab wifibot on the other hand, required an IOT-lab team to develop their own self docking station. A self- recharging mechanism was required on the IoT-Lab mobile robot to enable testbeds to be carried out autonomously [174].

Figure 19: Mobile Nodes in FIT IoT-Lab

At present, the mobility method used for mobile robots in the IOT lab is a fixed circuit-based mobility and this method falls under the category of predictable uncontrolled mobility. In future, the IoT-Lab will add two more modes of mobility namely, model-based mobility such as random waypoint mobility[27] and manhattan mobility[28] and user controlled mobility [175].

2.2.16. Mobile Nodes at NITOS Testbed

The NITOS wireless testbed is one of testbed facilities offered by the Fed4Fire federated community. NITOS focuses on the provision of testbed facilities for experimenting with wireless communication research that includes mesh networks, cloud computing, cellular networks, WSNs and computer wireless networks [176–180].

Mobile robot based testbed facilities developed by NITOS testbeds were based on the present need for mobile nodes with real mobility in their testbeds [177, 181] The NITOS team used iRobot Create as its robot platform equipped with an Alix motherboard and Arduino Uno as the robot controller. In addition,

[26]`http://www.turtlebot.com`
[27]`https://en.wikipedia.org/wiki/Random_waypoint_model`
[28]`https://en.wikipedia.org/wiki/Manhattan_mobility_model`

a webcam, a digital accelerometer and an ultrasonic range finder were also installed as sensors for mobile robot localisation purposes. The Alix motherboard was equipped with two Wi-Fi interfaces (Atheros AR5006), where the first controlled the robot and testbed while the second was utilised for wireless multi-hop networking [181].

The NITOS team believed that augmented reality-based localisation was the practical choice for the mobile robots that they developed whereby each waypoint destination of the mobile robot mobility path was placed with different specific pattern and the webcam was used to recognize the patterns to ensure that mobile robots were positioned at the desired waypoints in the testbed. A GUI-based application was developed to control and monitor the movements of each of the mobile nodes involved.

Mobile robots in NITOS testbeds are still in the prototype level and have not been optimised for general use [181].

Figure 20: NITOS Mobile Node

3. Technical Review

In this section, the discussion centers around the hardware and software used in previous research when robots were developed in their testbeds.

It is to be noted that in most cases, the discussion on previous testbed facilities did not reveal the technical aspects regarding mobile node facilities that were used in the testbed laboratories, especially for public testbed laboratories. Most testbed facilities that provide technical information is 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. The remaining testbed facilities merely states some technical specifications of mobile nodes in the testbed facilities without elaborating much details.

The discussion herein is related to the technical aspects of mobile robot usage in MANET testbeds which includes exploring the trends and advancements in robot technology usage chosen by robot-based MANET testbeds. The conditions needed for suitable construction of good robot-based MANET testbed facilities can be deduced and applied in the future.

Table 1: Technical Summary of Robot-Based MANET Testbed

	Hardware			Software		Mobile Robot Mobility
Testbed	**Robot Platform**	**Robot Controller**	**Sensors and Other Components**	**Robot Software**	**Testbed Management System**	**Mobility and Localisation**
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	Dekstop GUI interface	RFID based localisation
Proteus	Traxxas Stampede RC Car Chassis	Mini-ITX x86 board and Arduino	* GPS * Compass sensor	* Player * ROS	Command Line Interface	* Random waypoint mobility * User defined mobility
w-ilab.t	iRobot Roomba	in-house board	* Wheel encoder * Bump sensors * IR sensors * Wi-Fi interface	ROS	* Emulab Framework * GENI Framework * OMF/OML Framework	* Random mobility with position logging * User controlled mobility * Odometry * RSSI based localisation
ARUM	Lynxmotion 4WD Rover	Lynxmotion Atom Bot Board	* IR Cameras * Reflective ball as marker	Inhouse	Inhouse	* Fixed circuit-based mobility * Motion capture based monitoring

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	Hardware			Software		Mobile Robot Mobility
Testbed	**Robot Platform**	**Robot Controller**	**Sensors and Other Components**	**Robot Software**	**Testbed Management System**	**Mobility and Localisation**
Sensei-UU	LEGO Mindstorms	Smartphone	* IR sensors	Inhouse	Inhouse	* Fixed circuit-based mobility * RSSI based monitoring
Kansei	Acroname Garcia	Stargate board	* Ceiling mounted cameras * IR sensors * Ultrasonic Sensors	Inhouse	GENI Framework	Centralised visual localisation
CONET-IT	Pioneer 3AT	Netbook	* LIDAR * Microsoft Kinect * GPS * IMU sensors	ROS	* CONET Framework * GENI Framework	* Random waypoint * user control mobility
	RC car chassis	PC-104 embedded PC	* GPS * IMU sensors * IR sensors			
CONE	LEGO Mindstorms	LEGO NXT	* Ultrasonic sensors * Colour sensors	Inhouse	Inhouse	* No localisation * Random move in fixed area
Roomba MADNet	iRobot Roomba/Create	Linksys WRTSL54GS wireless router		Inhouse	Inhouse	* No localisation * Random move based on wireless signal RSSI
Explorebots	Rogue ATV	Rabbit 3000 microprocessor		Inhouse	Inhouse	* No localisation * Movement controlled by user
SCORPION	iRobot Create	Unknown		Inhouse	Inhouse	* No localisation * Random move in fixed area

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	Hardware			Software		Mobile Robot Mobility
Testbed	**Robot Platform**	**Robot Controller**	**Sensors and Other Components**	**Robot Software**	**Testbed Management System**	**Mobility and Localisation**
MOTEL	e-puck	iRobot Create Controller		Inhouse	Inhouse	Centralised visual localisation
iRobotSense	iRobot Create	Asus X200CA	* Compass sensor (HMC6352) * Wheel encoder	Inhouse	Inhouse	* No localisation * Random move
IoT-Lab	Turtlebot2	Netbook	* Microsoft Kinect * IR sensors * 1-axis Gyrometer * Bumper sensors * Cliff sensors * Wheel drop sensors	ROS	GENI Framework	Fixed circuit-based mobility
	Wifibot	Intel Atom based SBC	* Microsoft Kinect * IR sensors			
NITOS	iRobot Create	Alix Motherboard	* Wheel odometry * Webcam * Black and white pattern boards	Inhouse	GENI Framework	Fixed waypoint mobility

3.1. Hardware Platforms

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 [182–187].

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 favorite 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) [182–187].

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 [88], MINT-2 [124–126], Proteus Roomba [124–126], w-ilab.t [140, 141, 143], Roomba MADNet [161, 164], SCORPION [67] and iRobotSense [168].

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 [17, 149, 150] and Cone Testbed [160, 162].

The Acroname Garcia robot platform also was a popular choice in several MANET testbeds such as the Emulab Mobile Mobile Emulab (TrueMobile) [85, 97] and Kansei Testbed [151, 152].

There are also other readymade robot platforms that were utilised, such as e-puck that was used in the MOTEL testbed [156, 166, 167], the Pioneer 3AT robot platform used in CONET-IT [89–91, 158, 188], the Lynxmotion 4WD rover robot platform used in ARUM [135, 136] and theRogue ATV robot platform used in Explorebot [165].

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 [17, 149, 150], custom made circuit boards such as w-ilab.t [140, 141, 143] 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 [160, 162] and also Atom Bot Board Lynxmotion [135, 136], 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 [124–126], a solution that was quite rare in mobile robot design.

Some mobile robots have used laptops/netbooks as their robot controller, e.g. ARUM [135, 136], CONET-IT (Pioneer 3AT platform) [89–91, 158, 188] and IoT-lab (turtlebot2 platform) [174] 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 robot s 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 [135, 136] or fish eye cameras such as in the MOTEL testbed [166] to track the location and movement of mobile robots. Most testbeds used color pattern recognition to identify different mobile robots identities such as Mobile Emulab [85, 97, 114–116], MINT-m [117] and MOTEL [166], 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 [181] 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 [17, 149, 150] and ARUM [135, 136] that used fixed circuit-based mobility and they were usually equipped with infrared sensors to detect black linex placed on the floor to guide their movements.

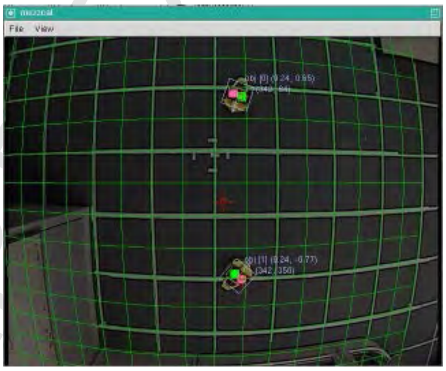
For testbeds that used the iRobot Roomba and iRobot Create, wheel encoders that were available on Roomba or Create were fully utilised as an aid in determining the distance, speed and direction of their movements using the odometry method to support the localisation mechanism as used in the MINT-2 mobile robot [124–126], w-iLab.t [140]and Explorebot [165].

Robot-based MANET testbeds that used the Acroname Garcia robot platform for mobile robots such as Mobile Emulab.Mobile Emulab (TrueMobile) [85, 97] and Kansei Testbed [151, 152], 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 [98, 127].

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 [90].

Figure 21: Mobile Emulab's Ceiling Mounted Camera View for Centralised Visual Based Localisation



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 [85, 97, 114–116], MiNT- m [117], MINT-2 [124–126], ARUM [135, 136], Kansei [151, 152] and Sensei-UU [17, 149, 150]. 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.

Figure 22: Fixed Radio Signal Attenuator on ARUM Mobile Node

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 MAD-Net that used a Liniksys 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-iLab.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.

Figure 23: Sensor Nodes Used in CONET-IT

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 [117], libAra that used a DES-testbed platform [189] and Pharos testbed that used a combination of an OMNeT ++ simulator and a click modular router [129, 132].

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.

4. Critical Review

In this section, we critically analyze the approaches that are used in previous researches. Identical in almost all past researches related to the implementation of robotic based MANET testbed, is that they all have a similar motivation, namely to produce MANET testbed platform with real MANET implementation that would run utilizing real hardware with each MANET nodes within in its testbed posing its own controllable real mobility. So far, all mobile testbed implementation have claimed to produce a mobile testbed that is cheap and easy to be installed that caters for MANET however until today, none of the previous testbed implementation have been widely utilised in MANET research area.

Table 2: Robot-Based MANET Testbed Criteria Summary

Testbed	Purpose and Accessibility	Scope	Usability	Controlability	Repeatability	Reproducibility	MANET Dev Tools
Mobile Emulab	Public	Mobile Sensor Network	Medium	Low	High	Medium	None
MiNT-m	Community	Mobile Sensor Network	Medium	Medium	High	Low	Hybrid Simulator
MiNT-2	Community	Mobile Sensor Network	Medium	Medium	High	Low	Hybrid Simulator
Proteus	Community	Various	Low	High	Medium	Medium	Click Modular Router
w-ilab.t	Public	Wireless Network	High	High	High	High	Click Modular Router

Table 2: Robot-Based MANET Testbed Criteria Summary

Testbed	Purpose and Accessibility	Scope	Usability	Controlability	Repeatability	Reproducibility	MANET Dev Tools
ARUM	Community	MANET, VANET, DTN	Medium	Medium	High	Low	None
Sensei-UU	Community	Mobile Sensor Network	Medium	Medium	High	Low	None
Kansei	Public	Mobile Sensor Network	Medium	Low	High	Low	None
CONET-IT	Public	Wireless Network	High	High	High	High	None
CONE	Private	MANET, DTN	Low	Low	Low	Low	None
Roomba MADNet	Private	MANET	Low	Low	Low	Low	None
Explorebots	Community	Mobile Sensor Network	Medium	High	Low	Low	None
SCORPION	Community	MANET, DTN	Medium	Low	Low	Low	None
MOTEL	Community	Mobile Sensor Network	Medium	Medium	High	Low	None
iRobotSense	Private	Mobile Sensor Network	Low	Low	Low	Low	None
IoT-Lab	Public	Mobile Sensor Network	High	High	High	High	None
NITOS	Public	Wireless Network	High	Low	High	High	None

4.1. Purpose, Accessibility and Scope of Testbed Facilities

From our observations, there are three categories of objectives and purpose in robot-based MANET testbed namely;

i. MANET testbeds for specific purpose (private testbed)
ii. MANET testbeds for community usage

iii. MANET testbeds for public access

In the first category, some MANET testbed facilities have been identified as those created specifically for just one particular study or experiment. Examples of some testbed facilities created for such research purposes include the CONE project [160, 162] and Roomba MADNet [161, 163, 164] with their one-off usage characteristics. Once the project was completed, no further development or improvements were made on the testbed platforms. Robot- based MANET testbeds in this category are only accessible by the owner of the testbed facilities to carry out experiments for their own research purposes.

The second testbed category was developed for various research and experimentations that could be used either within the same field or in different fields within community groups. Community members share testbed facilities that they jointly develop on a rotation basis to perform their experiments. Examples of testbed facilities used only for internal community members are MINT, Pharos (Proteus mobile node) and ARUM.

Usually, community-based testbed facilities are used in similar research areas such as in wireless networks or MANETs. MINT and ARUM testbeds are examples of testbed facilities in the same research area. However, there are also community- based testbed facilities that cater for a variety of different fields such as Pharos that uses the Proteus mobile robot for robotic research, MANETs and wireless networks.

The last category is MANET testbed facilities for public access. This category was developed as a public facility to be utilised by researchers from all over the world. In normal circumstances, public robot-based MANET testbeds can be accessed by testbed users remotely via a web based interface.

Public access testbed facilities are usually developed to serve similar research interests that are related to general networking. The type of sub-networking that can be supported are dependent on the testbed facility provider. Some public access testbed facility laboratories are available for MANET research and some of them are equipped with robot-based MANET testbed facilities. On the other hand., some public access testbed laboratory provide facilities to conduct wireless networking research that covers and includes a wider area scope such as MANET, static mesh networks, WSNs, MSNs, DTNs, Wi-Fi, WiMAX, Bluetooth, ZigBee, IoT, Cellular Networks (including 2G, 3G and 4G networks) and other user defined radio signals.

Most public MANET testbed facilities are part of federated network testbed laboratory facilities such as GENI (Global Environment for Network Innovations) Federation[29] [190], Fed4FIRE (Federation for Future Internet Research and Experimentation)[30] [191], CONET (Cooperating Objects Network of Excellence) Testbed Federation[31] [158, 159] and PlanetLab[32] [192]. Federated testbed facitilties provide several advantages as users are able to utilise more than one testbed laboratory in the same testbed federation using the same identity authentication. Furthermore, federation members share their resources to further improve the quality and strength of each testbed laboratory and this facilitates various experiments and research from all over the world. Examples of robot-based MANET testbeds developed for public access are IoT-LAB, myth, CONET-IT and w-iLab.t.

4.2. Usability and Controllability of Robot Mobility in Testbed Facilities

In this section, the discussion focuses on the level of usability, configurability and controllability of mobile robot movement and the activities that are involved within the robot-based MANET testbeds that are

[29] `https://www.geni.net`
[30] `http://www.fed4fire.eu`
[31] `http://web.archive.org/web/20100926201955/http://www.cooperating-objects.eu/testbed-simulation/testbed-federation/`
[32] `https://www.planet-lab.org`

reviewed. The purpose of this discussion is to observe the types of methods, approaches and the technologies used in the MANET testbed facilities that are related to controlling and monitoring the mobile robots during experiments. Furthermore, the ease of use of the testbed interfaces when controlling and monitoring the mobile robots by the testbed users is also examined.

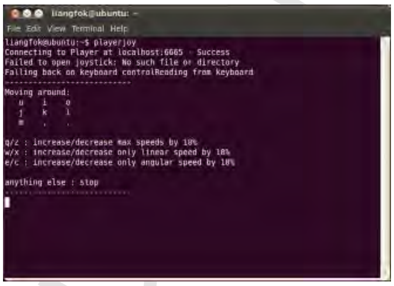
4.2.1. Usability

Testbed interface to manage mobile node resources can be divided into three main types, namely,

i. Command Line Interface (CLI) such as those used to control the Proteus mobile nodes in Pharos testbed and Roomba MADNet.
ii. Desktop GUI as used in the MINT and MINT-2 testbeds.
iii. WebWeb based GUI as used in the w-iLab.t CONET testbed.

CLI is a user interface with the lowest usability level as compared to desktop GUI and web based GUI. Although the CLI provides more flexibility and the ability for users to have more control on the testbed but it requires users to be well versed with each of the commands and their options and most users are not able to master it properly and efficiently.

Figure 24: CLI Based in Proteus to Control Robot's Mobility



Desktop GUI enables better interactions for testbed users and provides higher usability. Testbed users perform experimental configurations and are able to conduct the experiments with ease as compared to CLI. However, users need to perform some installation processes on the testbed client terminal before its desktop GUI based testbed interface can be used. Furthermore, if any changes occur when upgrades or improvements to the testbed management system are made, the desktop GUI software needs to be re-developed and re-aligned to the changes on testbed management system. At the same time, users need to reinstall the software to get new updates and features. Other challenges exist, particularly when the developed desktop GUI software is not multi-platform in nature and therefore this limits the type of client platform that can be utilised when using the testbed facilities.

Figure 25: MiNT MOVIE Testbed Management Software

GUI Based Controller | Overhead Camera View

A testbed interfaces that uses web based GUI is apparently the most ideal. Besides ease of use, it do not have the same problem as the GUI interface testbed. Users are not required to install any software to use it but instead only a web browser within the computer terminal is required in order to access the testbed management system. Testbed users are also not required to perform any additional upgrade process when upgrades are made to the testbed management system. A web based testbed interface also enables the use of almost all the computer platforms to conduct experiments in testbed facilities, as per requirements. The user only needs compatible web browser software.

Figure 26: w-iLab.t Web Based Control Panel for Mobile Node in Testbed

Usually, testbed facilities utilised for specific experiments or private usage, do not emphasize on the usability of the testbed system as this is not the main goal for testbeds in this category. Testbeds for CONE research and Roomba MADNet testbed facilities are examples of testbed facilities in this category as they were developed and meant for internal users only.

Testbed facilities that are meant for community usage encourage the usability of the testbed system. Usability of the testbed system allows for shorter experiment times which allows more experiments to be performed by community members using the same testbed facilities. An example of a robot- based MANET testbed in this category is the ARUM testbed. In public testbed facilities, usability stands as one of the most important factors in the design of the developed testbed system. Examples of public testbeds with high usability are CONET-IT, w-iLab.t, IoT-LAB and NITOS testbed systems.

The usability of the testbed interface is very important in public testbed facilities as it is used by large numbers of users remotely. If the usability of a public testbed is low, only a few users are able to use the testbed facilities.

4.2.2. Controllability

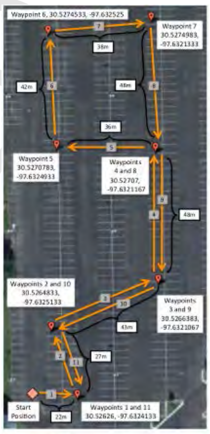
Controllability of the mobility of mobile nodes in MANET testbeds on the other hand, involves the degree of control that can be performed by the testbed users towards mobile node facilities in MANET testbeds. Emphasis is given on the type of mobility of the mobile nodes provided in the MANET. Controllability of mobility in robot-based MANET testbeds can be divided into three categories; which are

i. Fixed circuit-based mobility
ii. Fixed mobility model list
iii. User controlled mobility

Fixed circuit-based mobility is the easiest mobility method to set up but testbed users do not have control on the mobility of the mobile nodes in order to modify them according to their needs. Fixed circuit-based mobility provides the lowest controllability of mobile nodes as it does not allow users to control the number of mobile nodes used and the timing of mobility for each mobile node. Examples of robot-based MANET testbeds that use fixed circuit-based mobility are Sensei-UU, ARUM and IoT-Lab.

Some testbed facilities provide a list of mobility models that can be used by the users such as the random waypoint mobility model, metropolitan mobility model, mobility model group and social mobility model. Mobility models used are mostly inspired by other mobility models that are used in network simulators like ns-2, ns-3, OMNeT ++, QualNet, OPNET and NETSIM. Unlike network simulators, mobility models used in robot-based MANET testbeds are used to determine the pattern of multiple mobile robots when experiments are conducted.

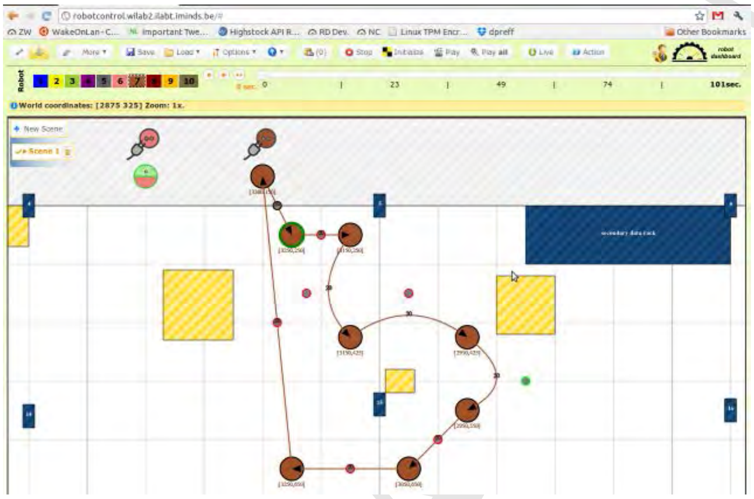
Figure 27: Waypoint Mobility in Pharos Testbed



The highest controllability of mobility for robot-based MANET testbeds is user controlled mobility. User controlled mobility can be divided into two subcategories distinguishable as mobility in which users manually perform the setup or in the second subcategory, in which users adds other mobility model algorithms into the testbed system as required. In the first subcategory, users perform a manual setup on the mobility of mobile nodes, choosing one from the two available setup methods. The first method is by setting up multiple waypoints manually or secondly, by setting the walk path of the mobile nodes during the experiment. Examples of testbeds that allow users to set their own mobility of mobile nodes are Pharos, MiNT and w-iLab. t.

The approach used in the second sub-category on the other hand, allows users to add new mobility model algorithms as additions to the mobility models already provided in the testbed system to suit the requirements and needs of the users. An example of a testbed facility that allow users to add a mobility model into the testbed system is IoT-LAB.

Figure 28: User Defined Mobility Path of Mobile Nodes in w-iLab.t



4.3. *Repeatability and Reproducibility of Real Mobility in Testbeds*

When the level of controllability of real mobility is high, then the repeatability and reproducibility of the mobile nodes movement is high. In any scientific research that also includes MANET, the repeatability and reproducibility of the experiments are very important as the credibility, preciseness and accuracy of the experiments are determined and dependent on it. Among the reasons why mobile robot technology is selected to provide real mobility in MANET testbeds is mainly due to the fact that this method provides the most efficient method that allows the movement of the mobile nodes to be repeatable and reproducible when experiments are conducted [17]. This is because the higher the level of controllability of real mobility, the higher the repeatability and reproducibility of the movement of the mobile nodes in the experiments.

Nonetheless, not all the MANET testbeds that were reviewed in this work are repeatable and reproducible in nature. This is because, the accuracy of the mobile robot localisation that is used in the testbeds is the key factor that would determine whether or not the mobility of the mobile nodes can be repeated or reproduced.

In this section, the characteristics of the repeatability and reproducibility of the mobility of the mobile nodes in the reviewed MANET testbeds are outlined.

4.3.1. *Repeatability*

In scientific research, observations on experiments conducted have no serious bearings and are not regarded as scientific observations if the experiments are not performed repetitively [193]. Furthermore, the repeatability of an experiment is very important to ensure that uncontrolled parameters or external factors such as wireless communication interferences and signal noise during the testbed runs can be obtained randomly through repeated tests to ensure unbiased testbed results [17].

Hence, experiments carried out in MANET testbeds must also be repeatable in their characteristics and this includes the mobility pattern of the mobile nodes. The repeatability of the movement of the mobile nodes in the MANET testbeds can be described in simple terms as the ability to repeat the movement of each mobile node in the same testbed based on position, direction of the movement and all the activities involved when moving.

To achieve repeatability in MANET testbeds is difficult and costly [22, 53]. To generate the repeatability of real mobility in testbeds is even more difficult as each mobile node requires the capability to move in the same mobility pattern, at the exact same period of time and at the same time be able to perform and obtain the same results from the previous experiments [194]. Therefore, most MANET testbed developers have used an emulation method to create a repeatable mobility mechanism in their testbed [22].

Among the reasons for the lack of repeatability in the movement of the mobile nodes movement are the lack of controllability features available in the testbed [17]. A high controllability of real mobility in the MANET testbed is achievable by developing a mobile robot localisation and monitoring system that is reliable and accurate. With a highly reliable and accurate mobile robot localisation, the movement of mobile nodes in a MANET testbed can be repeated thus reducing biasness on the experimental results.

Some of reviewed MANET testbed facilities in this work that were identified to operate with characteristics of repeatability on the mobility of mobile nodes were Sensei-UU, Kansei, and CONET, w-iLab-t, FIT IOT and NITOS laboratory testbeds. This was because all of the testbeds had mobile robot localisation and positioning systems that were reliable and accurate.

In addition, repeatable experiments can only be realized if the testbed facilities have the ability to store mobile node movements in the form of experiment configurations and descriptions. Public testbed facilities such as w-iLab-t, CONET, FIT IOT Laboratory and NITOS have high repeatability of mobility as this feature is particularly vital in public testbed facilities in order to ensure that the results obtained are regarded as scientifically valid.

The repeatability of mobility in MANET testbeds is easily implemented by using physical tracking (line tracing) to determine the movement of the mobile nodes. Control on the movements of the mobile robots is relatively easy as each mobile robot only needs to follow a black line on the floor using IR sensors and the monitoring system determines the current position of the mobile robots. However, the main disadvantage of this particular method is the limited and inflexible movement patterns that cannot be diversified.

For a virtual path method such as that used in Mobile Emulab and MINT testbeds, mobile nodes movement was found to be more flexible as it created different random waypoints for each experiment conducted and the same movement pattern could be repeated many times. This method however, required a mobile robots localisation and positioning system that was much more complex but it did allow better flexibility in providing controlled mobility of the mobile nodes.

There are also testbeds where movements of the mobile node[s] were non-repeatable as they were not equipped with a mobile robot localisation and positioning system such as CONE, MADNet Roomba serial connector and iRobotSense. Although the experiments were carried out repeatedly but the repetition used different mobile node movements as the mobility pattern was random and uncontrolled. As there was no mechanism to determine the current position and direction of each mobile node, the level of controllability of the mobile node mobility was low and results of the mobile node movements were unrepeatable.

It is believed that irrespective of whether the MANET testbed is private or public, the scope of experiment is specific or generic, the repeatability aspects of real mobility should be taken into account as this will be the determining factor that would affect the credibility of the experimental data and conclusions as whether or not, it will be accepted as scientifically valid by the research community.

4.3.2. Reproducibility

In the Oxford English Dictionary, reproducibility is defined as "the extent to which consistent results are obtained when repeatedly produced". In other words, reproducibility is the ability to completely or almost completely duplicate an experiment or study by other researchers who are conducting the experiment independently [195].

A reproducible experiment enables a research to be validated by other researchers to strengthen and verify that the findings obtained from their research are credible [196]. Any scientific hypothesis in an undertaken experiment should be reproducible to allow independent validations to be performed by other researchers as it is the core of the scientific method [196, 197]. Popper once said in his book 'The Logic of Scientific Discovery' that "a non-reproducible single occurrence poses no significance to science" [193].

MANET testbeds that are able to run reproducible experiments also require testbed facilities that can run repeatable experiments. However, repeatable testbed facilities are not enough to execute reproducible experiments. To allow the movement of mobile nodes in the testbed during an experiment to be reproducible, testbed facilities need to be able to record movements of mobile nodes with the exact similar timings and activities or processes that are involved during a specific mobile node movement.

Most of the older generation robot-based MANET testbeds (before 2010) had similar problems in conducting reproducible experimental testbeds in other locations. This was because robotic technology that was available at the time was either very expensive or the mobile robot localisation used depended on the local infrastructure conditions [17]. Thus, in the newer generation of robotic-based MANET testbeds (during and after 2010), the latest robotic technology was used which was cheaper and easier and hence, the experiments performed could be easily reproduced by other researchers.

Examples of robot-based MANET testbeds that can perform reproducible experiments are CONET, w-iLab.t, FIT IOT lab, Kansei testbed and NITOS. This is because all of the aforementioned testbeds use the latest easy-to-obtain robotic technology that enables real mobility for MANET experiments to be conducted with ease and better performance. Furthermore, testbed configurations provided by robot-based MANET testbeds use wider network testbed frameworks such as the GENI Framework and OMF-OML framework. Hence, testbed configurations, mobile node movements and all their activities can be easily reproduced on another testbed using the same framework.

Therefore, the development of the present robotic technology has facilitated the development of robot-based MANET testbeds that are capable of producing an environment for reproducible experiments. Additionally, whether or not the testbed developed is private, experiment-specific or is a public testbed, network testbed frameworks that are recommended for use that are widely used by others are the GENI framework and OMF-OML framework that can improve the reproducibility aspect of the experiment conducted in testbed facilities that they develop.

4.4. Tools for MANET Implementation, Deployment and Debugging for Experiments

Among the main reasons why only a few researchers have used the testbed approach to conduct their experiments is because of the fact that the development of a real implementation of any MANET solution is a highly difficult and complex process. Implementing a suggested solution of MANET using a simulation model is far much easier as researchers only need to focus on sections that are of interest to them. Developing a real implementation of a MANET suggested solution requires multiple and varied technical skills, high commitment, dedication and a long time to complete.

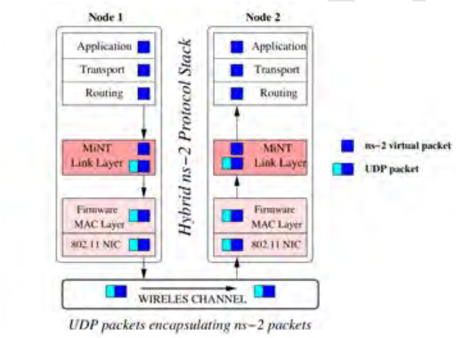
Mechanisms to facilitate areal implementation process of MANET is important because it can increase the amount of MANET research using testbed platforms as a tool to test the suggested solutions developed by

MANET researchers. MANET implementation in real world testbeds should be made to be at least as easy as MANET implementation in network simulators. In addition, the mechanisms should also allow simulation results to be validated with testbed results in improving the quality and accuracy of the simulation model of MANET solutions.

There have been a few developed hybrid types of simulators for MANETs and WSN such as [198], sensorsim [199], EM* or EMStar [200, 201] and TOSSIM [202].

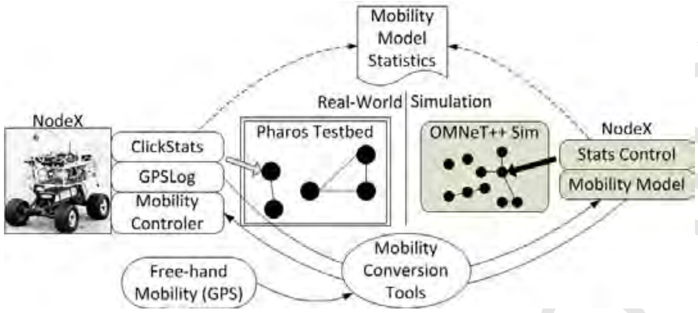
Based on previous MANET testbed implementations that were reviewed, several solutions proposed by previous researchers from their testbeds were recorded. Among them are MINT that introduced a hybrid simulator that was developed. De [117] developed a modified hybrid simulator from am ns-2 network simulator by replacing the simulation model of the link layer, MAC layer and physical layer of the simulator with wireless card drivers, firmware, and a real wireless channel respectively. Hence, the ns-2 based simulation model implementation could be reused as a real implementation in the testbed through the use of hybrid simulator.

Figure 29: MiNT Hybrid Simulator Architecture



In the Pharos, a Click modular router was used to facilitate MANET implementation testbed to be as simple as MANET simulations using simulation models in a network simulator [130–132]. The Click modular router is a software platform that allows the development of modular, flexible and configurable. Each component in Click performs simple router functions such as packet classification, queuing and packet scheduling. The modular design allowed Click users to focus only on the development of routing implementation specifically on the area of interest without the need of thinking about other unrelated and irrelevant components [203]. In the Pharos testbed, Click was used to validate implementation developed in an OMNeT ++ network simulator and the data obtained from the testbed was then compared with the data obtained from the OMNeT++ simulation[130–132].

Figure 30: Proteus Unified Simulation and Testbed



MANET solution deployment and debugging in the testbed's mobile node are also very important because when conducted manually, they will reduce the autonomy and simplicity of the testbed operation. A manual deployment and debugging process of a MANET solution to each individual mobile node is not practical and efficient in any testbed operation. Therefore, a distributed deployment and distributed mechanism is required in MANET testbeds especially in mobile node facilities.

In the MANET testbeds that were reviewed, only the MINT testbed platform discussed the mechanisms for software deployment and debugging in detail. MINT developers used FIAT (Fault Injection and Analysis Tool) as the software component to enable distributed deployment and debugging of various MANET solutions which allowed experiments to be conducted in the MINT testbed with ease.

There are public access MANET testbed that provides the Click modular router in their facilities such as w-iLab.t, where its usage in testbed facilities can be found in the user's manual. However, the use of the Click modular router in public MANET testbeds has yet to be discussed critically and academically.

From these observations, it was found that no research has seriously investigated on the potential use of supporting tools such as the Click modular router[33], ns-3-click bridge[34] and FINS framework[35] in the development of MANET solutions as part of the facilities that are available in MANET testbeds.

5. Conclusions and Suggestions for Future Work

Based on the studies and observations reported in this work on MANET testbeds that use mobile robot technology for real mobility, it was found that this approach was less popular compared to simulation methods. However, MANET researchers from all around the world have begun to realize the importance of the existence of such methods in MANET testbeds. Among the main reasons for the lack of use of testbeds as a platform in the experimental implementation of MANET research is the various complexities and technical know-hows that the researchers need to confront in order to develop mobile robots as well as the high costs incurred to develop the facility.

At present, robot technology is growing rapidly making it increasingly easy to be learnt and understood even by non-robotic experts. ROS frameworks at the moment, have a range of readymade components that can be utilised without having to master in-depth robotic skills, and is as easy as using API software without the need of knowing details on how each process works in the background.

[33] http://read.cs.ucla.edu/click/click
[34] https://www.nsnam.org/docs/release/3.24/models/html/click.html
[35] http://finsframework.org

Even robot components are becoming increasingly cheaper and easier to obtain due to current rapid open hardware and maker culture movements where even adolescents and young children have the ability and capacity to develop their own mobile robot.

Apart from the complexity of the mobile robot itself, researchers also find it difficult to implement the suggested solution that they themselves developed such as new MANET routing algorithms, MANET network coding approaches and cross layer solutions in real world implementation as compared to the form of simulation models. Moreover, the need for proper execution of the implementation developed towards each and every mobile node further increases the complexity that researchers are already faced with. Hence, to facilitate mobile robot technology for MANET testbeds, there exists an urgent need to simplify the process of research idea implementations so that they can be easily implemented or at least, can be nearly equivalent to the implementation of the suggested solutions offered in a simulation model.

It is also believed that the use of technology such as the Click Modular Router and hybrid simulators like ns click (ns-2 or ns-3 bridge to Click Modular Router) are able to solve the problems that are mentioned. Testbed implementations will then become so much easier to perform and will be as easy as using simulation models. As for distributed deployment and debugging processes, the use of a latest open source solution like Puppet can simplify the process of using real implementation in testbed facilities.

Although the technology to overcome the disadvantages of using testbeds, particularly ones that involve mobile robot testbeds is already in existence, this newfound technology has yet to be fully exploited in existing MANET testbeds and its promising potential should be harnessed and expanded in future developments of MANET testbeds.

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Author Profile

	**Farkhana Muchtar** (farkhana@gmail.com) is currently a Ph.D. candidate at Faculty of Computing, Universiti Teknologi Malaysia. She received Diploma and B.Sc. Degree in Computer Science from Faculty of Computing, Universiti Teknologi Malaysia, Johor Bahru, Malaysia, in 1997 and 2000 respectively. Later, she obtained Master Degree of Computer Science (under research mode programme) from School of Computing, Universiti Utara Malaysia, in 2007. Her current research interests include information-centric networking, pervasive computing, IoT and mobile ad hoc network.
	**Abdul Hanan Abdullah** (hanan@utm.my) received Ph.D. degree from Aston University, Birmingham, U.K., in 1995. He is currently a Professor with the University Tekhnologi Malaysia (UTM), Johor Bahru, Malaysia. From 2004 to 2011, he was the Dean of the Faculty of Computer Science and Information Systems. He is currently heading the Pervasive Computing Research Group under KEconomy Research Alliances, UTM. His research interests include wireless sensor networks, mobile ad hoc networks, network security, and next-generation networks. He has professional experience serving as Chief of Editor of IJ-CLOSER and several international journal as an editor.