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A Critical Review of MANET Testbed Using Mobile Robot Technology

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A Critical Review of MANET Testbed Using Mobile Robot Technology

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Abstract. This paper is a continuation of our previous paper under the same topic, MANET testbed using mobile robot technology. In our previous paper, we studied the topic by scrutinizing all the technical aspects and presented it as a technical review. However in this paper, we study the topic and presents it as a critical review that dwells into four aspect, namely (i) purpose, accessibility and scope of testbed facilities, (ii) usability and controllability of robot mobility in testbed facilities, (iii) repeatability and reproducibility of real mobility in testbeds, and (iv) tools for MANET implementation, deployment and debugging for experiments. With the wealth of information on the topic provided in this paper, the content of this paper is expected to be a source of reference for MANET researchers who are at a crossroad when selecting the preferred mobile robot technology and approach to suit their own specific needs.

1. Introduction

Recently, MANET (Mobile Ad Hoc Network) researchers have shown increased interest in using mobile robot technology for their testbed platforms. This paper therefore extends the technical discussions of our previous paper titled *"A Technical Review on MANET Testbed Using Mobile Robot Technology"* [1] by scrutinizing it as a critical review.

2. Critical Review

2.1. 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, and (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 [2, 3] and Roomba MADNet [4-6] 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 [7], Fed4FIRE (Federation for Future Internet Research and Experimentation) [8], CONET (Cooperating Objects Network of Excellence) Testbed Federation [9, 10] and Planet Lab [11]. 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, NITO, CONET- IT and w-iLab.t.

2.2. 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 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.

2.2.1. 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, and (iii) Web 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.

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 redeveloped and realigned 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.

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.

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.

2.2.2. Controllability. 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, and (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.

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.

2.3. 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 [12]. 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.

2.3.1. 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 [13]. 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 [12].

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 [14, 15]. 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 [16]. Therefore, most MANET testbed developers have used an emulation method to create a repeatable mobility mechanism in their testbed [15].

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 [12]. 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.

2.3.2. 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 [17].

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 [18]. 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 [18, 19]. Popper once said in his book 'The Logic of Scientific Discovery' that "a non-reproducible single occurrence poses no significance to science" [13].

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 con- ducting 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 [12]. 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.

2.4. 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 sensor sensorsim [20, 21], EM* or EMStar [22, 23] and TOSSIM [24].

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 [25] developed a modified hybrid simulator from 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.

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 [26-28]. 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 [29]. 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 [26-28].

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 tool such as the Click modular router ns-3-click bridge and FINS framework in the development of MANET solution as part of the facilities that are available in MANET testbeds.

Table 1. Robot-Based MANET Testbed Criteria Summary

Testbed	Purpose and Accessibility	Scope	Usability	Controllability	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
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
CONE-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
Explorebot	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

3. Conclusion

The targeted objective of this work was achieved, that is to comprehensively discuss and analyse on the topic of mobile robot usage in MANET testbeds. Thus, it is hoped that this article is able to assist potential users to easily choose their preferred mobile robot technology and approach that is suitable to his own needs.

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