NetCar: A Testbed for Mobile Sensor Networks

R. B. KORKMAZ[1], K. KIZILIRMAK[1], and İ. F. ŞENTÜRK[1]

[1] Bursa Technical University, Bursa/Turkey, ramazan.burak.korkmaz@gmail.com
[1] Bursa Technical University, Bursa/Turkey, kevserkzlrmk@gmail.com
[1] Bursa Technical University, Bursa/Turkey, izzet.senturk@btu.edu.tr

***Abstract* - Mobile sensor networks (MSNs) enable monitoring inhospitable areas without risking the human life in an autonomous manner. However, due to limited energy and exposure to harsh environmental conditions, the network can be subject to node failures. Depending on the network topology, location of the failure and its scope, the network can be partitioned into multiple isolated segments. Network partitioning can have catastrophic effects on the application due to the lack of data exchange and coordination among the partitions. The coverage declines and the fidelity of the collected data deteriorates. Considering the limited intervention to the application area, a self-configuring self-healing solution is required to restore connectivity in the network. An intuitive approach is exploiting mobility to restructure the network topology and link the partitions. In this paper, we present a mobile platform, named NetCar, which enables controlled mobility to facilitate MSNs. We discuss the design of NetCar and evaluate its performance in terms of energy consumption in various terrain features and levels. NetCar provides the basic building block to enable MSNs and can be used as a testbed to evaluate connectivity restoration algorithms for MSNs.**

***Keywords* - Mobile sensor network, testbed, robot, connectivity restoration, energy consumption.**

I. INTRODUCTION

THE recent advances in microelectromechanical systems (MEMs) has paved the way for low-cost low-power sensors coupled with wireless communication capabilities. By employing several sensor nodes forming a mobile sensor network (MSN), the phenomena can be monitored at a larger scale [1]. Despite availability of energy harvesting [2], most sensors are equipped with limited batteries that deem energy conservation. Therefore, typically, low-power wireless communication techniques are employed such as 6LoWPAN [3] that provides IPv6 connectivity over IEEE 802.15.4 based networks. Due to the limited transmission range of the facilitated radio technology, sensors form a multi-hop network. In the network, each sensor is regarded as a node. To connect the network with the rest of the world (e.g., cloud), a base station (BS) is employed. BS is less restricted in terms of energy and communication range and acts as a gateway between the network and the remote user. Since only a few nodes are expected to be located within the communication range of the BS, network-wide collaboration is required to deliver the sampled data.

Considering the limited on-board batteries and the tendency of deployment in areas with inhospitable surroundings [4], the network can be subject to node failures. Redundancy may compensate some node failures. However, network coverage will decline if the point of interest is monitored by the failed nodes exclusively. Furthermore, failure of the cut-vertex nodes will partition the network into segments isolated from each other. In such a scenario, only the nodes within the partition of the BS can deliver their data. The data collected by the rest of the nodes in other partitions cannot be delivered to the BS even if the nodes are still functional. Consequently, coverage declines drastically and the fidelity of the collected data degrades.

Depending on the application (e.g., battlefield surveillance, volcano monitoring, etc.), intervention to the application area may not be feasible. Thus, a self-healing solution is required. Mobility can be employed in various forms (e.g., random, controlled, etc.) to improve some of the network performance metrics including coverage [5] and network lifetime [6]. In this paper, we are particularly interested in controlled movement where the nodes can be relocated in a controlled manner. Controlled mobility can be exploited by attaching sensor nodes on mobile robots [7]. In a reactive manner, the node can control the mobile platform and move on-demand.

Mechanical movement incurs excessive energy cost [8] and therefore, mobility should be applied in a controlled manner and must be avoided unless it is required. In this paper, we assume the employment of controlled mobility to restore the network connectivity in partitioned mobile sensor networks. Various mobility-based connectivity restoration schemes are available [9]. One approach is moving the partition as a block towards another partition to link them. Note that the mobility of a single node may link the partitions. Thus, block movement is expected to cause redundant movement. Another approach is limiting the movement to a single leader node that sustains recovery with a single relocation at each step. If the relocation of the leader is not sufficient for recovery, a new leader is selected and the recovery proceeds in an iterative manner. Another approach is employing a mobile data collector (MDC) that visits partitions to collect their data and forward it to the BS. The mobile platform that we present in this paper is independent from the applied recovery scheme and can be used in sensor networks to enable controlled mobility. NetCar can be used as a testbed to evaluate the employed connectivity restoration algorithms. In this paper, we discuss the design details of the mobile platform and present its energy consumption characteristics in various scenarios. Note that the application area where the nodes are deployed may be formed of varying terrain types and elevation levels. Depending on the terrain type, friction force applied to the mobile node will not be the same [10]. Therefore, energy consumption must be evaluated according to the considered terrain features. In this paper, we have considered three different terrain types, namely marble, grass, and concrete roads. Marble road represents an indoor environment while grassy and concrete roads are outdoor environments. In order to investigate the relationship between the movement direction and the mobility cost, we have also considered movement on a curved path. Finally, to assess the impact of the road gradient on the energy consumption, we have varied the gradient angle of the road and applied mobility both uphill and downhill.

The rest of the paper is organized as follows. The design of NetCar is discussed in Section II. Energy consumption model of NetCar is evaluated in Section III. The paper is concluded in Section IV.

II. DESIGN

NetCar is a custom made mobile platform to enable controlled mobility in sensor networks. NetCar can also be used as a testbed to evaluate mobility scenarios in mobile sensor networks. The current version of NetCar is the preliminary design and supports basic mobility features. The controller is based on Arduino that provides flexibility to enhance its features in the future.

A. Chassis

The chassis of NetCar is commercially available [11]. 4WD all-terrain mobile platform enables deployment in areas with harsh terrain types. We have performed experiments on various terrain types including marble, grass, concrete, and wood. We have also varied the road gradient up to 20 degrees. It should be noted that the gradient can be increased even further but we restricted the experiments due to the limited range of the road platform. Some of the specifications of the chassis can be found in Table 1.

Table 1: Specifications of the chassis [11].

Wheel diameter	120 mm
Wheel width	60 mm
Platform length	195 mm
Platform width	140 mm
Length of body	270 mm
Width of body	280 mm
Platform height	120 mm
Platform weight	1280 g
Ground clearance	26 mm

B. Controller

The control unit is connected with different modules, sensors, and actuators. Some of the key responsibilities of the control unit are sensing the environment, performing calculations, and controlling the actuators (e.g., motors). We have employed Arduino [12], an open-source electronics platform, as the control unit. Arduino boards consist of an Atmel AVR microcontroller with various amounts of memory, pins, and features based on the model [13]. The boards have digital and analog pins to supply voltage and receive data. By changing the state of the pin, Arduino controls integrated circuits. Analog pins can convert analog voltage to digital data by using an ADC. The number of bits used in ADC determines the precision of the conversion. NetCar employs Arduino Mega 2560 as the control unit. This board has a 10-bit ADC that is sufficient to perform basic conversions. The board has 54 digital I/O pins. 14 of these pins are capable of generating PWM signals. The board also has 16 analog pins and a 16 MHz crystal oscillator with 4 KB EEPROM. The popularity of the Arduino platform with a wider community, which delivers several open-source projects every year, was the decisive factor in selecting the platform. The number of available pins and the cost of the board determined the Arduino model.

C. Peripheral Units

This section outlines the peripheral units on NetCar.

1. Motor Driver

NetCar has two BTS 7960 [14] half bridge motor drivers. Each motor driver has one p-channel high side MOSFET and one n-channel low side MOSFET with a microcontroller. The BTS7960 can operate up to 43 A. This maximum limit gives us a large margin of power to support mobility on terrains with rough conditions.

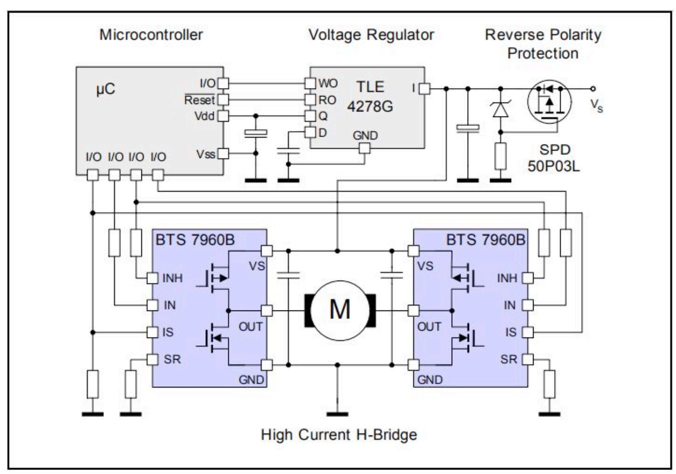

Figure 1: BTS7960 motor driver with a dc motor connection.

Motor drivers on NetCar control four geared dc motors. One of the motor drivers controls the right wheels and other one controls the left ones. By controlling different sides of NetCar, we can ensure the linear motion of the mobile or rotate it. Providing different levels of PWM (pulse width modulation) signals on each side enables controlling the direction of mobility. A detailed discussion on the PWM signal can be found in Section III.C. Figure 1 illustrates the application of the motor driver with single motor. Note that, NetCar drives two motors in parallel simultaneously.

2. Gear Dc Motor

Gear dc motors are popular in mobile robot applications since motor drivers can control them easily. NetCar is equipped with a standard 12 V gear dc motor (Zhengke ZGA25RP 100RPM [15]). Employed dc motor supports up to 100 RPM. This rotational speed ensures mobility on all-terrain.

Table 2: Specifications of the gear dc motor [16].

Rated voltage	12 V
Load speed	100 RPM
Rated speed	90 RPM
Gearbox length	19 mm
Rated current	0.52 A
Rated torque	0.263 N.m
Maximum torque	0.597 N.m

III. EXPERIMENTAL EVALUATION

In this section, we evaluate the energy consumption characteristics of NetCar in different scenarios. First, we discuss the current sensor that we use in the rest of the experiments and clarify the measurement methodology. Then we explain motor control and duty-cycle. Lastly, we provide results after introducing scenarios.

A. Measuring the Power Consumption

In order to investigate the power consumption characteristics of NetCar, we have employed a bi-directional, high-side current/power monitor named INA219 [17]. INA219 reports current in amperes and calculates power in watts. INA219 can sense from 0 to 26 V which is sufficient considering the employed PWM signal levels. A high-side sensor is preferred to ensure improved dependability.

INA219 exploits 0.1 ohm resistance to measure voltage with 12-bit ADC. This enables improved precision on obtained current values compared to an Arduino board that has 10-bit ADC. By taking advantage of 12-bit ADC and low resistance and tolerance resistance, it is possible to obtain %1 precision. Note that, it also has an option to change resistance and get higher resolution. Despite availability of power monitor on BTS7960 motor drivers, we opt to use INA219 due to improved precision and reliability.

B. Scenarios

In the experiments, we have considered various scenarios considering different terrain features and mobility modes as listed below:

- Terrain type: Indoor (marble) and outdoor (grass and concrete) as illustrated in Figure 2.
- Mobility direction: Straight path and curved path.
- Road gradient: Flat road, uphill, and downhill with varying gradient levels.

(a) (b) (c)

Figure 2: Considered terrain types for mobility; marble (a), grass (b), and concrete (c).

C. Motor Control

We employ pulse width modulation (PWM) to control the output torque of the DC motor. The main challenge of controlling a motor is the limitation of the states (e.g., on and off). When a dc motor is driven, the voltage that feeds motors shall change. Therefore, we must control DC voltage levels while our motors are operating. PWM offers a solution to this problem by providing the flexibility of changing the state of voltage supply that feeds the motor. If the state is changed faster than the controlled device can respond, device receives the average DC voltage. The percentage of the DC voltage is the proportion of time that spent as on and off. High PWM signal is regarded as the “on time”. The ratio of “on time” to “off time” is called the duty cycle. Duty cycle directly affects the average output voltage supplied to the motor. Low-frequency PWM signals can be generated through software. On the other hand, generating high-frequency PWM signals requires hardware support. Employed Arduino board provides 14 digital pins that support PWM output. PWM signal-duty cycle relationship is illustrated in Figure 3.

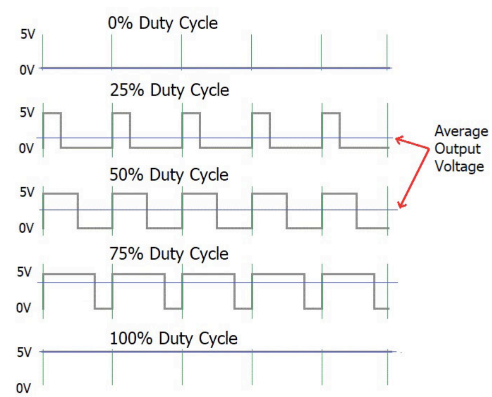

Figure 3: PWM signals and the duty cycle.

D. Results

This subsection discusses the results for evaluations. For each scenario, we repeated the experiment 10 times and reported the average for significance.

1. Straight path with different terrain types

In this subsection, we have evaluated energy consumption of NetCar while following a straight path on the road with different terrain types. The results are presented in Figures 3, 4, and 5 for marble, grass and concrete roads respectively. For each case, we have varied the duty-cycle of the motor and investigated the power consumption.

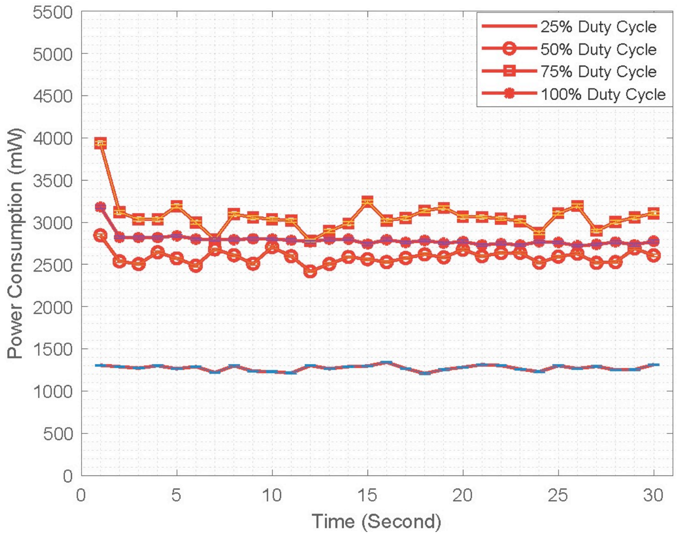

Figure 4: Power consumption on the marble road with respect to the duty cycle.

According to Figure 4, 25% duty cycle incurs the least cost as expected. An unexpected finding is the decline of the power consumption when the duty-cycle is increased from 75% to 100%. This can be attributed to the low-friction of the considered terrain type. We suspect the skidding of wheels due to the loss of road grip. Friction of the road is not sufficient to avoid the sliding of the tire rubber. Note that, NetCar is a 4WD all-terrain mobile platform that has tires more suitable to rough terrain conditions. As can be observed in the rest of the results, reduced power consumption is not a case for grassy roads when duty-cycle is set to 100%.

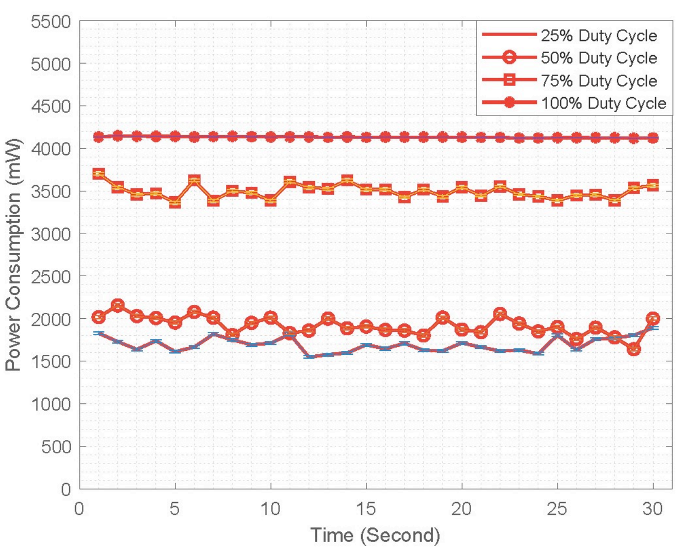

Figure 5: Power consumption on the grassy road with respect to the duty cycle.

Figure 5 signifies that the least power consumption can be attained with 25% duty-cycle as expected. When the duty-cycle is increased to 50%, power consumption increases slightly. Power consumption increases considerable upon increasing the duty-cycle to 75%. The highest cost is incurred when the duty-cycle is set to 100%. Considering the increased friction force of the grassy road, the phenomenon that we observed on the marble terrain is not applicable anymore. Note that the average power consumption is higher on grassy road compared to the marble road.

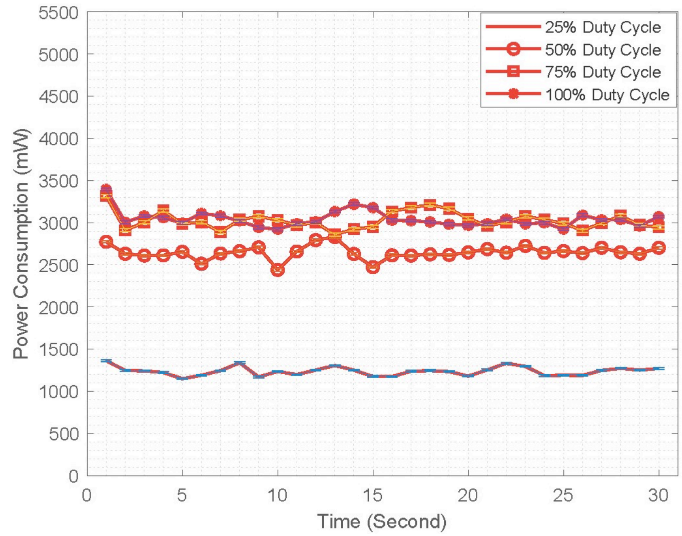

Figure 6: Power consumption on the concrete road with respect to the duty cycle.

The friction force of the concrete terrain is expected to be between marble and grassy roads. As Figure 6 indicates, obtained results show this relationship. As expected, 25% duty-cycle incurs the least cost. The cost increases considerably upon increasing the duty-cycle further. Despite increased cost with the increased duty-cycle, the cost difference is not as distinct as the grassy road. We have also observed declined power consumption on some of the results when the duty-cycle is increased from 75% to 100%. This cannot be generalized though. Results indicate possible skidding of the tires when the torque is increased on the concrete road occasionally.

2. Curved path on the marble road

In the second set of experiments, we have considered a curved path that NetCar makes a right turn while moving forwards. In this experiment, we set the duty-cycle to 100% and used the marble road. The results are depicted in Figure 7. It can be concluded from Figure 7 that power consumption increases considerably on the curved path compared to the straight-path movement. According to the obtained results, power consumption increases 46% upon following the curved path.

3. Straight path with various gradient levels

The last scenario investigates the impact of the gradient level on the power consumption. To implement this scenario, we used a custom wooden road platform to be able vary the gradient level as needed. Due to the limited length of the platform, we set the duty-cycle to 25% to control the velocity of NetCar especially when the gradient is negative (downhill). The results are illustrated in Figure 8. The gradient level is varied between -20 degrees and +20 degrees. Negative gradient indicates downhill movement (descending) while positive gradient denotes uphill movement (ascending). Flat gradient is represented with 0 degrees. In order to represent the power consumption during ascending and descending separately, we indicate the results on the positive part of the x-axis with two distinct lines denoting uphill and downhill movement in Figure 8. Note that downhill movement actually represents negative gradient in Figure 8. According to results, gradient level is highly correlated with the power consumption. Gradient increases power consumption during uphill movement and alleviates the cost during downhill movement.

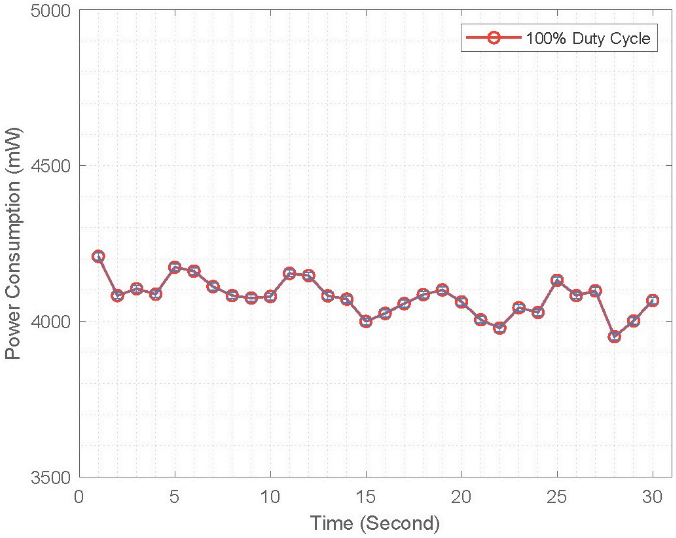

Figure 7: Power consumption upon following a curved path on the marble road with respect to the duty cycle.

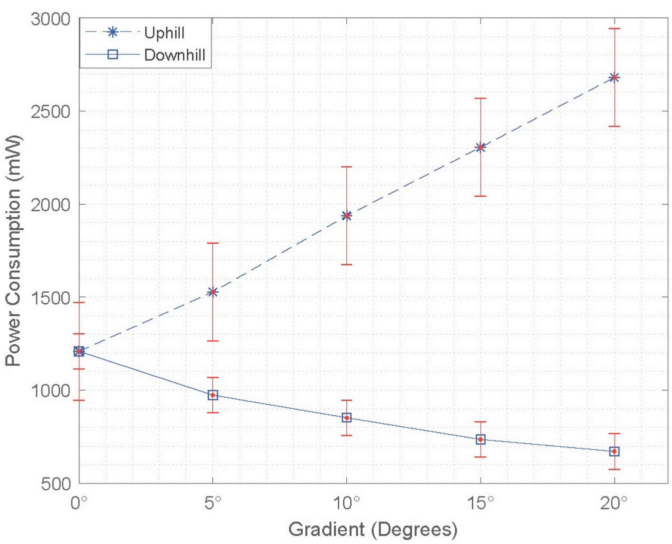

Figure 8: Power consumption when different gradient levels are applied on a wooden platform.

IV. Conclusion

NetCar is a mobile robot that can be employed in mobile sensor networks to enable controlled mobility. NetCar can be used as an actuator connected to sensors that can provide mobility to sensors upon required. NetCar can also be used as a testbed to evaluate algorithms designed for mobile sensor networks. NetCar is a 4WD all-terrain mobile platform that enables deployment in areas with harsh terrain features. In this paper, we have evaluated power consumption characteristics of the platform by considering different scenarios including various terrain types.

Acknowledgment

This work was supported by the Scientific and Technical Research Council of Turkey (TUBITAK) under Grant No. EEEAG-117E050.

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