mROBerTO: A Modular Millirobot for Swarm-Behavior Studies

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***Abstract*—Millirobots have increasingly become popular over the past several years, especially for swarm-behavior studies, allowing researchers to run experiments with a large number of units in limited workspaces. However, as these robots have become smaller in size, their sensory capabilities and battery life have been reduced. A number of these have also been customized, with few off-the shelf components, exhibiting integral (i.e., non-modular) designs. In response to the above concerns, this paper presents a novel open-source millirobot with a modular design based on the use of easily sourced elements and off-the-shelf components. The proposed milli-robot-Toronto (*mROBerTO*), is a 16×16 mm² robot with a variety of sensors (including proximity, IMU, compass, ambient light, and camera). *mROBerTO* is capable of formation control using an IR emitter and detector add-on. It can also communicate via Bluetooth Smart, ANT+, or both concurrently. It is equipped with an ARM processor for handling complex tasks and has a flash memory of 256 KB with over-the-air programming capability.**

I. Introduction

Small-scale robots range in size from mm³ to μm³ and have been categorized as milli-, micro-, or even nano-robots [1]. They are, typically, expandable in design, rapidly constructible, and have easy manageability with regards to maintenance and setup. They can operate individually, or collectively using swarm intelligence [2]–[4].

Millirobots have been utilized in large-scale wireless sensor networks (WSNs) [5], [6], micro-assembly [7], medicine [8], [9], and also have potential use in urban search and rescue [10], and surveillance [11] applications. For example, in [5], the challenge of reducing overall power consumption of a network was addressed using millirobots that were used as mobile nodes within a large WSN. In [7], a single robot was able to move with micron precision to show potential use in micro-manufacturing where end-effectors would grab components that are μm in length and assemble the components together. In [9], a pill sized robot with a camera and wireless communication module was used as an endoscope, as part of minimally-invasive treatment.

In [10], the use of millirobots in urban search and rescue was discussed where small robots would travel through small cracks in collapsed buildings to search for survivors. In [11], different millirobot gaits were compared and the potential use of these robots for surveillance was mentioned. Other examples of millirobots include robots that can pull objects heavier than their own body weight [12], bio-inspired legged robots [13], [14], and self-folding origami robots [15]. To-date, only a few units are commercially available [16], [17].

*This research was funded in part by the Natural Sciences and Engineering Council of Canada and the Canada Research Chairs Program.

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Larger millirobots (above 75×75 mm² footprint), [18]–[21], often have increased sensory capabilities and powerful processors along with larger battery capacity when compared to their smaller counterparts (less than 73×60 mm² footprint), [22]–[31]. For example, the E-Puck [18] and SwarmBot millirobots [19] have onboard cameras and Linux-based operating systems to complete complex tasks. The R-One millirobot, [20], [21], has static grippers that can lock onto other R-One robots as well as any oversized objects and can connect to an automated self-charging station.

As reported in the literature, although sensory capabilities are usually reduced as the size of the robot decreases, smaller millirobots can operate collectively in larger quantities and in relatively small areas. In [22], for example, the millirobot, *Robomote*, was equipped with a compass and distance sensor for moving to different locations autonomously in order to enable mobility in a large WSN.

The millirobots *Alice II* [23], *Jasmine* [24], *AMiR* [25], *Wanda* [29], *TinyTeRP* [26], [27], and *GRITSBot* [28] were targeted for swarm behavior. One of their common objectives is modularity where additional sensors can be attached to these robots for testing different research problems and applications as well as for educational purposes. *Alice II*, for example, can operate up to ten hours and a linear camera can be attached to the robot as an additional sensor. *Jasmine* is equipped with six pairs of IR emitters and receivers placed near the outer edges of the robot's chassis for all-around coverage of IR sensing and communication. *Wanda* and *AMiR* include software development tools for both low- and high-level control. *TinyTeRP* has an all-terrain add-on, where tracked wheels can be used for movement. *GRITSBot* has 3 stackable layers that consist of varying sensors and modules.

Two other millirobots, *Kilobot* [30] and *Colias* [31], have also been designed for swarm intelligence research but are limited in their modularity. *Kilobots* can operate in teams of more than a thousand units programmed via an over-the-air controller. *Colias* can reach a speed of up to 350 mm/s, which allows rapid movement over large areas.

Many of the millirobots reported in the literature use low-power IR communication, which is simple to implement but subject to slow data-transfer speeds and limited range. Robots that are modular in design have attachable modules with radio communication that allow for alternative communication protocols such as ZigBee [23].

II. *mROBerTO* Design

Design decisions for our proposed robot were made based on three key factors: increased modularity; maximum use of commercially available components for ease of production, assembly and maintenance; and, minimum possible footprint area without sacrificing processing power and sensing capabilities. Modularity is desirable such that additional sensors and future improved circuitry can be added to the robot with minimal disruption. Use of commercially available components allows others to duplicate our design and produce multiple units at low costs and in a timely manner. Similarly, repair and maintenance can be carried out efficiently through the use of off-the-shelf components.

Our proposed ***m***illi-***r***obot-***T***oronto (*mROBerTO*), is presented in Fig. 1. It has an envelope of 16×16×32 mm^3, and comprises of four modules: processing and communication (referred to as mainboard below), locomotion, primary sensing, and secondary sensing, Fig. 2. All modules are soldered together with the exception of the secondary sensing module, which is designed for rapid exchanging.

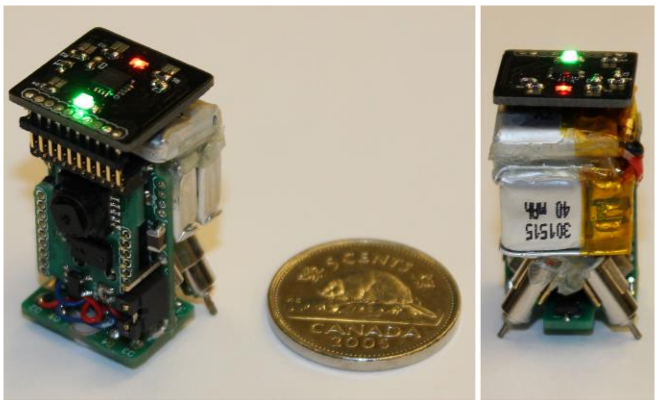


Figure 1. *mROBerTO* shown next to a Canadian nickel (diameter of 21.2 mm) for scale.

A. *Processing and Communication - Mainboard*

The mainboard is the core of mROBerTO that all other modules connect to, Fig. 3. It includes the Nordic nRF51422 system-on-chip (SoC), which has a 32-bit ARM Cortex-M0 running at 16 MHz with 256 KB flash, 32 KB RAM, and built-in Bluetooth Smart and ANT+ capability. Several features of the nRF51422 help achieve the abovementioned three key design factors.

The flexible general-purpose inputs/outputs (GPIO) feature of the nRF51422 allows any GPIO pins on the SoC to be configured as two-wire interface (TWI or I2C) and universal asynchronous receiver and transmitter/serial peripheral interface (UART/SPI). Such a configuration provides users with sufficient flexibility for utilizing novel and expandable primary and secondary sensing modules. Bluetooth low energy (BLE) allows high data-transfer rates (i.e., up to 1.0 Mbps) with low-power consumption. Fast transfer speed is desirable for transmitting large data such as images from the robot's onboard camera. The nRF51422 supports over-the-air programming, which saves time when setting up several of these robots, and, furthermore, it provides overall user-friendliness.

Other communication methods, such as IR and radio (i.e., Wi-Fi and ZigBee), were also considered during our design process. Bluetooth was chosen as the primary method of communication for its high data-transfer rate while still using low energy during operation. Additionally, on the nRF51422, BLE allows concurrent roles of broadcaster and observer, central and peripheral, through the use of Nordic's BLE protocol stack, SoftDevice 130. The nRF51422 also supports ANT+ with the use of SoftDevice 210/310, which is a proprietary networking protocol similar to BLE but allows additional network topologies that are not standard with current BLE, such as mesh and tree topologies. ANT+ and BLE can operate concurrently, increasing the information throughput of the robot.

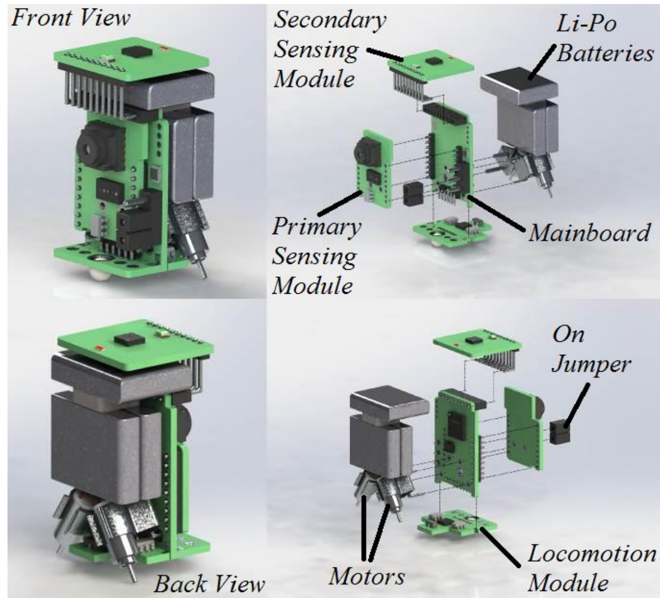


Figure 2. *mROBerTO*'s exploded-assembly view.

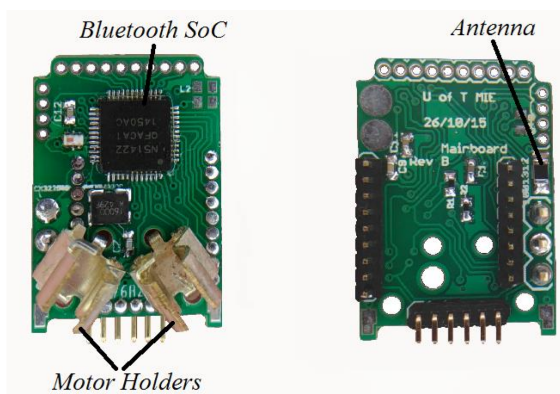


Figure 3. Mainboard module circuit board (back and front views).

B. *Locomotion*

Located below the mainboard is the circuit board of the locomotion module, which controls two 4 mm Nano Coreless motors manufactured by Precision Microdrives, Fig. 4. The motors are connected to an H-bridge for a differential drive configuration. The shafts of the motors are directly in contact with the floor surface and act as 'wheels'. The objective was to further simplify the design and remove the need for additional custom-made components, such as small drivetrains, that may cause maintenance issues. A 1/8" (≈3.175 mm) diameter polytetrafluoroethylene (PTFE) ball, typically found in ball bearings, is used as the front third contact point with the floor. While other materials such as stainless steel, aluminum, and glass were considered, PTFE was chosen for its low coefficient of friction and light weight.

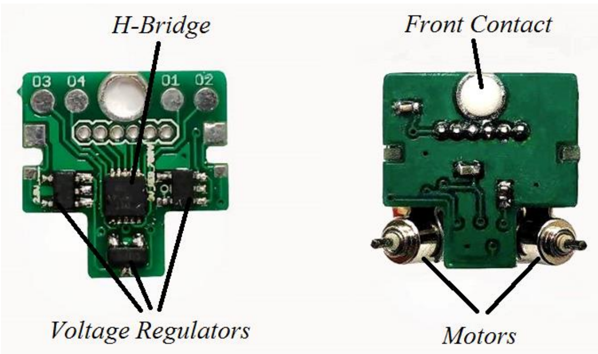


Figure 4. Locomotion module circuit board and motors.

With the above configuration, *mROBerTO* can move forward, in a straight-line, as slow as approximately 1 mm/s and as fast as approximately 150 mm/s, and can turn at approximately 500 deg/s. In order to reduce slippage, the heaviest component, the Li-Po batteries, were placed vertically above the motors, shifting the center of gravity near the center back area of the robot where the wheels are located, away from the front contact, Fig. 2.

There are, naturally, other methods to achieve a differential drive configuration without the use of wheels, such as a vibration system, made use of in the *Kilobot*. Based on our own experience, however, such locomotion systems, when employing commercially available low-end motors, are unsuitable for precise movements over long distances, primarily due to their nonlinear behavior and excessive slippage towards undesired directions.

In addition to having the H-bridge for the motors, the locomotion module also includes all the necessary voltage regulators for powering the rest of the modules. The objective was to maximize space on the other modules, so that they have ample room for including sensors and other ICs, and allow the user to design new sensor modules without worrying about power sources.

C. Primary and Secondary Sensing Modules

The primary sensing module has the most access to the SoC's GPIOs with 15-pins. The configuration adopted allows the inclusion of a variety of sensors, such as CMOS cameras and proximity sensors. For *mROBerTO*, the camera adopted was the Toshiba TCM8230MD that is capable of taking videos in VGA resolution at 30 fps. The camera can output RGB565 or YUV422 data via 8 parallel data pins.

In addition, for obstacle avoidance, a time-of-flight proximity sensor (VL6180X) was added to the front of the robot. This sensor was chosen for its small sized package ($4.8\times2.8\times1.0$ mm^3) and its 3-in-1 feature (i.e., proximity sensing, ambient-light sensing, and laser light source).

The secondary sensing module, placed on top of the robot, includes 2 LEDs (one green and one RGB), an inertial-measurement unit (IMU) with gyroscope, a magnetometer, and has 8-pin GPIO access to the processor. The LEDs were placed on the top of the robot for easy viewing and for finding the robot's global position in the workspace using an overhead camera, discussed in Section II.E. The LEDs can also be used for debugging purposes when programming firmware for the robots. Since *mROBerTO* is too small to install encoders on the wheels, the IMU with a magnetometer allows for feedback.

As noted above, the secondary sensing module has 8-pin GPIO access and is not soldered onto the mainboard to be easily exchangeable. This allows users to modify the sensing capabilities of the robot without rebuilding the entire unit. Two GPIO pins from the SoC can be connected to both the primary and secondary sensing modules, allowing for the use of one instance of TWI or serial peripheral interface (SPI) to communicate with both the primary and secondary sensing modules concurrently. Both sensing modules have access to the 2.8 V voltage regulator.

As abovementioned, another secondary sensing module was designed specifically for swarm behavior and formation control purposes. This module consists of 8 IR emitters and 6 detectors placed on the edges of the module for all around coverage.

D. Power Management

mROBerTO utilizes three 3.7 V Li-Po batteries in parallel for a total capacity of 120 mAH as its source of power, Fig. 2. The objective was to fit as much power capacity as possible onto the robot without requiring excessive space. The Li-Po batteries allow *mROBerTO* to operate for a minimum of about 1.5 hours at full-function; that is, the two motors operating at a pulse-width modulation (PWM) level of approximately 40% duty cycle to reach approximately 150 mm/s, using the IMUs with 10 ms update, turning on/off the proximity sensor and camera every second, having the LEDs on continuously, and the Bluetooth exchanging a packet of data (20 usable bytes) with the centralized controller every second.

E. Motion Control

An overhead camera utilizing OpenCV and a centralized Bluetooth controller can be used to find the global position of *mROBerTO* and provide closed-loop feedback control for trajectory following. When the robot is following a trajectory, it is given its current global coordinates and orientation every second along with next desired point on the path. The RGB LED (red LED for this example) on the robot determines the global location and the green LED in front of the robot is used to find its global orientation.

Multiple robots can operate concurrently in the same workspace for motion control since the RGB LED can be set to different colors for each individual robot on the floor. Using this positioning information, *mROBerTO* reaches the next desired point via its proportional-integral-derivative (PID) controller that is programmed in its firmware. The PID controller determines the necessary angular velocities the robot needs to output for each wheel and the angular velocities are translated into PWM signals for each motor.

Using the kinematic equations for differential drive and the same method of calibration found in [32], *mROBerTO* can be calibrated with the overhead camera. The calibration process involves sending a set of PWM signals to each motor for a set period of time and measuring the lateral and longitudinal errors between the final position of the robot and the desired position. Subsequently, the angular velocities of each wheel are calculated using the first and final position coordinates, the value of the test period, the wheels' diameter, and the axle length. When all data are collected, a translator between angular velocities to PWM duty cycle percentage is programmed for the left and right wheels.

F. Software

The main software of *mROBerTO* includes the header file libraries that have been coded for controlling all the abovementioned sensors and motors with high-level functions. For example, there exists a function through which one can input the desired angular velocity for each wheel, where the corresponding low-level instructions are, then, taken care of within the library. A set of instructions is also pre-programmed into the robots' firmware for calibration, for PID motion control, and for Bluetooth debugging purposes.

Nordic's SoftDevices are programmed for Bluetooth and ANT+ capabilities. One of the advantages of using nRF51422 is that the source code can be compiled using cross ARM GCC, which is a free software compiler and can be used with free popular integrated development environments (IDE) such as Eclipse. In addition, on-board debugging with Eclipse is possible using the J-Link programmer from SEGGER which uses the Serial Wire Debug interface of ARM.

As for high-level motion control, an overhead camera can be used with OpenCV 3.0 library to locate both the RGB LEDs and green LEDs of all robots in the workspace. The Bluetooth centralized controller, which consists of a USB Bluetooth smart ready dongle, can be utilized using the BlueZ 5.3X library.

III. Performance Benchmark

Table I presents an overview comparison of our *mROBerTO* with respect to other millirobots. As can be seen from the table, *mROBerTO* offers a rich range of sensor capabilities while being one of the smaller millirobots in existence. It also has a 32-bit ARM processor for handling complex tasks, and can last up to 6 hours of operation. In the following, we also provide a detailed description of *mROBerTO*'s performance as well as compare its performance to two other millirobots in Table I – the *Kilobot* and *TinyTeRP*. These robots were selected for comparison due to being comparable in size to *mROBerTO*.

A. Open-Loop Movement Control

Millirobots are often prone to misalignments/unbalances due to design/production/assembly problems, as well as motion slippage. As a first test, thus, open-loop control tests were performed in our laboratory to identify these deficiencies for *mROBerTO* (i.e., no IMUs or any form of odometry was used). The same tests were also carried out using a *Kilobot*. The motions of each robot were recorded using an overhead camera. The plots in Fig. 5 correspond to some representative results from our extensive experiments, as well as data extracted from [27] for the *TinyTeRP* robot. As one can note, *mROBerTO* (blue) has approximately 35 mm spread after a travel distance of 300 mm, the *Kilobot* (green) has approximately 235 mm spread, and the *TinyTeRP* (red) has approximately 115 mm spread.

B. Path Following

The second set of experiments utilized an overhead camera for the closed-loop control for *mROBerTO* motion via Bluetooth by a centralized controller and a PID controller pre-programmed into its firmware. Once the robot is at the starting position, it is given its current global coordinates and orientation obtained from the overhead camera along with next desired location on the path. The PID controller in the robot's firmware uses the data from the centralized controller to move to its next desired location.

TABLE I. Comparisons with current millirobots.

Robot (cost USD)	Foot-print (mm^2)	Processor	Commu-nication	Sensors	Power (hrs)
mROBerTO ($60*)	16 × 16	ARM 32-bit	BLE & ANT+	Light, range, gyro, camera, accelerometer, compass, distance, bearing	1.5 to 6
GRITSBot ($46*)	31 × 30	AVR 8-bit	WiFi	Light, gyro, accelerometer, distance, bearing	1 to 5
Colias ($30)	40 × 40	Atmel 8-bit	IR	Distance, bump, light, range, bearing	1 to 3
TinyTeRP ($75)	17 × 18	8051 8-bit	ZigBee	Gyro, accelerometer	0.5 to 1
Wanda (N/A)	51 × 51	ARM 32-bit	IR	Color, line, range, light, accelerometer	2.5
Kilobot ($50+)	33 × 33	Atmel 8-bit	IR	Distance, light	3 to 24
Alice II (N/A)	22 × 21	PIC 8-bit	IR	Bumper, range, camera	10
Jasmine ($130)	30 × 30	Atmel 8-bit	IR	Distance, light color, bearing	1 to 2

* Cost of parts per unit for order quantities of 25 units or more.
\+ Cost of parts per unit for order quantities of 100 units or less.

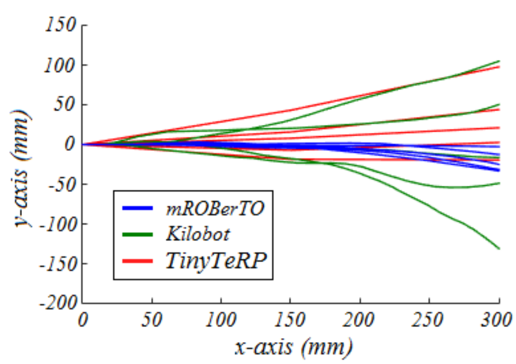
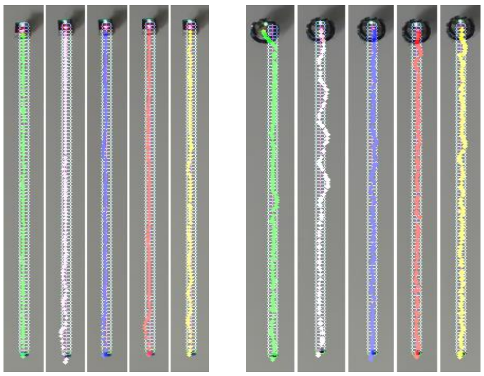


Figure 5. Open-loop testing.

Similarly, for comparison purposes, a *Kilobot* was also controlled via feedback from the overhead camera. However, instead of using Bluetooth communication, the *Kilobot* was controlled with an IR based overhead controller provided by K-Team, the manufacturer for *Kilobot*. One can recall that, unlike, *mROBerTO*, *Kilobots* are not equipped with any IMUs either. Thus, as stated in [30], *Kilobots* with stick-slip based locomotion using vibration motors cannot move over long distances with acceptable precision.

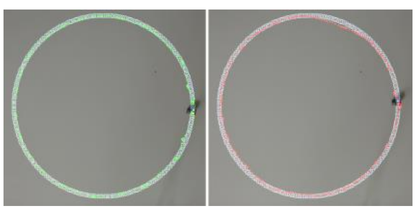
Thus, for a fair comparison, a *Kilobot* was controlled to move in small increments to follow a given path at a slow speed while being provided constant feedback from the overhead controller of its current position and next position on the path. In addition, the next desired location on the path did not change periodically, but instead, only changed once the robot was near or at the desired position and only then was the desired location changed.

Figures 6 to 7 show some sample test results for *mROBerTO vs Kilobot*, respectively, following different paths. For the straight line tests in Fig. 6, the robots travelled approximately 500 mm. For the circular motion tests in Fig. 7, the robots travelled on a circle with an approximately 500 mm diameter. Table II shows the error distributions obtained from runs with *mROBerTO* and *Kilobot*, respectively.

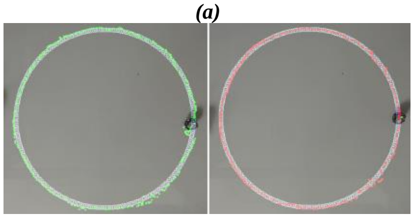


(a) ***(b)***

Figure 6. Straight-line tests for *(a) mROBerTO* and *(b) Kilobot*.



(a)



(b)

Figure 7. Circular path tests for *(a) mROBerTO* and *(b) Kilobot*.

TABLE II. ERROR DATA FOR PATH FOLLOWING TESTS.

	Straight-line (mm)	**Circular Path (mm)**
	mROBerTO / Kilobot	***mROBerTO / Kilobot***
Average Error	1 / 1	3 / 4
Max. Error Value	5 / 11	13 / 26
Standard Deviation	0.9 / 1.0	2.5 / 3.7

C. Swarm Capabilities

The majority of millirobots reported in the literature exhibit capabilities that are essential to swarm-behavior studies [33]–[41]. Thus, in order to briefly illustrate *mROBerTO*'s performance in relation to these robots, two specific tests are discussed herein: moving toward a stationary light source (beacon), and following a mobile beacon (i.e., a *leader*).

In the first test, *mROBerTO* moved towards a stationary beacon at a distance of 700 mm away, Fig. 8. A PID controller was implemented and utilized to direct *mROBerTO* toward the brightest direction, guiding it towards the stationary beacon. In the second test, *mROBerTO* followed a mobile beacon (the *leader*) moving at approximately the same speed, Fig. 9. The mobile beacon was moved using open-loop control, travelling forward while turning left and right every 2 s. For each test, the follower travelled approximately 600 mm. A PID controller, identical to that of the first test, was used to regulate the follower's movements. The results of all five tests are shown in Table III.

Figure 8. Go toward a stationary beacon tests (5 trials overlapped).

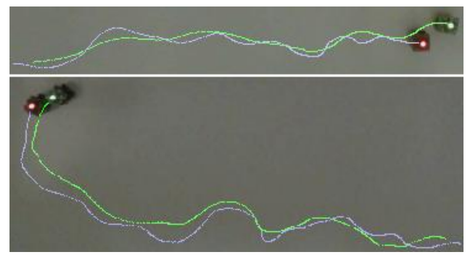


Figure 9. Follow the leader (shown in green) tests.

TABLE III. PATH ERROR DATA FOR FORMATION CONTROL TESTS.

	Go to beacon	***Follow the Leader***
Average Error (mm)	26	9
Max. Error (mm)	56	24
Standard Deviation (mm)	17.4	5.1

IV. CONCLUSIONS

In this paper, we presented the development of the novel small-sized (16×16 mm^2) modular *mROBerTO* millirobot. The robot is equipped with an ARM processor to carry out complex tasks and can be used individually or in a collective group. It is designed using only commercially available components for a simplified design and easy maintenance. Various network topologies can be utilized on *mROBerTO*, such as point-to-point, mesh, and tree topologies using its Bluetooth Smart and ANT+ communications. *mROBerTO*'s centralized controller utilizes an overhead camera for real-time feedback to follow a given path. Decentralized formation control, where the robot moves autonomously with respect to other robots, can be achieved with the secondary sensor module with IR emitters and detectors.

Extensive experiments have verified the performance of the robot to be as good as or better than commonly used commercial robots. Further experiments showed that *mROBerTO* can successfully locate a stationary beacon in order to move towards it. In addition, two robots were used to show *mROBerTO*'s ability to follow a leader and demonstrated its distributed capabilities.

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