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Robomote: A Tiny Mobile Robot Platform for Large-Scale Ad-hoc Sensor Networks[1]

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Abstract—
This paper introduces Robomote, a robotic solution developed to explore problems in large-scale distributed robotics and sensor networks. The design explicitly aims at enabling research in sensor networking, ad-hoc networking, massively distributed robotics, and extended longevity. The platform must meet many demanding criteria not limited to but including: miniature size, low power, low cost, simple fabrication, and a sensor/actuator suite that facilitates navigation and localization. We argue that a robot test bed such as Robomote is necessary for practical research with large networks of mobile robots. Further, we present a preliminary analysis of Robomotes' success to this end.

Keywords— **Robotics, mobile robots, sensor networks, ad-hoc networks, micro-robots, distributed robotics**

I. Introduction

This paper describes the design of the Robomote robot platform whose chief aim is enabling embodied research in large-scale distributed robotics and sensor networks. Such research has previously been prohibitive due to cost and size considerations. Our design allows the investigation of robotics problems in sensor networking, ad-hoc networking, massive scalability, and extended longevity, to name a few.

The advent of small, efficient integrated circuits, actuators, sensors, and communication circuits allows implementing robots that are a fraction of the size and cost of yesterdays predominant research platforms. Robomote is intended for use in large-scale sensor network research, therefore the production cost of hundreds of robots must be low. Likewise, if research is to be done indoors, (e.g. in the laboratory), the platform cannot take up too much space. Due to these considerations, Robomote occupies less than 0.000047m^3, and costs less than \$150 in parts.

Robomote is more than *1300 times smaller* than Pioneer sized robots which is a standard sized robot used in laboratories across the world. Further, Robomote has similar, though not identical, functional capabilities as these larger counterparts. With the use of the state of the art in micro-electronics it was possible to implement the Robomote with a wireless network interface for communication, accurate odometry and compass for navigation, infra-red and bump sensors for object detection, a solar cell for longevity, and a smart charging lithium-ion battery.

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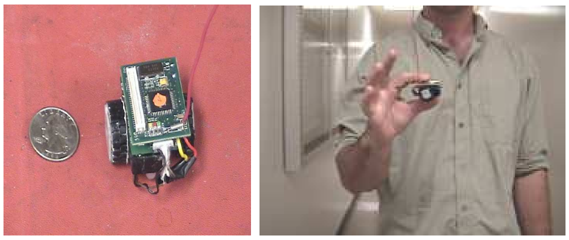


Fig. 1. Robomote occupies less than 0.000047m^3

II. Design Considerations

We address a three way design trade-off between size, cost, and functionality. Below we examine this space noting the obvious requirements of large-scale (e.g. numbering in the hundreds) robot networks.

A. Size

We place robots the size of humans on the large end of the size axis. Functionality is usually maximized at this scale given the large number of sensor and actuator options in this size range. Since most consumer and scientific technology has been developed in this size range, human scale robots benefit by using inexpensive, mass produced, off the shelf components. Because of this rich sensor and actuator domain, and because there do not exist comparable sensors and actuators on a smaller scale, larger robots can usually achieve a level of functionality that smaller robots cannot.

It is important to note that this fact will possibly (if not evidently viz. Moore's Law) change with the advent of Micro Electro Mechanical Systems (MEMS) and nano-scale technology. However, these technologies do presently exist as off-the-shelf products, and we must make do with what is available. It is also

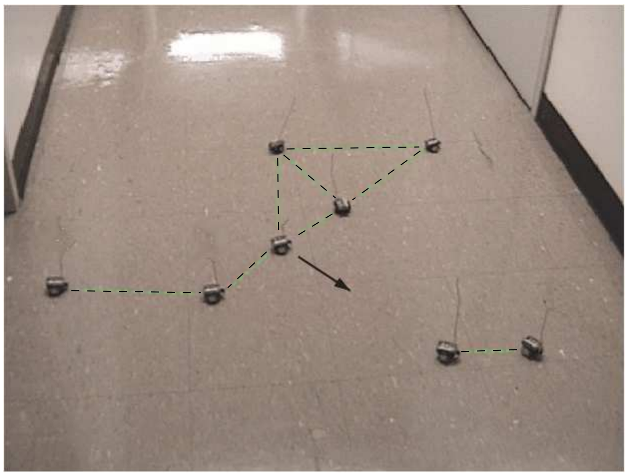


Fig. 2. Robomote network of eight nodes in less than 1m^2. This exemplar ad-hoc robot network is dynamically adjusting its topology to maintain network connectivity.

important to note that the environments of the macro (human) and semi-micro (Robomote) robots offer fundamentally different sensor and actuator experiences.

One drawback to large platforms is that it is difficult to do research with many of them because they require a large work space. Consider, for instance, a network of fifty Pioneer sized robots. The robot environment, the laboratory floor, is essentially 2 dimensional, thus we only consider the robots 2D footprint. Pioneers are approximately 0.25m^2; Robomotes are approximately 0.00114m^2. Thus, with an occupied versus unoccupied space density of 1 to 500 (see Figure 2 to get a visual idea for this density using Robomotes), 50 Pioneers require $6250\ \text{m}^2$, or about the size of a basketball court. With the same density, 50 Robomotes require less less than 30m^2, which is about the size of a small laboratory. Clearly, it is not feasible to work with hundreds or even thousands of robots that are the size of a Pioneer or much larger than a Robomote - even if the research budget can handle it.

B. Cost

Working with hundreds of robots necessitates scrutiny of individual robot cost. Platforms available for laboratory research typically cost on the order of thousands of dollars [1]. For instance, a basic Pioneer robot costs approximately $5000 and a basic Khepera I robot costs $1800. Since our goal is to enable embodied research with massive networks consisting of scores to hundreds of robots, the platform must be affordable. The relation of robot cost to robot size again points to the fact that off-the-shelf components are the best option. If the platform is too small it gets expensive due to the advanced technologies and fabrication techniques required (e.g. MEMS, micro assembly, etc.), and because of the lack of off the shelf components. Therefore, because the robot must be small we decided to go with the smallest yet still readily available components.

C. Functionality

When considering functionality one must consider the domain that Robomotes are expected to work in, and what they are expected to do in that domain. The Robomotes domain is the flat, featured office-like floor of a typical research building. The robot must be able to avoid objects, and move to a point that is given in relation to itself. Because the platform must be small, inexpensive, and power efficient, sensors like vision, laser range finders, and sonar are out of the question. Thus, to (help) solve the navigation problem, we settled on accurate odometry and a magnetic compass for navigation, and infra-red and bump sensors for object avoidance. Odometry error is shown in Table I and Figure 3.

While keeping Robomote small and inexpensive we strive to maintain two very important capabilities: navigation and obstacle avoidance. It is important to have this minimum sensor actuator suite because the Robomote must be able to navigate to a point (x,y) relative to its current position to within certain tolerances while avoiding obstacles. Thus, we strive for highly accurate low drift odometry as shown in Table I which is a representative sample of 10 odometric test runs.

The obstacle avoidance system was tested in the dynamic laboratory setting - e.g. nothing special was done to protect the Robomote. During a single 3 hour and 30 minute test run Robomote sent 132 `RM_OBJECT_DETECT` messages. The environment was not tailored to Robomotes limited sensors and actuators, however the robot was trapped or disabled only twice. During this time 239878 ticks were counted by the optical encoders; in other words the robot traveled 947.2 m at 0.27 km/h.

It is important to note that there are other sensors useful for navigation and localization, most notably acoustic and radio-based techniques. It is practical (i.e. sensors fit the small platform and low power demands) to do sound-based time of flight localization and there is active research along these lines [2]. Another method of localization is based on the received signal strength indication (RSSI) of other nearby Robomote radio communications [3], [4], [5], [6], [7]. Success along these lines has been mixed and it is not clear whether accurate localization based on radio signal strength is useful [8]. Ultimately, localization and navigation in mobile sensor actuator networks is still an open question - as is mobile robot localization

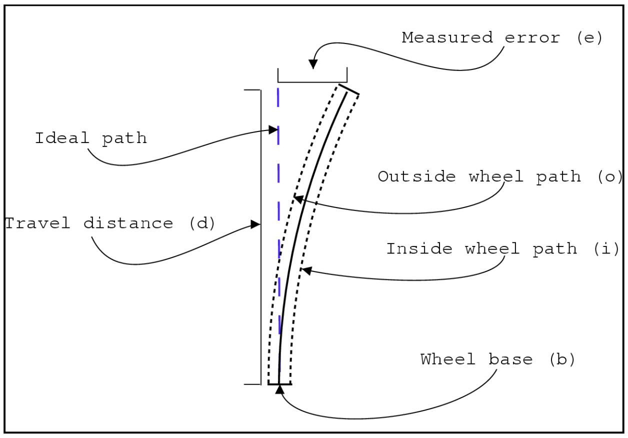


Fig. 3. Example of how odometric error is calculated.

TABLE I
ODOMETRIC ERROR WITH A WHEEL BASE OF 3.12CM

d(cm)	e(cm)	d vs. e	r(cm)	% dif
300	47	0.16	1938.2	0.16
300	52	0.17	1756.6	0.18
300	58	0.19	1580.5	0.20
300	54	0.18	1693.5	0.18
300	38	0.13	2387.3	0.13
300	56	0.19	1634.9	0.19
300	27	0.09	3346.8	0.09
300	49	0.16	1861.0	0.17
300	52	0.17	1756.6	0.18
300	39	0.13	2327.1	0.13
Avg	47	0.16	2028.2	0.16
Std dev	9.2	.03	510.6	0.16

and navigation in general. It is reasonable to hypothesize that working accurate localization in cluttered office like spaces will require a mixed approach that utilizes the benefits of many sensor modalities, such as a sound and radio combination [2], [9].

In conclusion, when considering the metrics (cost, size, and function), we made Robomote as small as possible while still taking advantage of off-the-shelf components and keeping a minimum key functionality level. As a result, Robomote is small, cheap, and serves its task.

III. Design in Detail

A. Hardware

The Robomote is a single printed circuit board with dimensions 3.81cm x 2.23cm based on an Atmel AT90S8535L 8-bit micro controller [10]. This chip was chosen for its rich code base and availability of programmer tools. This board, the "Robot" component, connects to a Renemote [11], the "Mote" component, making the complete "Robomote." The Renemote offers the radio communications interface [12] and controls the robot platform via RS232 serial commands. The serial API is detailed in section III-B.

Communication on the Renemote is based on 19.2 Kbps OOK(On-Off Key) at 916.5MHz ISM. The media access mechanism is a contention based Aloha type scheme with listen before transmission and random back-off. Transmission range of the Renemote can be varied in software from 20cm to 55m. However, indoor range varies dramatically depending on environmental conditions such as multi-path and reflection.

Renemote can be configured as a base station connected to a PC. This augments the sensor network with whatever networking capabilities the PC may have - e.g the fixed laboratory network and the Internet.

Robomote has two infra-red transmitters and one receiver mounted to face forward. The transmitters produce 940nm wavelength infra-red beams which are modulated at 40kHz over 1.5 kHz in order to reject the maximum amount of ambient light. The receiver has a viewing angle of 40 degrees with %80 sensitivity. Sensitivity can be increased up to 60cm by choice of resistor and by software(see III-B). The viewing angle can also be adjusted by changing the receiver shroud [10]. The receiver generates interrupts on the micro controller's external interrupt channel 0.

There is also an infra-red transmitter mounted to face backward to facilitate following behaviors. Along with infra-red, there are four bump sensors. These binary switches all share the micro controller's external interrupt channel 1. The Atmel AT90S8535L has a wake on external interrupt feature. Therefore, we also connect external interrupt channel 1 to the Renemote bus enabling Renemote to wake the Robomote from sleep mode.

The five infra-red transmitters (two front, one for each optical encoder, and one facing back) require 20mA operating current each. For long life experiments 0.1A continuous current draw is too much. Thus, power management becomes a software responsibility; this is achieved through polling (see section III-B).

For efficiency, all circuits are low voltage (3V). The battery can be anywhere from 2.9V to 5V. Bellow 2.9V the infra-red transmitters fail, though the rest of the system has been observed to function as low as 2.4V. Using 3 1.5V alkaline AAA batteries, the Robomote typically lasts 3.5 hours at 100% duty cycle.

Robomote consumes 102μA in sleep and 283mA in active mode. This includes 206mA of motor current at regular driving speed. Each subsystem (compass, object-detection, motors and optical encoders) can be disabled independently enabling different power management policies. With 3 1.5V AAA alkaline batteries (1635mAh) Robomote can sustain itself for 131 days in sleep mode or 3.5 hours when fully active. With the smaller 3.7V Li-Ion battery (160mAh) these change to 12 days sleep and 25 min operation time respectively.

The solar cell makes the Robotmotes suitable as nodes in sensor networks that are "always on". Further, because of the long operation life the solar cell permits, they are useful in long lived robot experiments. The solar cell produces 12mA at 4.5V which, while not enough to sustain Robomote in action, allows re-charging of the Li-Ion battery. In sleep mode even this limited power can power the platform indefinitely.

For actuators, there are two modified 7.0 oz-in. submicro servos that constitute two pulse width modulation controlled direct current gear head motors. These are controlled via the micro controller's timer/counter 1's dual pulse width modulation functionality. The wheels of the platform have 10 black and white tic marks for infra-red optical sensors which are used for odometry feedback. The diameter of the wheels is 2.54cm, which gives the Robomote a minimum odometric accuracy of 7.9mm per optical tic mark.

The compass is a 2-axis Honeywell HMC1021 IC. Configured as a 4-element wheatstone bridge, these magneto-resistive sensors convert magnetic fields to differential output voltage. From this two analog readings are obtained, one that senses the Earth's North-South, and another at 90 degrees to the first which offers West-East readings. These sensors are not absolute, and must be calibrated at robot initialization and periodically throughout usage, though it is possible to servo to either North, South, East, or West without calibration. The sensor output is amplified 370 times by a low noise instrumentation amplifier for a typical 920mv/Gauss output to the micro controller.

However, sensor readings are different from platform to platform and values change with frequent use of the motors. This necessitates the above mentioned ongoing calibration. Likewise, large metal objects affect the compass readings. Currently, it is only possible to servo to North East West or South with accuracy. As mentioned above, in laboratories the Earth's magnetic field is often dominated by other magnetic fields, thus it it not reasonable to expect absolute bearing information from the compass.

B. *Software*

There are eight serial commands the Robomote offers to the host controller. These allow the host (which can be any device supporting RS232 serial communication) to control motion and to react to detected objects

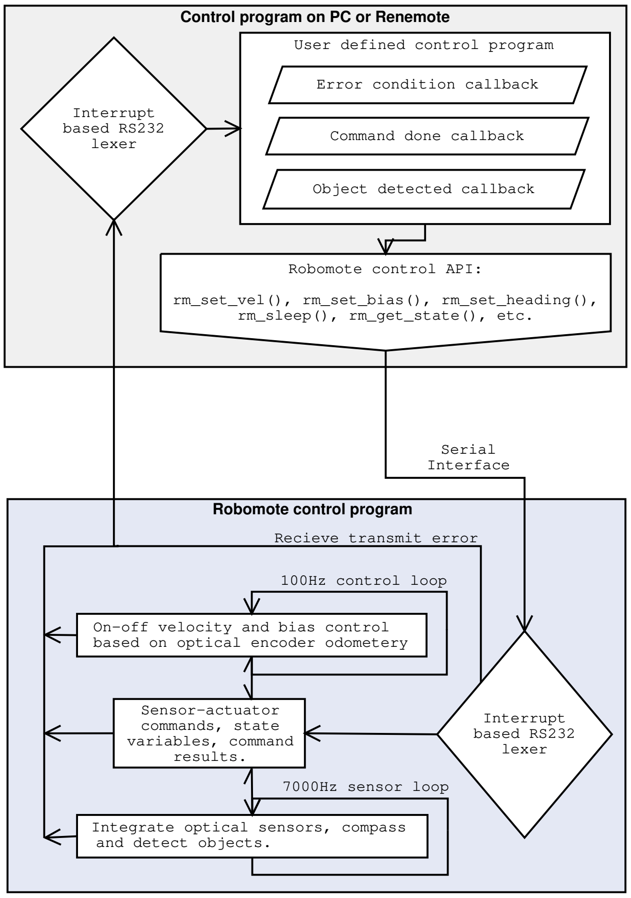


Fig. 4. Flowchart for Robomote control software. Control software components are cleanly separated by the serial interface.

(see Figure 4).

The two main software components are the lower level platform control loop on the robot ("robot part") and the master, or host, control program on either a PC or Renemote ("Mote part"). Currently, the host is a Renemote, and the platform is the robot whose hardware is described in III-A. The robot platform software implements a control loop that runs at 100Hz - though the optical encoders are polled and integrated at approximately 7kHz. The controller is a simple on-off controller that maintains a constant velocity based on a lookup pulse width modulation value and the number of encoder tic marks the left and right optical encoders report plus or minus some bias. It is also possible to servo to a desired compass heading - though only North South East and West have been evaluated. The accuracy of the compass is approximately 6 degrees.

The interrupt activated touch sensors cause the control loop to send an `OBJECT_DETECT` message to the controlling host. At this point the host control program causes a software interrupt that is a user defined function - the object avoidance callback function.

The infra-red sensor causes spurious interrupts, and must be smoothed via filtering and integration. Ultimately the control loop sends the host an `OBJECT_DETECT` message if the variable `ir_threshold`, which is set by the Renemotes' call to `rm_set_ir_thresh(threshold)`, is exceeded.

The design ensures that Robomote has the necessary sensors and actuators for object avoidance, odometric navigation and compass navigation. The hardware and software design allow the robot platform be used in mobile sensor networks.

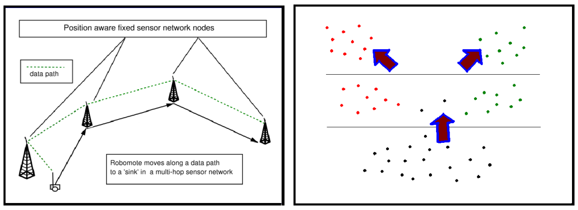
IV. Enabling Novel Research

Current research in sensor networks focuses predominantly on fixed wireless networks in which the nodes are not mobile. These networks consist of many network sensor nodes placed in a fixed pattern (though the pattern may be random if, for instance, the nodes are dropped by planes - e.g. scattered like dust). On the other hand, Robomotes allow such networks to dynamically alter their topology. Thus, sensor networks become actuated sensor networks, or sensor/actuator networks.

The Internet Engineering Task Force(IETF) defines a Mobile Ad-hoc Network (MANET) as *"an autonomous system of mobile routers (and associated hosts) connected by wireless links–the union of which form an arbitrary graph. The routers are free to move randomly and organize themselves arbitrarily; thus, the network's wireless topology may change rapidly and unpredictably. Such a network may operate in a stand alone fashion, or may be connected to the larger Internet."*

Thus, while most embodied distributed robotics research is an example of true ad-hoc networking, fixed wireless networking is not. Most sensor network research uses fixed networks. Robomotes allow certain types of fixed wireless networks [13], [14] to overcome this barrier. The Robomote makes the network topology dynamic, and thus truly ad-hoc. As a simple example of Robomote usefulness as a research platform to the ad-hoc networking community, consider using Robomote as a test bed for ad-hoc routing protocols. It would be difficult to assemble hundreds of laptops with 802.11b cards and have people move them randomly in a fixed area. Further, such a study would require a massive space. On the other hand, it would be trivial to do this using Robomotes.

Consider a network with a dynamic topology that actively moves nodes in order to maximize (or minimize) some characteristic (see Figure 2). For example, a network that autonomously moves nodes to locations of low signal strength to improve throughput along a



(a) Robomote following a diffusion data path in a fixed directed diffusion sensor network.

(b) Massive Robomote network allows investigation into 'intelligent swarm' behavior.

Fig. 5. Immediate research directions using Robomote as the main platform. [15] [16]

multi-hop transmission path [13]. While such work is possible with currently available robot platforms (or human-laptop mobile nodes), it is not realistic to do on the scale of hundreds of nodes. Robomotes make such research practical.

As another example of possible (and intended) research with the Robomote, consider swarm or flock type distributed artificial intelligence research [16], [17], [18], [19], which to our knowledge has previously only been done in simulation [20]. The most popular platform for this type of research is currently the Khepera [21]. The Khepera is highly functional yet prohibitive due to high cost.

To conclude, there is a plethora of low hanging fruit on the Robomote research tree. The platform, with emphasis on size, cost, communication, and navigation, enables empirical study of the above examples and more. Without such a platform, such research is difficult.

V. Conclusions

We have presented the design of a small inexpensive robot (the Robomote) based on the off-the-shelf components. Robomote is and will increasingly be used in large-scale sensor network research. To make this possible, production cost must be minimal. Further, because the platform is intended for use in the laboratory, it cannot take up too much space. With these constraints in mind, Robomote is less than $0.00005\mathrm{m}^3$, and costs less than \$150 in parts.

With the use of the state of the art in microelectronics it was possible to implement the Robomote with a wireless network interface for communication, accurate odometry and compass for navigation, infrared and bump sensors for object detection, solar cell for longevity, and a smart charging Lithium ion battery. Leveraging this powerful sensor and actuator set ensures Robomotes' usefulness.

The advent of smaller more efficient integrated circuits, actuators, sensors, and radio communication circuits allows implementing robots that are a fraction of the size and cost of yesterdays predominant research platforms. For example, the Robomote is a small fraction of the cost of contemporary robot platforms available on the market today.

The Robomote has been designed with the chief aim is enabling embodied research in distributed robotics and sensor networking that has previously been prohibitive due to cost, size, and scale. Robomotes initial reception is positive; the platform is being adopted and used.

VI. Future Work

There is active work on localization in sensor networks and Robomote is already being used to further explore this realm. For example experiments in fixed multi-hop datapath following in directed diffusion networks has begun (see Figure 5). The obvious next step, though in a different direction, is to implement theory that has been done in simulation from the distributed artificial intelligence "smart swarm" community, thus bringing a much needed embodied aspect the field [16], [17], [18]. There is a rich synthesis possible between networking and robotics, and ultimately both fields benefit. These are our immediate directions in a vast new research space.

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