DESIGN, PRODUCTION AND DEVELOPMENT OF MINI/MICRO ROBOTS TO FORM A COOPERATIVE COLONY

A THESIS SUBMITTED TO

THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

OF

THE MIDDLE EAST TECHNICAL UNIVERSITY

BY

DİLEK BAŞARAN

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

THE DEPARTMENT OF MECHANICAL ENGINEERING

SEPTEMBER 2003

Approval of the Graduate School of Natural and Applied Sciences.

Prof. Dr. Canan ÖZGEN
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Prof. Dr. Kemal İDER
Head of Department

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Prof. Dr. Abdülkadir ERDEN
Supervisor

Examining Committee Members

Prof. Dr. Bülent PLATİN

Prof. Dr. Abdülkadir ERDEN

Assoc. Prof. Dr. Tayfun AKIN

Dr. Buğra KOKU

Asst. Prof. Dr. Burhanettin KOÇ

ABSTRACT

DESIGN, PRODUCTION AND DEVELOPMENT OF MINI/MICRO ROBOTS TO FORM A COOPERATIVE COLONY

BAŞARAN, Dilek

M.Sc., METU Mechanical Engineering Department

Thesis Supervisor: Prof. Dr. Abdülkadir ERDEN

September 2003, 115 Pages

Design, production and development of individual mini/micro robots and then formation of their cooperative colony are the main topics of this thesis. The produced mini/micro robots are as small and light as possible. In addition, they are multifunctional (programmable), flexible and intelligent while maintaining a very low production cost. Mini/micro robots, called MinT-DB series are able to communicate with each other to work cooperatively. Moreover, these robots can be the basis for the future studies considering the application of artificial intelligence and modeling of live colonies in the nature.

Traditional design, production and assembly techniques have been used widely up to now. However, none of them were related with the mini/micro scale. Therefore, this thesis can help people in understanding the difficulties of the design, production, and assembly of the mini/micro systems under the light of the reported science.

In this thesis, instead of examining a specific application field of mini/micro robotic systems, a technology demonstrative work is carried out. Therefore, this thesis contributes to the mini/micro robotic technology, which is also very new and popular in today's world, with the robots having the dimensions of 7.5x6x6 cm.

Keywords: Modularity, Autonomous Mini/Micro Robots, Multi-Agent Systems, Artificial Intelligence, Robotic Communication and Cooperation, Control, Mechatronics.

ÖZ

KOOPERATİF BİR KOLONİ OLUŞTURMAK İÇİN MİNİ/MİKRO ROBOTLARIN TASARLANMASI, ÜRETİLMESİ VE GELİŞTİRİLMESİ

BAŞARAN, Dilek
Yüksek Lisans, ODTÜ Makina Mühendisliği Bölümü
Tez Danışmanı: Prof. Dr. Abdülkadir ERDEN

Eylül 2003, 115 Pages

Mini/mikro robot tasarımı, üretimi, geliştirilmesi ve sonrasında kooperatif bir koloninin oluşturulması bu tezin ana konusudur. Üretilen mini/mikro robotlar olabildiğince küçük, ve hafiftirler. Bu mini/mikro robotların çok fonksiyonlu (programlanabilir), esnek, ve akıllı olma özellikleri yanında üretim maliyetleri de minimum düzeydedir. MinT-DB serisi ismi verilen bu mini/mikro robotlar, kendi aralarında iletişim kurarak bir görevi birlikte yapabilmektedirler. Ayrıca bu robotlar, yapay-zeka ve doğadaki canlı koloni sistemlerinin robotik uygulamalara aktarılması konusunda yapılacak olan çalışmalara da temel oluşturmaktadırlar.

Klasik tasarım, üretim ve montaj teknikleri günümüze kadar yaygın olarak kullanılmıştır. Fakat, bu tekniklerin hiç biri mini/mikro ölçülerle ilişkilendirilmemiştir. Dolayısı ile bilimsel bir format altında yayınlanan bu tez, mini/mikro boyutlardaki sistemlerin tasarımı, üretimi ve montajında karşılaşılan zorlulukların daha kolay anlaşılmasına yardımcı olmaktadır.

Tez kapsamında mini/mikro robotik sistemlerin özel bir uygulama alanı üzerinde durulmamış, ancak teknoloji gösterimi nitelikli bir çalışma yapılmıştır. Bu tez dünyada da çok yeni ve popüler olan mini/mikro robot teknolojine 7.5x6x6 cm. boyutlarında üretilen robotlar ile katkıda bulunmaktadır.

Anahtar Kelimeler: Modülarite, Otonom Mini/Mikro Robotlar, Robot Kolonisi, Yapay Zeka, Robotik İletişim ve Yardımlaşma, Kontrol, Mekatronik.

TO MY FAMILY

&

TO HALİL BİL

ACKNOWLEDGMENT

I would like to express sincere appreciation to Prof. Dr. Abdülkadir Erden for his valuable guidance, encouragement and insight throughout this thesis.

I would like to express my deepest gratitude and appreciation to Assoc. Prof. Dr. Tayfun Akın and Asst. Prof. Dr. Burhanettin Koç for their invaluable studies, which are MEMS Technology and piezoelectric ultrasonic micro motors respectively. Their support and guidance enhanced my horizon about micro systems technology.

I offer sincere thanks to TÜBİTAK-MİSAG for their support and guidance. This thesis is funded by TÜBİTAK-MİSAG with the name of Project 209. After getting the financial support of TÜBİTAK-MİSAG, this work has been accelerated and come to the fınal stage in a short time.

I am also grateful to Utku Avgan, Ali Emre Turgut, Alper Erdener for their suggestions, encouragement and enthusiastic helps.

Special thanks to Halil Bil for everthing and his invaluable friendship.

Finally, I wish to thank to my parents A. Coşkun Başaran, Güzin Başaran and my brother Tolga Yener Başaran for their never ending support, trust, encouragement and patience.

TABLE OF CONTENTS

LIST OF TABLES

TABLE

LIST OF FIGURES

FIGURE

LIST OF SYMBOLS AND ABBREVIATIONS

<u>A</u>

AI	: Artificial Intelligence

<u>B</u>

BSII	: Basic Stamp II control card from Parallax Inc.

<u>C</u>

c	: Stiffness
CNC	: Computer Numerical Control
CAD	: Computer Aided Design
CAM	: Computer Aided Manufacturing

<u>E</u>

EPFL	: Ecole Polytechnique Fédérale de Lausanne
EEPROM	: Electrically-Erasable Programmable Read Only Memory
EOD	: Explosive Ordnance Disposal
E_{μ}	: Energy loss by friction
E_p	: Potential energy

<u>F</u>

FIRA	: Federation of International Robot-soccer Association
F	: Acceleration, gravity or impact forces
F_{μ}	: Friction force
F_w	: Wind, lift or drag forces
f	: Clock frequency
f_o	: Structural eigenfrequencies

<u>H</u>

h	: Altitude

<u>I</u>

IC	: Integrated Circuit

J

JST	: Japan Solderless Terminal connector

L

L	: Characteristic length of reference
LAMI	: Laboratoire de Microinformatique
LIGA	: German acronym for Lithographie, Galvanoformung, Abformung An acronym from German words for lithography, electroplating, and molding is a micromachining technology originated in the early 1980s at the Karlsruhe Nuclear Research Center.

M

MinT-DB	: Made in Turkey by Dilek Başaran
MİSAG	: Makina, Kimyasal Teknolojiler, Malzeme ve İmalat Sistemleri Araştırma Grubu Mechanical Eng., Chemical Tech., Material Science and Manufacturing Systems Research Grant Committee
MMR	: Mini/Micro Mobile Robot
ME	: Mechanical Engineering
MEMS	: Micro Electro Mechanical Systems
METU	: Middle East Technical University
m	: Mass
M	: Torque

N

N	: Number of transistors

O

OEM BSII	: Original Equipment Manufacturer Basic Stamp II control card from Parallax Inc.
OTP-ROM	: One-Time Programmable Read Only Memory.

P

PCB	: Printed Circuit Board
P_{CPU}	: Power of a microprocessor
PIC16C57	: A microcontroller from Microchip
PIC 16F877	: A microcontroller from Microchip
PID	: Proportional, Integral, Derivative
PWB	: Printed Wiring Board
PWM	: Pulse With Modulation

Q

Q	: Volume

R

RMB : Roulements Miniatures Bienne

S

SSSA : Scuola Superiore Sant'Anna (SSSA)

σ : Stress

T

TÜBİTAK : Türkiye Bilimsel ve Teknik Araştırma Kurumu
Scientific and Technical Research Council of Turkey

U

ULB : Université Libre de Bruxelles

UXO : Unexploded Ordnance

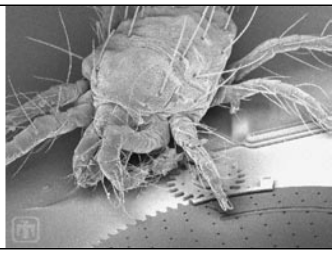
V

V_{dd} : Power supply voltage

CHAPTER I

INTRODUCTION

The integrated approach to design, the strong fusion and augmentation of functions and the abandon of the discrete components assembly are the very special features of microengineering. Microengineering aims at developing technologies and methods to design and fabricate machines with size from some millimeters down to few microns. These machines are called micromachines by Japanese and mini/microrobots in North America and Europe. The design and fabrication of micromachines cannot be applied by traditional methods and technologies, because they create completely new problems. During the last ten years, microfabrication technologies derived from microelectronics and from precision machining have allowed to accurately fabricate smaller 3D mechanical and electromechanical components. This new trend is known as micro electro mechanical system (MEMS) technology. The availability of microcomponents (mechanisms, motors, sensors, electronics and batteries) with MEMS Technology as seen in Figure 1.1 and Figure 1.2, allows fabricating integrated subsystems (microsystems) by providing mini/micro machines to perform complex tasks in the microworld [1, 2 and 3].

	
Figure 1.1 Ant and gear produced by LIGA Technology of MEMS [3].	Figure 1.2 Mite and gear produced by MEMS Technology. Thickness of gear is equal to the thickness of a single human hair [3].

Since micromachines or microrobots are extremely small machines comprising minute (several millimeters or less) and highly sophisticated functional elements that allow them to perform delicate and complicated tasks, microrobots have many potential uses across different application fields. Due to this, the number of microrobots increased; and today mini/micro robotic colony and/or cooperative mini/micro robotic colony system developments are gaining speed all around the world. The categorization of the robotic systems into the mini/micro scale and the concept of mini/micro robots are analyzed in Chapter 6.1 in detail.

1.1 COOPERATIVE MINI/MICRO ROBOTIC SYSTEMS

A multiple robot system is composed of many robots with a comparatively simple hardware and software architecture and limited functionality than a single complex robot system. Multiple robot system and its properties can be more easily understood just by analyzing the advantages and the disadvantages of this system.

1.1.1 ADVANTAGES OF THE SYSTEM

The advantages of the cooperative swarm (colony) systems can be classified into four main categories described as follows.

1.1.1.1 COORDINATION AND COOPERATION

A team of robots has distinct advantages over single robots with respect to sensing as well as actuation as stated in [4 and 5]. For example, when manipulating or carrying large objects, a given load can be distributed over several robots so that each robot can be built much smaller, lighter, and less expensive [6 and 7]. As for sensing, a team of robots can perceive its environment from multiple disparate viewpoints. In such a system, a task is not completed by a single robot but instead by a team of collaborating robots. Team members may exchange sensor information, help each other to scale obstacles, or collaborate to manipulate heavy objects. A single robot, on the other hand, can only sense its environment from a single viewpoint at a given time, even when it is equipped with a large array of different sensing modalities. Communities of cooperative robotic agents working towards a common goal have the potential to perform a task faster and more efficiently then the same number of agents acting independently [8].

1.1.1.2 MODULARITY, MAINTENANCE, DEBUGGING AND DESIGN

Since multi robotic systems are formed from simple individual robots, the complete robotic system is very flexible. With the modularity properties of individual robots and the swarm system, complex systems can be broken down into smaller ones to help in both design and analysis. Therefore, the design of both the individual robots and the colony system are simplified; maintenance and debugging of these can be accomplished easily [9].

1.1.1.3 MANUFACTURABILITY, SCALABILITY, REDUNDANCY AND COST

Number of components of an individual robot in a multiple robotic system is smaller than the number of components in a single robot system. This makes manufacturing of the individual robot easy and cheap. In addition to that, since the cost of individual robots in a multiple robotic system is little, many identical robots can be manufactured. In this way, redundancy and scalability of the system increases [9].

1.1.1.4 FLEXIBILITY, RELIABILITY, REPAIRABILITY AND ROBUSTNESS

Reliability and repairability increases the robustness of the system. In order to increase the robustness, two conditions must be satisfied. One of them is to keep the individual robots as simple as possible so that robustness of individual robots is high. The other condition is designing the system such that the effect of individual robots on the overall behavior of the system is minimized; i.e., functional decentralization of the overall system must be performed. For example, if a single robot fails or any of its capabilities are lost, the team can still continue the task with the remaining robots as stated before. Since there are many robots of the same kind available in the system, the failure of one robot does not mean anything in the macro scale as stated in the redundancy concept. Since, the others can easily be replaced with the failed robots. Therefore, both the macro scale system and the failed robots have the reparability properties [9 and 10].

1.1.2 DISADVANTAGES OF THE SYSTEM

Although there are many advantages of using multi robotic systems stated above, there are also some handicaps of this system for the current technology. Some of these handicaps, which are active research topics in the world, can be categorized as follows;

- Decreasing the size and volume of the robots require more time investment and integration effort.

- Providing coordination and cooperation among the individual robots is very difficult while organizing the multiple robotic systems to act in harmony.
- Extensive amount of communication is needed between the modules to satisfy the coordination and cooperation [9].

1.2 COOPERATIVE MINI/MICRO ROBOTIC SYSTEM APPLICATIONS

Mobile micro robots (MMR) are desirable for any small restricted places where a task should be fulfilled. In particular, where flexibility and adaptability are required, MMRs may be the only viable solution. Examples could be exploration in small environments [11], fixing unexpected failures in small plants and process automation or microfactories. In addition, those small robots are shown to be very convenient for basic research in collective and bio-inspired robotic studies [12]. First, their small size permits to use a large number of units in a reasonable space extensively. Second, the simplicity and limited computational resources fit well with the relatively simple fundamental algorithms governing social insects. In return, these researches should establish rules how to design the controllers of collaborating robots. A group of small simple robots might thus solve more complex tasks [13 and 14]. Therefore, these artificially intelligent mini/micro robots find a broad range of application in every field. Some most promising applications for multi mini/micro robotic systems are:

- Searching for items or resources in unconstrained and unknown environments such as surveillance and maintenance applications;
- Safe locationing and removal of land mines and other Unexploded Ordnance (UXO);
- Dangerous and hazardous environments like chemical plants and nuclear power plants monitoring, where distributed viewpoints are required;
- Exploration in small environments and small restricted places such as plume detection;
- Fixing unexpected failures in small plants;
- Applications, where flexibility and adaptability are required;
- Process automation and/or microfactory applications;
- Researches on collective robotics and bio-inspired robotics for education;
- Medical applications, military applications and space missions.
- Entertainment and defense applications [15]

1.3 STATE OF ART IN COOPERATIVE MULTI MINI/MICRO ROBOTIC SYSTEMS

Mini/micro robots will be the basis of studies concerning the artificial intelligence and the modeling of robotic systems as live colonies in the nature. Up to now ants, termites and tiny walking insects are studied for these purposes. In future, this swarm (colony) studies will be extended to the flying biological models such as bees, wasps and other micro scale flying insects, which are equipped with hi-tech MEMS sensors, actuators and computational power.

For example, the Micromechanical Flying Insect project (MFI Project) aims to study the possibility of flying. The goal is to develop a 25 mm (wingtip-to-wingtip) device capable of sustained autonomous flight as seen in Figure 1.3. The MFI is designed based on biomimetic principles to capture some of the exceptional flight performance achieved by true flies. The device uses piezoelectric actuators and flexible thorax structures. It will be powered by lithium batteries and solar cells. A first phase was research on fly flight aerodynamics and on analysis, design and fabrication of MFI actuators, thorax and wings.

Many universities are working on the micro scale flying robots as seen in Figure 1.3 and in near future they are going to produce swarm of flying insect robots from the developed ones.

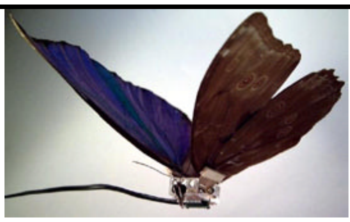
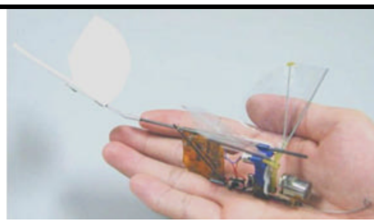
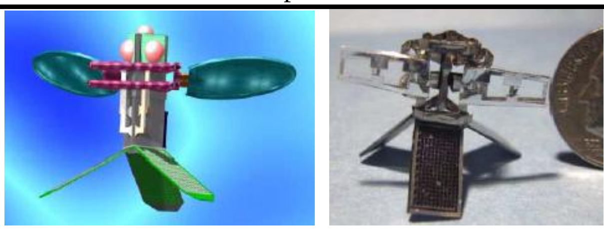
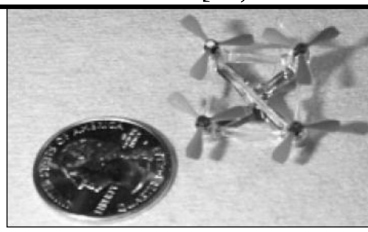
 Beatiful Morpho [17 and 18].	 Caltech Microbat [17, 19 and 20].
 Mock-up of the Berkeley micromechanical flying insect, (MFI) wingspan 25 mm and final mass target 100 mg [16, 17, 21 and 22].	 Mock-up of the Stanford Mesicopter with four 1.5 cm rotors and a mass of 3 g [17 and 23].

Figure 1.3 Micro flyers technology.

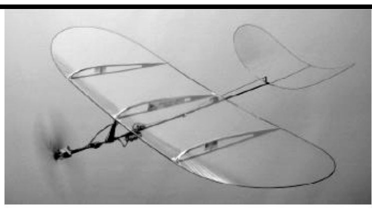
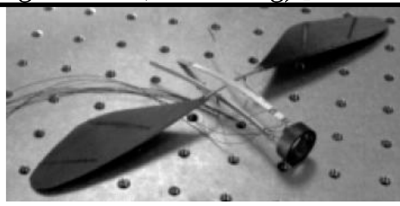
 Vanderbilt University Mesoscale flying robot using piezoelectric actuators [24].	 Institut für Mikroteknik Mainz’s uncontrolled helicopter (Length 24 mm, mass 0.4 g) [17 and 25].
 SRI Flapper [17 and 26].	 Vanderbilt University Mesoscale flying robot [17 and 27].

Figure 1.4 Other applications of micro flyers technology.

1.4 MOTIVATIONS OF THE THESIS

The main motivating factors for this thesis can be classified as follows:

- Excitement For Small-Size Technology: Integrating mechanical components, sensors, electronic and computational devices into a small package; creating intelligent, robust, small size, light, simple, low cost, low power consuming and nature - friendly mini/micro robots;
- Miniaturization: Observing the differences between the classical (traditional) and miniaturized design, manufacturing, assembly techniques;
- Inspiration From Nature: Desire to create autonomous cooperative mini/micro robotic agents, which can communicate with each other to accomplish a given task collaboratively;
- Collaboration: To study the collective behavior with a small quantity of mini/micro robots and to understand the basic principles of cooperation in living insect societies such as ants, bees and others in nature.
- Intelligence: Acquire knowledge in highly integrated intelligent systems;
- Competitiveness: Having technology demonstrative, intelligent cooperative mini/micro robotic swarm (colony).

1.5 AIMS OF THE THESIS

The aims of this thesis can be categorized as follows:

- To design, develop, manufacture and test individual autonomous, mobile mini/micro robots on which, actuators, sensors, intelligence, control, power supply and communication modules are integrated into a very small package. In other words, to provide a mobile micro robot (MMR) platform as small as possible, integrating the necessary elements to make an intelligent autonomous system.
- To produce mini/micro robots, which are very small in size (a few centimeters), light, robust, multifunctional (programmable) with very low power requirements and the production cost.
- To form a technology demonstrative cooperative multi agent mini/micro robotic system,
- To produce a small robotic community from the interactions of many simple individuals performing multi-tasks cooperatively;
- To inspect the difficulties of the design, manufacturing and assembly processes of the mini/micro systems while comparing and observing the differences with the traditional techniques;
- To contribute to the micro robotics and micro electro mechanical systems (MEMS) technology by just starting to work on these kinds of topics.

1.6 SCOPE OF THE THESIS

The steps followed in completing this thesis are given in the historical order as follows:

- Using actuators, special sensors, communication modules and some small mechanical parts available in local market; very small prototype mini/micro robot has been manufactured.
- After the sizes of the prototype mini/micro robot was minimized and the requirements were satisfied, the number of the robots has been increased to form a small mini/micro robotic colony or swarm.
- With the communication modules, these tiny robots have communicated with each other to perform the given task together.
- Different tasks are given to the communities of cooperative robotic agents, and the behavior of each robot has been observed (like in the nature).

- Meanwhile, the differences between the classical (traditional) and miniaturized design, manufacturing, assembly techniques has been compared.
- Finally, technology demonstrative and very small mini/micro robotic colony had been obtained.

1.7 OUTLINE OF THE THESIS

Outline of this thesis can be concisely given as follows:

- Chapter 1, as presented throughout in this section provides a brief introduction to this thesis.

- Chapter 2 is devoted to the detailed literature survey section concerning the individual autonomous mini/micro robots, mobile mini/micro robotic colony systems and other mini/micro sized state of the art robotic agents;

- Chapter 3 presents the design, development, production and assembly of the single mini/micro robots;

- Chapter 4 comprises the colony production from the individual mini/ microrobots, mission details of this swarm system and the implementation of cooperation and coordination tasks in a collaborative mini/micro robotic swarm environment;

- Chapter 5 covers the observations, implementation results and the experiments of the produced mini/micro robotic system;

- Chapter 6 concludes this thesis by discussing the outcomes; as well as recommendations for future works.

CHAPTER II

LITERATURE SURVEY

As stated in Chapter 1, microrobots have many potential uses across diverse area, such as education (artificially intelligent multi agent systems, robot competitions, and exhibitions), military applications, space missions, medical applications and microfactory applications.

Therefore, this chapter is devoted to the detailed literature survey about individual, colony mini/micro mobile robots and their application field analysis as well as miniaturization study and design considerations of mini/micro robotic systems.

The brief summary of well-known individual and swarm type mini/micro robotic systems in the mentioned application fields can be seen in Table 2.1 and Table 2.2 respectively [28] to get an introductory idea of how small and functional they are.

In the following sections, these mini/micro robotic systems are analyzed in detail according to their main application fields.

Table 2.1 Summary of individual mini/micro robotic systems.

Robot	Size [cm]	Volume [cm^3]	Battery Type	Motor Type	Run Time [min]	Speed [cm/s]	Year
EMRoS	< 1 cm (Each)	~ 1	Watch Battery	Watch Move.	5	~11	1992
Kity	2.5x2.47x2.59	16	Watch Battery	DC Motors	10	5	1994 - 1995

Table 2.1 Summary of individual mini/micro robotic systems (continued).

Robot	Size [cm]	Volume [cm^3]	Battery Type	Motor Type	Run Time [min]	Speed [cm/s]	Year
Meloe	-	14	Watch Battery	Watch Move.	100	2	1996 - 1997
Inchy	2.54x2.54x2.54	16	Ni-MH	Smoovy ø 5	30	30	1997
Pollicino	-	16	Watch Battery	Wobble	15	10	1999
Mirosot 100	7.3x7.4x6.3	~ 340	Ni-MH	DC Motors	-	150	-
Pearls	< 5 cm (Each)	-	Ni-MH	DC Motors	-	-	2001 - 2002
New MARV	-	4	Watch Battery	Smoovy ø 3	10	1	2002

Table 2.2 Summary of colony (swarm) mini/micro robotic systems.

Robot	Size [cm]	Volume [cm^3]	Battery Type	Motor Type	Run Time [min]	Speed [cm/s]	Year
MIT_Ants	3.5x3.5x3	36	Ni-Cd	3 DC Motors	20	15	1995
MARS (Old)	-	16	Lithium	Step Motors	10	4	1995
MARS (New)	Ø: 3.5 H: 3.2	30	VL Rechar.	Step Motors	10	4	1999
Millibots	7x7x7	343	Ni-MH	DC Motors	90	Max. 20	2000
Khepera (New)	Ø: 7 H: 3	115	Ni-MH	DC Servo Motors	60	100	2002
Alice (New)	~ 2	8	Ni-MH	Watch Move.	600	4	2002

2.1 EDUCATION, ROBOT CONTESTS AND DEMONSTRATIVE APPLICATIONS

Miniaturization studies are carried out in many universities/institutes/labs around the world. They demonstrate the final mini/micro robotic systems in the exhibitions as hi-tech technology indicators, while forcing the limits of the robots’ sizes. With the produced mini/micro robotic systems, these universities also participate in robotic competitions to force the limits of the technology even further. However, making the smallest robot in the world is not meaningful for everybody. Besides the smallest sizes, the robots should also have intelligence and autonomy to strike the people with admiration. Therefore, within the last decade many artificially intelligent and autonomous mini/micro robotic systems are developed for educational (artificial intelligence, biological system implementations into swarm robotics and modeling etc.) as well as demonstration and competition purposes. In this section, intelligent and autonomous small robotic systems are categorized in two groups, which are individual and colony mini/micro robots made for the education, demonstration and competition purposes.

2.1.1 INDIVIDUAL MINI/MICRO ROBOTS

Individual mini/micro robots are single robots produced for the education, demonstration or competition purposes of this category. A detailed analysis of the individual mini/micro robots can be found under following headings.

2.1.1.1 KITY

Kity was developed in 1994-1995 at the Robot Intelligence Technology Lab (RIT) of the Korea Advanced Institute of Science and Technology (KAIST) in Korea. Kity is an autonomous micro-robot with a maximum speed of about 5 cm/s and the size of less than about 16 cm^3. It consists of two micro-switches for detecting contact to the wall (2 contact sensors), 2 DC motors, two 3-Volt Lithium batteries, and an 8-bits Intel's i8051 compatible microprocessor. It should be noted that the robot is completely built by hand using no printed circuit board (PCB). The electronic components are not assembled on a PCB as usual but a lot of small wires connect everything together. This method permits a saving of some space and the cost of the PCB. On the other hand, big amount of time is necessary to assemble the robot and damages are difficult to repair.

To control Kity only 2 digital control signal outputs to the DC motors and 2 digital input channels to receive signals from contact sensors are used. Wheels are geared to the DC motors with the gear ratio 9:100 as seen in Figure 2.1. Because only unidirectional ‘on-off’ control is used within this system, Kity can go forward, turn left, and right, but cannot go backwards.

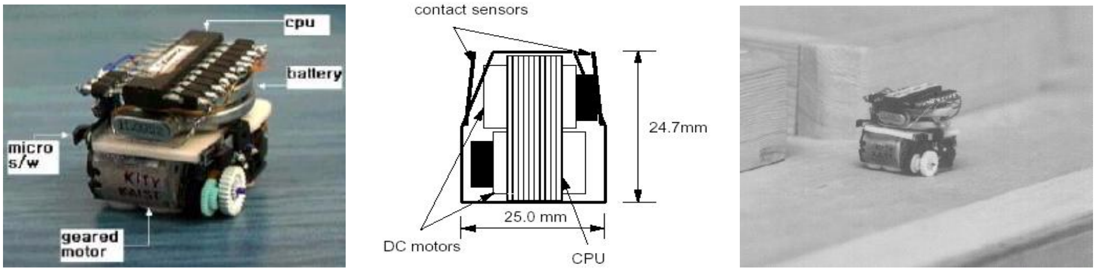


Figure 2.1 Structure of the micro-robot Kity in 2D and 3D views [28 and 29].

By imitating the immune system in living organisms, an interesting artificial intelligence (AI) technique for dynamically changing environment is developed to control the behavior of Kity. This model is used for dynamic problems dealing with unknown environments rather than static problems. With this model, a table-look-up immune network is proposed for the proper behaviors of the microrobot in a maze. The aim is to solve a problem of finding a way from start point to a goal point via 5 control points in the maze while accomplishing the conditions given by the maze contest. These conditions and the goals for the robots are to run the shortest path in a minimum on the maze. With this model, it is possible to generate enough rules to make the robot achieves the goal by navigating freely in a maze with a very small number of sensors, limited memory and calculation capacity. Kity demonstrated its efficient algorithm by winning the 1st price at the International Micro Robot Maze Contests of 1995, 1996 and 1997 [29].

2.1.1.2 JEMMY

Jemmy is tiny 1 cm^3 robot developed by LAMI and EPFL in Switzerland (1995-1998) as seen in Figure 2.2. It is driven by 2 RMB Smoovy motors, which are 3 mm in diameter. It has 4 passive infrared sensors. Embedded PIC 16C710 microcontroller generates the 3-phase signals for motors, performs time-to-voltage conversion to read the sensors, and communicates using a single-wire bidirectional link with an optional supervision unit.

Precision gearing and 8 miniature ball bearings are used on Jemmy. Due to the small sizes of Jemmy, power is provided by tiny wires. However, it was the winner of the International Micro Robot Maze Contest '97, Nagoya (Japan) in 1 cm^3 category [30].

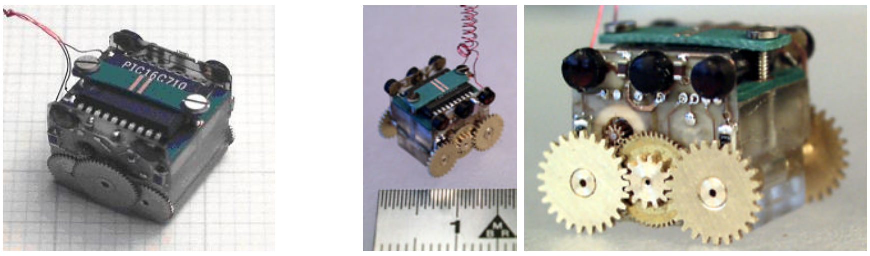


Figure 2.2 Jemmy and 1cc mobile micro robots [30].

There is another 1cc mobile robot of EPFL and LAMI as seen again in Figure 2.2. This microrobot uses 2 Smoovy motors with 3mm diameter from RMB. A first gear transmits the movement to the second level gear, which is used as a wheel. A PIC 16C54 drives directly the motors. 2 photo-transistors and 1 LED have been bonded on the side in order to follow a wall [31].

2.1.1.3 INCHY

Inchy is modular and autonomous 1 $inch^3$ robot developed by EPFL and LAMI (1997). As seen in Figure 2.3, it includes 3 rechargeable Ni-MH button cells providing autonomy for 15 to 30 minutes. There are two 5 mm diameter synchronous RMB smoovy motors, by which speeds of over 30 cm/s can be achieved. Inchy has 4 infrared proximity sensors, which can be replaced by other devices simply by exchanging the removable top PCB. The PIC16C84 microcontroller performs the same tasks as in Jemmy. Although this robot has been designed to be autonomous, it can be controlled with the same supervision unit as Jemmy; i.e., single-wire bidirectional communication channel [30].

Figure 2.3 Inchy [30].

2.1.1.4 MELOE

In 1996-1997, the micro-robot Meloe was developed in ULB [32]. The two versions of Meloe1 and Meloe2 given in Figure 2.4 are micro-robots of less than 1 cubic inch in volume and are powered by LAVET type watch motors. The energy comes from small watch batteries. They are controlled by an on-board PIC microcontroller. Meloe1 has a sensor set in order to follow a line on the floor, whereas Meloe2 is reprogrammable [28].

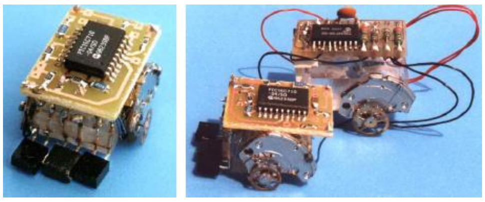


Figure 2.4 Meloe1 version and both versions of Meloe microrobots [28 and 32].

2.1.1.5 POLLICINO

Pollicino is a micro-robot developed in SSSA, Italy. Figure 2.5 shows the teleoperated version from 1995-1996. The overall dimensions of the teleoperated micro-robot are 10 mm x 10 mm x 10 mm. The operator controls the microrobot by a remote joystick and flexible ultra miniature wires. It has a maximum speed of 10 cm/s and can climb a slope of 15 degrees. The main innovative component in the teleoperated version is the micromotor which is based on variable reluctance working principle and moves step by step. This is a novel type of electromagnetic wobble micro-motor [33]. Two micromotors are used to actuate the wheels of the microrobot that includes only few parts (9 in total) which are fabricated by precision machining and assembled manually. The micromotor is driven by a sequence of current pulses and performs about 340 steps per revolution. The micromotor generates a torque of 350×10^{-6} N.m at each step and a maximum speed of about 180 rpm. The heart of the control circuitry is a PIC16C73 microcontroller that implements the control algorithm allowing the microrobot to move forward, backward and turn left or right. The microrobot participated in the 1995-1999 Micro Robot Maze Contests in Nagoya, Japan, and won two first prizes. In 1999 an autonomous adaptation with batteries and sensors was also built with a volume of 1 $inch^3$. It has similar specifications regarding motors and speed. Three slightly different versions of microrobot have been fabricated in MiTech laboratory, SSSA named as CS-01/03. The main difference between the three microrobots is the technology used to deposit the insulating layer on the rotor of the micromotors [34].

Figure 2.5 Pollicino [34].

2.1.1.6 AIRAT2 MICRO MOUSE ROBOT

Figure 2.6 shows AIRAT2 is a micro mouse robot developed for educational activities by Active Robot Ltd. in UK, 2000. It uses an 8051 CPU. AIRAT2 emits a beam of light and uses sensors to receive the amount of light reflected back. The CPU utilizes the JS8051-A2 board. It uses powerful outside resources such as LCD, ADC, two external timers, self-flash writing and more.

Figure 2.6 AIRAT2 micro mouse robot [35].

The sizes of AIRAT2 robot are 114 x 88 mm and it uses 6 sensors, enabling it to move diagonally. Other components of AIRAT2 robot are JS8051-A2 CPU board, 144 x 67 mm aluminum body frame, 2 aluminum wheels with 51.3 mm rubber tires, 2 small ball caster wheels, two H546 stepping motors, 6 unit (EL-1KL) IR LED and (ST-1KL) phototransistor sensors, (BTG- 47) frequency driven piezo buzzer, 1 power and 3 user LEDs, reset and user keys, 2 packed Ni-Mh (7.2 Volt 450 mAh) batteries and RS232C (115,200 bps downloading) serial. In addition to that, a PC simulator enables the user to understand more easily the high-level mouse search algorithm using C program [35].

2.1.1.7 MIROSOT-100 SOCCER ROBOT

MIROSOT-100 is a soccer robot with 73x74x63 mm sizes developed for FIRA Tournaments in 1996 and commercially available in Microrobot NA Inc., Canada. MIROSOT-100 has 2 precision-geared 2224R006SR DC motors with 512-pulse/rev IE2-512 encoders and a L298 motor driver. The speed of soccer robot is 1.5 m/s and it is powered by a 7.2V packed Ni-MH (450 mAh) battery. It also incorporates an EPLD chip, which has encoder input processing logic and PWM hardware logic. This robot uses an AMD (AM188ES 40 MHz) CPU employing INTEL 8086 architecture. 1Mbit (AT89C010A) flash memory and 1Mbit (68100) SRAM is also used with this CPU. It is constructed from a duralumin frame allowing it to easily withstand the incidental bumping and pushing as seen in Figure 2.7. Two LED displays, BiM418 or BiM433 RF modules, 2 user and 1 reset push button keys are the other features of MIROSOT-100 soccer robot [36].

Figure 2.7 MIROSOT-100 soccer robot [36].

2.1.1.8 PEARLS FAMILY TINY ROBOTS

The robot shown in Figure 2.8, called PEARL MK2, is one of the PEARL family’s robot developed in late 2001 by Choi Chanhak in Korea.

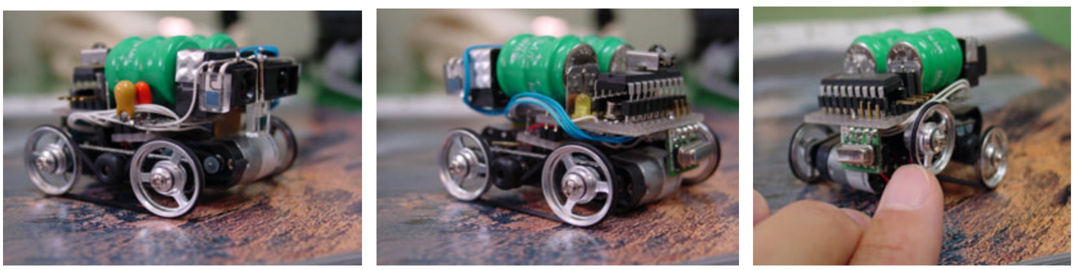


Figure 2.8 PEARL MK2 [37].

It is modular in design with its one IR receiver module, one RF module, 3 luminous intensity sensors and 1 IR object detector module. Power is provided from two small Ni-MH rechargeable batteries, 3.6V/70mAh. The used computer is PIC16C711/4MHz. Two small dc geared motors with encoders propels PEARL MK2. It can drive in rough terrain with its unique suspension system, which took the final form in 2002 as shown in Figure 2.9. This robot is a good mobile platform to experiment on various things about autonomous robot and collaboration of small robotic systems in education [37].

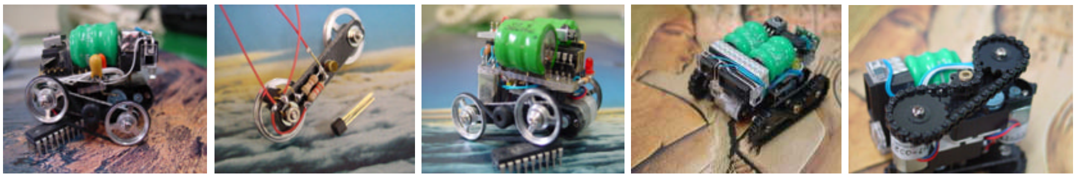


Figure 2.9 Wheels with encoders and unique suspension system development [37].

2.1.1.9 TINY LINE TRACER

Tiny line tracer has dimensions of less than 5 cm. It uses almost the same parts with PEARL MK2 robot as seen in Figure 2.10 and produced by Choi Chanhak in Korea. The differences between them are the 9 V battery and the IR sensors. 9V power on Tiny line tracer is reduced to the 5V by using 7805 voltage regulator due to the voltage limit of PIC16F84. As the name implies, the only task of this robot is to follow the lines for the educational purposes [37].

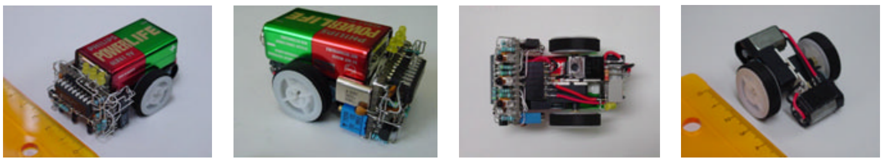


Figure 2.10 Tiny line tracer robot [37].

2.1.1.10 PEACE, NADO ROVER AND TV REMOTE CONTROLLED TINY MOBILE ROBOT

Peace is developed in fall 2001 again for educational purposes by Choi Chanhak in Korea. It uses a lithium battery and solar cell, which are different than the other PEARLS family robots. On the other hand, Nado Rover has 3.6 V NiCd batteries with 65 mAh current capacity. It is inspired from the Sojourner robot, which is designed for the exploration task of Mars. Tiny mobile robot controlled by a TV remote is also developed in summer 2000 [37]. The pictures of these 3 robots can be seen in Figure 2.11 respectively.

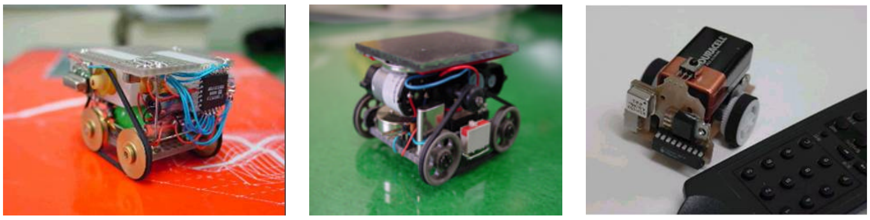


Figure 2.11 Peace robot, Nado rover, Tiny robot and TV remote [37].

2.1.1.11 EMROS

EMRoS are the world's smallest robots (~1 cm^3) developed by Seiko Epson Corporation in Japan just for demonstration purpose. There are 4 types of EMRoS robots, which are Monsieur, Nino, Ricordo, and Rubie. The world’s smallest robot is the Monsieur developed in 1992. The shell is made of silver and even of gold for special versions. Light sensitive robot is less than 1 cm high, mass 1.5 g, and is made of 97 separate watch parts [38]. It is capable of reaching speeds of up to 11.3 mm/s for about 5 minutes when charged. Figure 2.12 shows EMRoS microrobots. Besides their instinctive, dynamic movements, EMRoS microrobots can learn and try new movements [39]. The two “eyes” are sensitive to the light and the flashlight which included in the robot’s box can be used to attract the robot. The main advantages are the very small size, the nice shape and the simple recharge method. The power autonomy is of some minutes and afterwards the robot is just placed in its box to recharge. The robot’s whiskers provide the electrical contact to the charging station. The Monsieur won a design award at the International Contest for Hill-Climbing Micromechanisms [40].

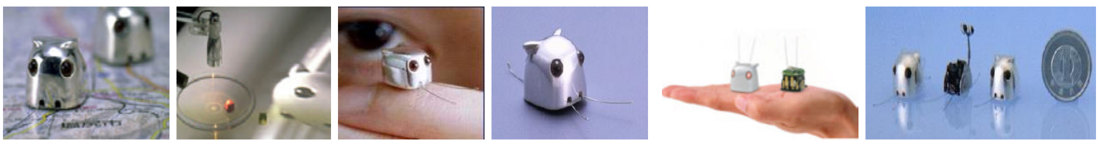


Figure 2.12 EMRoS microrobots and Monsieur II microrobots [38, 39 and 40].

Seiko Epson has also developed a small robot, Monsieur II-P with a volume of 7.8cm^3 and mass of 12.5 g in 1993 as seen in Figure 2.12. It travels at a speed of 150 mm/s. Wheels are activated by a self-developed ultrasonic motor with 0.4 mm diameter. The built-in Bluetooth module enables wireless control of the new robot. This function makes the new robot bigger than Monsieur, which has only the function to follow light. New robot employs three 1.7-volt zinc-air batteries connected in a series for driving power and it has 5 hours autonomy. The 3 batteries have a mass of 4.3 g in total, whereas the mass of the robot is 12.5 g. It travels at about 70 mm/s under control and 150 mm/s when not under control via Bluetooth [41].

2.1.1.12 BEAM ROBOTS

Beam robots are usually solar powered vehicles. Some of these vehicles are about 1cubic inch including a solar cell and special actuators (beam muscles). Sometimes a light sensor helps the robot to direct towards the light and thus to ‘survive’. The company Solarbotics presents examples of such small solar powered robots as seen in Figure 2.13 [42 and 43].

Figure 2.13 Beam robots [42 and 43].

2.1.2 COLONY MINI/MICRO ROBOTS

Swarm or colony type mini/micro robots found in literature can be categorized as follows:

2.1.2.1 KHEPERA

In 1993 Swiss company K-Team S.A. produced Khepera robots, which have both small size and computing complexity [44]. They are 7 cm in diameter (old versions 5 cm) as seen in Figure 2.14 and are capable of significant on-board processing. These robots are modular and support the addition of sensor and processing modules. They are designed to work alone or communicate and act with other robots. Khepera robots achieve mobility from a pair of centimeter sized wheels housed in the center of the robot. Khepera allows real world testing of algorithms developed in simulation for trajectory planning, obstacle avoidance, pre-processing of sensory information, and hypotheses on behavior processing, among others [45]. A large number of extension modules make it adaptable to a wide range of experimentation.

Figure 2.14 Khepera robots and modularity [44 and 45].

2.1.2.2 MARS

The first MARS was built in 1995 by Fukuda [46] in Japan and a newer version in 1999 [47]. The two versions are similar as seen in Figure 2.15. The older version is more compact and fits in 1 inch^3 whereas the newer is bigger but more functional and powerful. Both versions have two Seiko stepping motors with reduction gear 1/68, photo sensors and infrared bidirectional communication to the base station. The new MARS has a diameter of 3.5 cm and a height of 3.2 cm (volume 30 cm^3), 4 proximity sensors and one light sensor. With VL rechargeable batteries the run time is about 10 min. The robots are used for research of group behavior control. In this field Fukuda proposed the concept of Cellular Robotics [48].

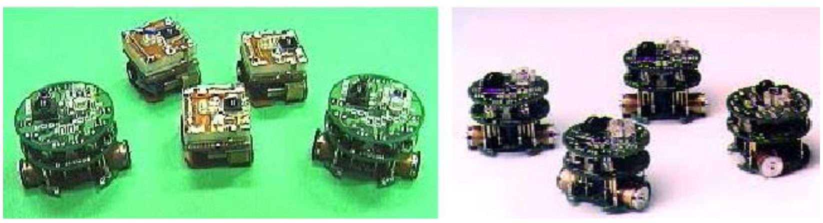


Figure 2.15 New, old MARS versions and a group of new MARS [46, 47 and 48].

2.1.2.3 ALICE

Alice was first developed at Autonomous Systems Lab. of EPFL in 1995. Motivation of the design is to produce the cheapest and the smallest intelligent mobile robot to study collective behavior with large quantity of robots. Figure 2.16 shows the evolution of Alices over 8 years and Table 2.7 summarizes the specifications and improvements of Alices.

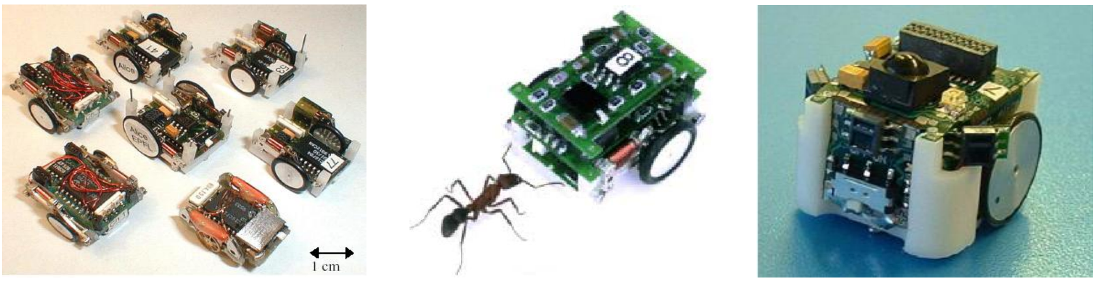


Figure 2.16 Evolution of ant size Alice prototypes over eight years [53, 54 and 55].

2.1.2.3.1 ALICE-1995

It was able to follow a black line on a white paper. This robot worked well but had several drawbacks such as the wheel slippage on smooth surfaces, assembly/disassembly problems and one time programmable microcontroller [49].

2.1.2.3.2 ALICE-1996

In 1996, Alice was modified to take part in the International Micro Robot Maze Contest in Nagoya. The control loop for this maze is based on a global and a local feedback. The global feedback is realized by a human operator piloting the robot with an infrared-based unidirectional remote control. While the local feedback allows driving the robot automatically in between two walls using two optical small distance sensors on both sides of the robot. In this design, some of the drawbacks of the first robot are eliminated [50].

2.1.2.3.3 ALICE-1997

In 1997, the objective was to build the mini robot as flexible as possible, able to sense obstacles and receive wireless commands. Software flexibility is assured by the re-programmable EEPROM microcontroller, while hardware flexibility is obtained with extension connectors for additional sensor modules in the new Alice. A module with 2 proximity sensors and an infrared receiver extends the basic functionality of this prototype.

From this version on, bidirectional watch motors with rubber tires, which extend the mobility and grippage of surface, were used.

2.1.2.3.4 ALICE-1998

In 1998, a big effort towards simplification of assembly was made on Alice [51]. Any loose wires to the motors have been avoided and all components were put onto a flexible print as seen in Figure 2.17.

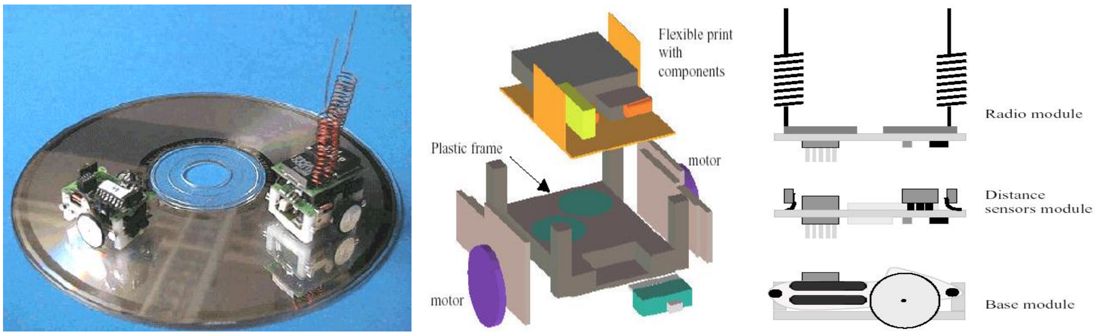


Figure 2.17 Alices on a CD-ROM, base module assembly and modularity of Alice [51].

This plastic frame and the bigger rubber tires absorbed part of the shocks. With a smaller connector and a serial bus concept, more sophisticated extension modules like a four direction proximity sensor module and bidirectional radio communication module were used. This version won the International Nagoya Maze Contest 1998, as an autonomous system.

2.1.2.3.5 ALICE-1999

Alice-1999 version called as LAMAlice was developed for the space mission domain by Autonomous Systems Lab. of EPFL. A simple two-module structure (upgradeable to more modules) offering advantageous off-road characteristics and flexible blade-wheels has been developed with this version to provide high obstacle overcoming properties with torque limited low power systems. The wheel structure of LAMAlice is given in Figure 2.18.

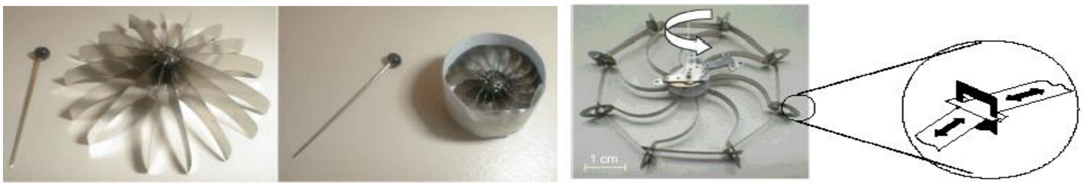


Figure 2.18 Opened, folded and alternative blade-wheel design respectively [52].

An interesting feature is the substantial volume reduction achieved by folding these wheels for transportation. A new, simple and passive locomotion concept, which might be interesting for planetary exploration has been developed with Alice-1999 prototype nanorover. LAMAlice is a four-wheel drive rover which is composed of two separate parts linked together with a flexible passive coupling as seen in Figure 2.19 and detailed specifications of it is given in Table 2.3. This configuration allows a “push-pull” effect improving the overcoming of an obstacle and offers good gripping [52].

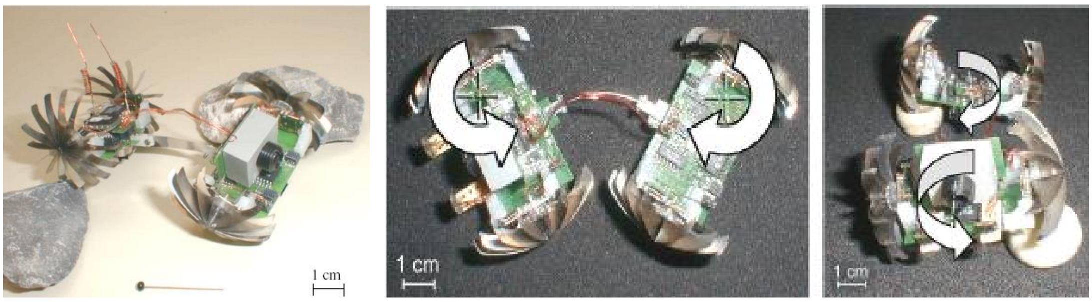


Figure 2.19 Nanorover LAMAlice, horizontal flexion and torsion [52].

Table 2.3
Main characteristics of Nanorover LAMAlice

Dimensions [cm]	11x6x4
Front Module Mass [g]	15
Rear Module Mass [g]	14
Power Consumption [mW]	~ 40
Autonomy [h]	~ 20
Maximum Speed [cm/s]	1
Minimal Turning Circle Diameter [cm]	15
Maximum Obstacle Height [cm]	4
Maximum Slope [°]	37

Table 2.4
Mean free path (MFP) comparisons

Properties	Sojourner	LAM Alice
MFP of Viking Landing Site 1	9.6	15.1
MFP of Viking Landing Site 2	2	6.6
Mass [kg]	11.5	0.03
Robot Folded Volume [dm^3]	~ 45	~ 0.2

New features are bigger wheels, symmetrically mounted on a common axis, and a regulated power supply. This solution with 3 batteries and a voltage regulator stabilize power supply voltage until 10 mA, and thus additional modules have enough power to work properly. When compared with the Sojourner robot, which is the famous one in small rover robots, LAMAlice robot has the advantages stated in Table 2.4.

2.1.2.3.6 ALICE-2001

Applications of mobile mini robots (MMRs) like remote inspection tasks in small pipe systems and in narrow-labyrinth-like environments were investigated for Alice-2001 as seen in Figure 2.20. Navigation task experiments, like local localization, global localization and map-building are carried out with Alice 2001 [53].

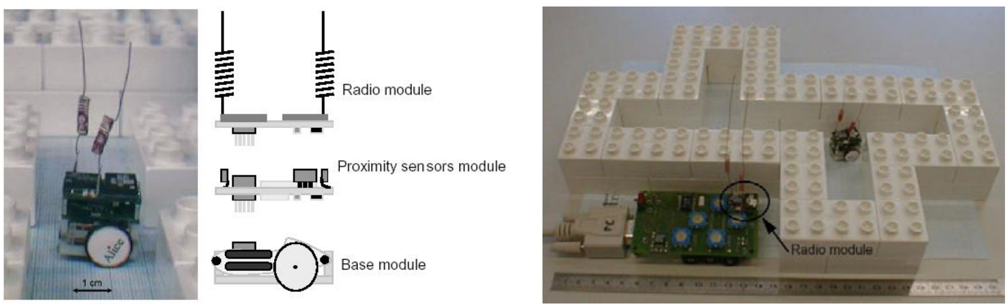
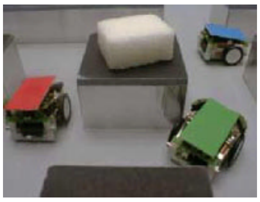
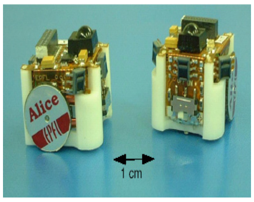


Figure 2.20 Alice in a 3 cm narrow labyrinth and the composing modules [53].

2.1.2.3.7 ALICE-2002

In year 2002, Alice, having the sizes of 21x21x12 mm, is presented. It has autonomy of around 10 hours [54]. Table 2.5 shows power consumption of components. Different ways of communications are available for Alice-2002 such as unidirectional IR communication for the behaviors like obstacle avoidance or wall following, bidirectional IR communication for robot to robot short range communication and bidirectional radio communication with an external supervisor. This allows for automatic map building in simple labyrinths [55].

Table 2.5 Power consumption of each subsystem on sugar cube sized Alices [54 and 55].

	Unit	Average [mW]	Peak [mW]
 	Motors (1x)	1.5	2.5
	CPU	3	
	Sensors	0.5	18
	Infrared RX	0.6	1
	Local Communication	-	18
[54], [55]	Radio RX	3	3
	Radio TX	-	30
	The robot	~ 10	~ 45

2.1.2.3.8 ALICE-2003

Alice-2003 and the improvements of specifications can be seen in Table 2.6 [56].

Table 2.6 Specifications and improvements of Alices over years.

Alice's Years	1996	1998	2001	2002	2003
Dimensions (mm)	21x21x19	21x21x18	21x21x22	21x21x12	22x21x20
Mass			8 g	5 g	11 g
Velocity	20 mm/s	20 mm/s	40 mm/s	40 mm/s	40 mm/s
Power Cons. mW	< 10	4 - 7	9 - 18	4 – 10	12-18
Power Autonomy	10 hours	10 hours	5 hours	10 hours	10 hours
Alice's Years	1996	1998	2001	2002	2003
Proximity Sensor Range	-	-	30 mm	-	40 mm
Infrared Remote Comm.	6 m	6 m, 500 bps	-	6 m, 500 bps	10 m
IR Local Comm.	-	4 cm, 500 bps	-	4 cm, 500 bps	6 cm
Radio Communication	-	10 m, 1000 bps	10 m, 1000 bps	10 m, 1000 bps	-

The chassis module of Alice-2003 is produced by plastic injection giving the robot some flexibility and protecting it against mechanical shocks as seen in Figure 2.21. Rubber tires also help to absorb shocks. Therefore, the robots are to some extent protected from improper manipulations. The system and its functionality can be extended by just plugging on new modules [14, 57 and 58].

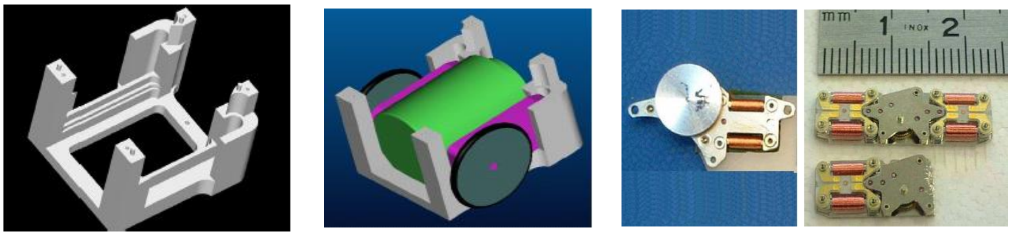


Figure 2.21 Basic mechanics of Alices and special watch motors with gear sets [14 and 28].

LAVET [3] watch motors have been chosen for Alices. These motors have a very low power consumption (0.5 - 2 mA); they are highly optimized and easy to control (6 steps per rotor revolution and directly driven from 3 microcontroller pins). A gear with ratio 180 is included in the motor block again as seen in Figure 2.21, in which the left motor was used in Alice-1999 and the right one used in Alice-2003. The final motor version comes with 2 independent motors acting on the same axis (minute and hour) that have to be split [28].

Alice-2003 has up to 10 hours autonomy with rechargeable battery. They fit perfectly to the robot dimensions but the problem is the low maximal current due to the high internal resistance. Now accumulators are used even if they have a much lower capacitance/volume ratio. The new solution also includes a voltage regulator to stabilize the power supply.

The system is controlled by a PIC16F877 microcontroller, which is also characterized by low power consumption (about 1 mA @ 4MHz). Other important features are its size (PT44, 12x12x1 mm), integrated peripherals (ADC, USART.) and the 8K flash program memory.
SFH9201 IR proximity sensors from Infineon are used for robot-robot local communication. The robot is able to see obstacles up to 4 cm away and to do local communication up to a distance of 6 cm. The base of Alice contains an IR receiver for standard TV remote controllers, which are cheap and easy to find devices. The communication is unidirectional.

Radio module contains the HX1000 as transmitter and the RX1020 as receiver, both working at 433.92 MHz. With this transceiver, the robot is able to communicate with other robots or with a host computer. This feature is of high interest to exchange information between robots or to supervise the status of a robot by means of a host computer. The transmission of data in both directions was tested up to a distance of about 10 meters at 1 KBauds.

The sensor TSL2301 from TAOS is used and the optics was created around it, Figure 2.22. Camera can be read out directly by the main processor with a serial protocol. Chip has 102x1 pixels and an integrated 8 bit ADC so that the PIC can easily manage the information flow. It still works at 3 Volt and with a picture refresh rate of 50 Hz, the consumption is 2.2 mA. Typical features that such sensor can detect are bright spots, vertical black and white lines.

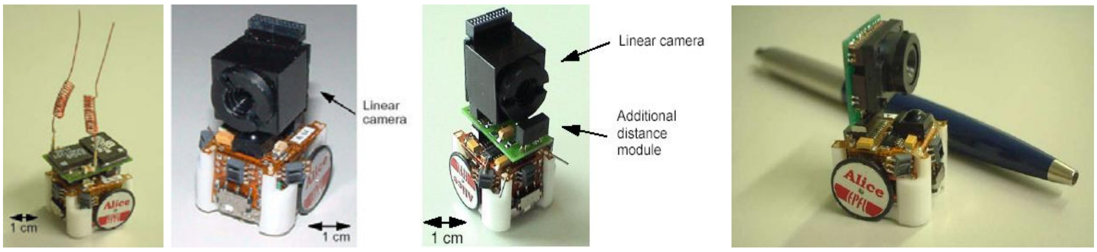


Figure 2.1 Radio module and linear camera module of Alices [28].

With the study on Alices, small size, increased robustness, long power autonomy, software and hardware flexibility and low cost properties are achieved on autonomous micro robotic systems. Ongoing projects for the Alices can be categorized as navigation in small labyrinth (localization and map building), soccer kit tournament applications for education, collective behavior investigation, mixed society robots-insects cooperation and communication.

Table 2.7 Component improvements of Alices over years [14, 51, 53, 54, 55, 56 and 57].

<table>
<tr><th>Alice’s Years</th><th>1995</th><th>1996</th><th>1997 /1998</th><th>1999 (Nanorover)</th><th>2001</th><th>2002</th><th>2003</th></tr>
<tr><td>Chassis</td><td colspan="2">PCB</td><td colspan="5">Flexible PCB & Plastic Frame</td></tr>
<tr><td>Motors</td><td colspan="2">2 Monodirectional Watch M.</td><td colspan="5">2 Bidirectional Swatch Motors</td></tr>
<tr><td>Energy source</td><td>1Lithium Battery (3V)</td><td>Small Watch Batteries</td><td>2 Silver-Oxide Battery (1.55V)</td><td>3 Silver-Oxide Battery (1.55V) + Voltage Regulator</td><td>3 Button Cells V377</td><td>3 Button Batteries (1.5 V, 23 mAh) + Voltage Regulator</td><td>Varta 3/V40H, Ni-MH Rechargeable</td></tr>
<tr><td>Microprocessor CPU</td><td>PIC16C71</td><td>PIC16C84, SMD Package With EEPROM</td><td>PIC16C84</td><td>PIC16F84</td><td>PIC16F84 (8 bit CPU, 68 RAM, 1K Word ROM)</td><td>PIC16F84 @ 4 MHz</td><td>PIC 16F877 (8 bit CPU, 6 RAM, 8K Word Flash)</td></tr>
<tr><td>Sensors</td><td></td><td></td><td></td><td>SIEMENS SFH 900 x 4</td><td colspan="3">4 IR Proximity Sensors: SFH900 and SFH9201/1-2 (Siemens)</td></tr>
<tr><td>Communication Modules</td><td>-</td><td>-</td><td>-</td><td>IR and TV Remote Control Receiver, Bidirectional Radio Communication</td><td>(0.2 mA)
Photodiode,
An Amplifier and
A Filter.</td><td>One way IR with Dedicated Circuit (1 Diode + 2 OpAmps), One Way IR With RC5 Standard, Both Ways Radio. On-Off keying</td><td>Radio Module: HX1000 Transmitter, RX1020 Receiver, IR Receiving Module: TSOP1836ss3V</td></tr>
<tr><td rowspan="2">Other Modules</td><td colspan="2">1 LED, 2 Photo Transistors,</td><td rowspan="2">2 Channel A/D Converter, Batteries Holder, Oscillator and Power Switch, Extension Bus</td><td>Extension Connector, Batteries Holder, Oscillator, Power Switch and Capacitor.</td><td>Radio Receiver RX1020 @ 433.92 MHz by RFM</td><td rowspan="2">4 Proximity Sensors (For Local Communication),</td><td>24 Pin Bus Connector</td></tr>
<tr><td colspan="2">Oscillator, Power Switch</td><td>CMOS Camera APS256D From CSEM</td><td>Radio Transmitter HX1000 @ 433.92 MHz by RFM (On-Off Keyed)</td><td>Camera Module: TSL2301 TAOS Sensor, Optics, 8 bit ADC</td></tr>
</table>

2.2 MILITARY APPLICATIONS

Mini/micro robotic applications are usually supported by army and military companies due to their high technology properties. These robots can be used for the surveillance and explosion removal tasks and as spies for the military applications. Some examples to these application fields can be seen in following sections.

2.2.1 INDIVIDUAL MINI/MICRO ROBOTS

It is seen that, there are individual mini/micro robot for the military applications in the literature. And their details are given under the following titles.

2.2.1.1 MARVS AND MINI ROBOTS AT SANDIA NATIONAL LABORATORY

In 1996, Sandia's Intelligent Systems Sensors and Controls department produced a Mini Autonomous Robot Vehicle (MARV). It is a one-cubic-inch robot containing all the necessary power, sensors and controls on board. MARV is made primarily from commercial parts using ordinary machining techniques. MARV employs two on-board sensors developed at Sandia to locate and track buried wires containing radio frequency signals as seen in the first picture of Figure 2.23. This robot was improved over the years with obstacle detector sensor, radio and temperature sensor. A chemiresistor integrated micro system has been developed in partnership with the Intelligent Systems and Robotics Center, which integrates 4 gas sensors and their control electronics on single silicon ASIC [59 and 60]. Printed circuit boards were used in the improved bodies of MARVs. With new packaging techniques of electronics, wheel design, and body material, researchers have shrunk the volume and masses of the robots to 1/4 cubic inch and 1 ounce (~28 g) respectively in 2002.

Figure 2.23 MARV and minirobots, which turns on dime and parks on nickel [28 and 59].

This new mini robot is powered by 3 watch batteries for about 10 minutes and rides on track wheels propelled by two 3 mm Smoovy motors with gearbox attaining a speed of 20 inch/minute (~ 1 cm/s) as seen again in Figure 2.23. The mechanical frame is built using the rapid prototyping technique stereolithography. The material is lightweight, strong, and can be formed in complex shapes. The robot body has cavities for the batteries, the electronics embedded glass substrate, axles, motors, switches and other parts. This new mini robot was built to demonstrate that micro autonomous vehicles could handle jobs as diverse as locating and disabling land mines, detecting chemical or biological weapons [60 and 61].

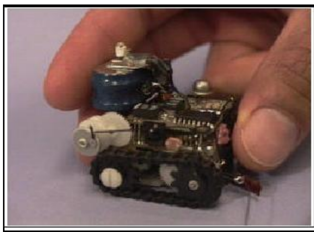
2.2.2 COLONY MINI/MICRO ROBOTS

Colony mini/micro robots, produced for the military studies, can be seen in the following sections.

2.2.2.1 MIT'S ANTS

Main focus of explosive ordnance disposal project is to study how a community of robots can effectively clear an area of unexploded ordnance. Cubic-inch size microrobots are used as a physical simulation of full scale mine sweeping mobile robots as given in Table 2.8. As seen in Figure 2.24, if one robot finds a land mine, it signals its position to the others like in nature.

Table 2.8 Ants' technical specifications



Properties	British Unit	Metric Unit
Width (Excluding Whiskers)	1.4 inch	35.56 mm
Length (Excluding Whiskers)	1.4 inch	35.56 mm
Height	1.2 inch	30.48 mm
Mass	1.18 oz	33.45 g

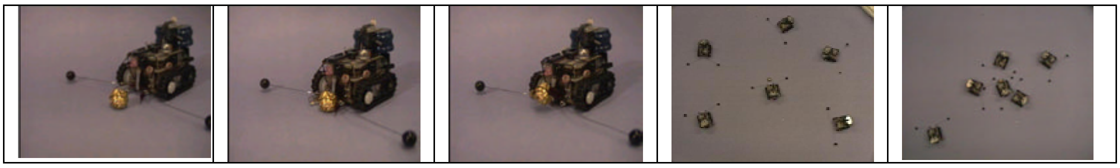


Figure 2.24 Ant's mandibles and Ants clustering around EOD [62, 63 and 64].

2.2.2.1.1 SENSOR MODULES

On each side of the robot, there is an IR receiver and a light sensor. Light sensors detect ambient light levels and can be used as a solar compass for navigation. The IR receivers detect four-bit communications signals from other robots and base stations. Each sensor has a field of view of about 90°, so the robot is able to determine the direction of the source relative to itself. However, the sensors do not detect the range of the transmission source. The front of the robot has 2 bump sensors and 5 touch sensors. The bump sensors detect collisions with stationary objects and other robots. Two of the touch sensors are built into the bump sensors. The remaining three are built into the mandibles. They use conductivity to detect the presence of small balls of brass foil simulating unexploded ordnances.

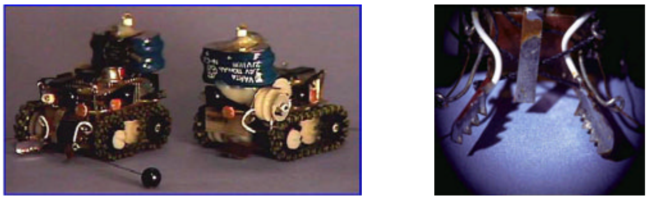


Figure 2.25 Close look of Ants, Ants' sensors and Ant's mandibles [63 and 64].

2.2.2.1.2 COMMUNICATION MODULES

There are 2 IR emitters on each robot as seen in Figure 2.25. The one IR emitter is mounted on the front of the robot and has a range of about 1 inch. The signal is directional, so the transmitting robot has to be facing the receiver. The other IR emitter is mounted on the top of the robot and has a range of about 1 foot. The range of this signal is important and is defined as the communication distance. Its signal is omni-directional, so any robot within range can detect it. There are also stationary IR emitters with an adjustable range from 1 to 5 feet. All of the communications are local and untargeted. The advantages of this approach are the simple, low power design and the reduction of communications bandwidth that each agent has to process. The number of robots that can be within communications range is limited by the amount of physical space around the receiver robot. Hence, bandwidth is limited by sensor range, not by community size. Therefore, it allows the population to be scaleable to any size while the processing requirements of individual agents remain constant.

2.2.2.1.3 CHASSIS MODULE

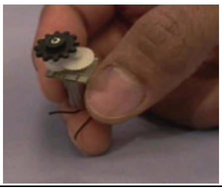
The Ants are made by an innovative 3-D printed circuit board construction technique. Therefore, the robots are built relatively easily and cheaply. However, it is very hard to assemble them since many of the solder joints require accuracy within 0.127 mm.

2.2.2.1.4 ACTUATION MODULE

Each robot has 3 motors - two for locomotion and one to actuate the mandibles. The robots run on two treads, like a tank, which allows them to rotate about their vertical axis. Table 2.9 shows the specifications of the actuation module of Ants.

Table 2.9 Ant's actuation module specifications

Specifications	British Unit	Metric Unit
Motor Stall Torque	0.5 oz.inch	3.53 N.mm
Wheel Radius	0.25 inch	6.35 mm
Maximum Speed	0.5 ft/sec	152.4 mm/s
Gear Ratio	59:1	59:1



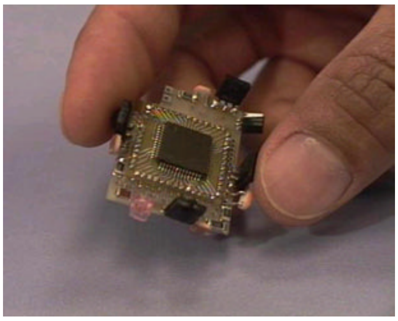
2.2.2.1.5 POWER SUPPLY AND SERIAL PORT MODULE

The Ants use a 2.4 V Nickel-Cadmium rechargeable battery formed by 2 Varta VT110 1.2 V NiCd Cells. Depending on software, each robot runs for about 20 minutes. Battery voltage sensor modules give robots an idea of how "tired" they are. They have recharging circuitry built-in so that in the future they will be able to go recharge themselves automatically. Each robot has a little serial port on the side. It can be used for downloading software, or attaching a computer monitoring the status of the robot.

2.2.2.1.6 MICROPROCESSOR MODULE

The Ant's CPU is an 8-bit Motorola MC68HC11E9 microprocessor running at 2 MHz with Xicor X68C75 8k EEPROM memory. TQFP package chip seen in Figure 2.26 is great for building robots because it has extensive input/output hardware built right into the chip.

Figure 2.26 Ant's microprocessor [63].



This research was founded by a grant from the Naval Explosive Ordnance Disposal (EOD) Technical Division [62, 63 and 64].

2.2.2.2 MILLIBOTS

Millibots are about 7x7x7 cm size mini mobile robots produced for collaborative surveillance tasks. As seen in Figure 2.27, different robots may carry different sensor payloads, such as a camera, sonar, or chemical sniffers. By sharing sensor data with each other, team as a whole can obtain a better image of the environment. The small sizes of robots guarantee accessibility through narrow passageways. Although, Millibots have limited capabilities, by collaborating with each other, they are able to accomplish important tasks.

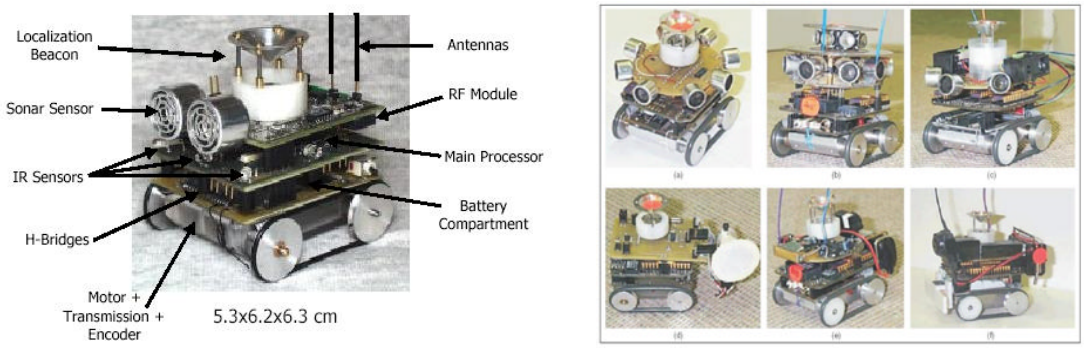


Figure 2.27 Millibots team and their modules [65 and 66].

Millibots can extend their utility beyond a single robot to overcome physical obstacles. They can dock with each other like a train in which all robots collaborate to push the lead robot over an obstacle as seen in Figure 2.28. Plastic tread design was used for rough surfaces like rugs and a rubber tread design was used to crawl up smooth inclined surfaces.

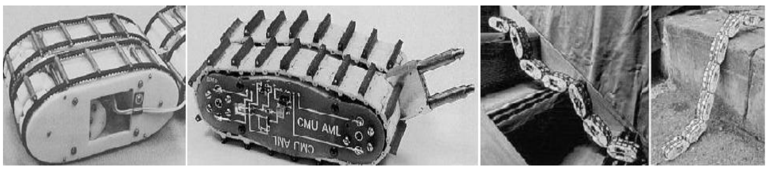


Figure 2.28 Millibot train unit; climbing normal and double height stairs [67].

Millibots are powered by two 3.2 V Ni-MH with which they run about 90 minutes. Since, these batteries are safe, easy to charge and provide an acceptable energy density.
Each Millibot is composed of a main processor with optional communication and sensor modules housed on a mobility platform. Interface of the modules is a standardized bus for power and inter-module communication. Each module contains its own microprocessor that enables the inter-module communication and performs low-level signal processing functions for sensors and actuator control. Currently, each main processor provides a set of dedicated slots that are capable of servicing up to six sensor or actuator modules.
A second possible inter module communication implementation is based on I^2C bus design. This bus design and communications protocol allows multiple modules to be connected to a common two-wire bus. One wire provides a high speed, synchronous clock while the other provides a two way data line. All messages on the data line are pre-appended with an address header identifying the target module. This interface is less restrictive than the dedicated slot method because it allows more modules to be connected to the same processor without having to designate separate pins.

To provide two-way communications within the group, each Millibot is equipped with a radio frequency transmitter and receiver. These units exchange data at 4800 bps at a distance of up to 100 meters. The choice of units is based primarily on size and power considerations. Millibots can also be equipped with a camera to resolve the real problems. Current camera dissipates about 1.5 Watts of power; so it cannot be used continuously like other sensors.
One ultrasonic sonar module provides short range distance information for obstacles between 0 and 0.5 m. The second module provides longer range information for obstacles between 0.15 m and 1.8 m. Figure 2.29 shows the locations of the modules on Millibots.

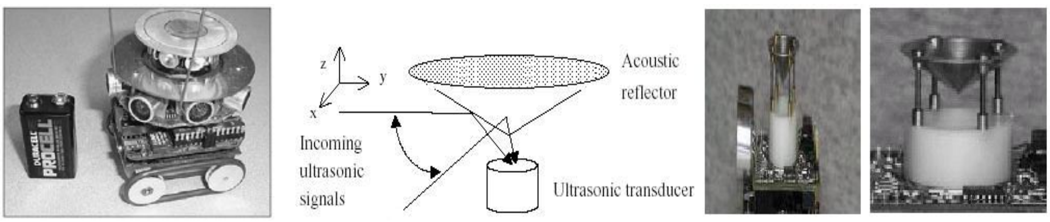


Figure 2.29 Long range sonar, wireless communication, acoustic reflector modules [66].

Most sonar elements operate at a fixed frequency determined by their mechanical construction. Therefore, two robots using ultrasonic sensors in the same area may cause interference for each other. To provide continuous obstacle detection, Millibot carries an infrared proximity module. It includes an array of 5 infrared emitter-detector pairs with 0.25 m ranges. Although, proximity detectors cannot be reliably used for range determination of objects, they can be used very effectively in conjunction with a sonar detector module.

For distributed robotic applications that require robots to share sensor information, it is critical to know the position and orientation of the robots with respect to each other. Conventional localization systems; such as global positioning systems (GPS), dead reckoning, landmark recognition or map-based positioning do not offer a viable solution for Millibots. To overcome the problems, a novel method has been developed that combines aspects of GPS, land-mark based localization, and dead reckoning. The method uses synchronized ultrasound pulses to measure the distances between all robots and then determines the relative positions of the robots through trilateration, which is an important relaxation when exploring unknown environments.

This research is funded in part by the Distributed Robotics program of DARPA/ETO under contract DABT63-97-1-0003 and by the Institute for Complex Engineered Systems at Carnegie Mellon University [8, 65, 66 and 67].

2.3 SPACE APPLICATIONS

Due to their low production cost, weight and flexible properties, mini/micro robot development studies are carried out extensively for the space applications. In the following sections some examples in these fields can be observed.

2.3.1 10-GRAM MICROROVERS FOR MARS

10-Gram Microrovers could spread out and collect different data collaboratively as seen in Figure 2.30. If each robot has a few sensors and are programmed to disperse around the landing area, it might be possible to gather more data than their size would suggest. Having more than one rover also allows for greater mission flexibility and reliability to explore Mars [68 and 69].

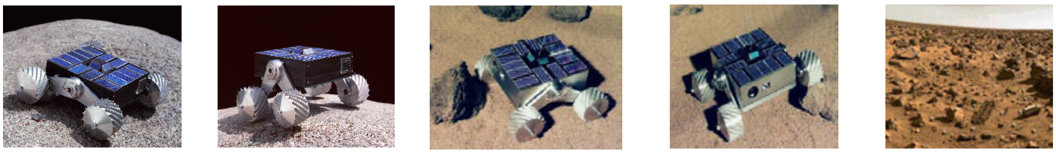


Figure 2.30 Nanorovers and Microrovers for Mars surface exploration [68 and 69].

2.3.2 SOLETTE AND HOPETTE

Solette, with mass of 30 g, was the first step towards a 10-gram rover as seen in Figure 2.31. It is completely autonomous and solar powered. There is a 9600 baud radio transceiver for communication with the base station. Energy collected from solar panel is stored in a 1 Farad capacitor to power the robot. On robots of this scale, wheels turn out to be the limiting mobility factor, since most obstacles are larger than the robot [68 and 70].

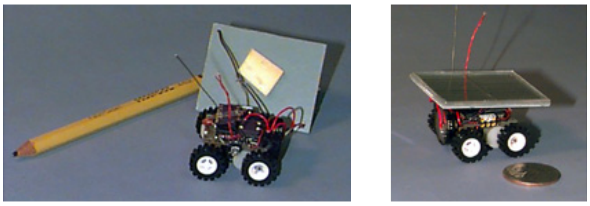


Figure 2.31 Scale comparisons with a pencil and with a penny [68].

The answer to the wheel problem is Hopette robot, which hops from obstacles. The goal is to have a 15 grams hopper with camera, in addition to all components from Solette [68 and 70]. Microsatellites and nanorovers are the main microrobotic applications for the space missions.

2.4 MICROFACTORY AND PLANT APPLICATIONS

To manufacture tiny precision parts of watches, cameras, and electronic appliances, much smaller production equipment is needed, which are microrobots.

2.4.1 MICROROBOT IN JAPAN

A micromachine system can be used as a plant inspector without human. Pioneers of these micromachines are produced in Japan and used for the maintenance of fine tubes in power plants. Because, working in a power plant for a human is quite dangerous. So, if the micromachines are produced, they can pass through the tubes, find the places that are out of order and repair the defected regions, while not interrupting the work of the whole system [1].

2.4.2 TINY ROBOT DEVELOPED IN JAPAN

Mitsubishi, Sumitomo Electric and Matsushita Research Institute have developed a micro-machine with the size of an ant that can crawl around thin pipes, inspect and even fix problems at power plants since 1989. The sizes of box-shaped robot are only 5x9x6.5 mm. It has a pair of round connectors on both sides that can be linked up with other robots for climb up and down a pipe. With a mass of only 0.42 grams, the robot can lift objects twice as heavy as itself and can move at a speed of 2 mm/s. In addition to that, they can be sent in to the running plants such as electric and nuclear power plants [71].

One another example in this field is the robot that will be sent to the Chernobyl nuclear reactor in Ukraine to help detect problems. The robot, which uses technology from silicon graphics, will scan the reactor, by sending a photo-realistic, 3D image to the researchers that can be checked for problems [72].

2.4.3 PERFORMANCE OF A 7-MM MICROFABRICATED CAR

A 7-mm-scale miniature car was manufactured as a conceptual model of a micromachine. The car consists of a chassis, a shell body, and an electromagnetic motor whose diameter is l mm. The motor consists of a core shaft, a coil, and a cylindrical permanent magnet magnetized by a special tool. The car runs at the maximum speed of 100 mm/s by electric power with the wheel driven mechanism. The moving characteristics are investigated in detail by a high-speed video camera. Through the experiments, problems of the moving mechanism for micromachines are studied [73].

2.4.4 MICROCAR

The dimensions of the Microcar produced by Denso Corporation are: 4.8 mm long, 1.7 mm wide and 1.7 mm tall; i.e., volume of about 14 mm^3 as seen in Figure 2.32. In 1995, the Guinness book of records awarded a world record certificate to DENSO Corporation for development of the world's smallest motorized car [74]. Microcar has a total of 24 parts which come in 13 different types including body, tires, spare tire, wheels, axle, bearings, headlights, rear lights, front bumper, rear bumper, step, number plate and emblem. This car is motorized and moves at 1 cm per second but, it is not autonomous [75].

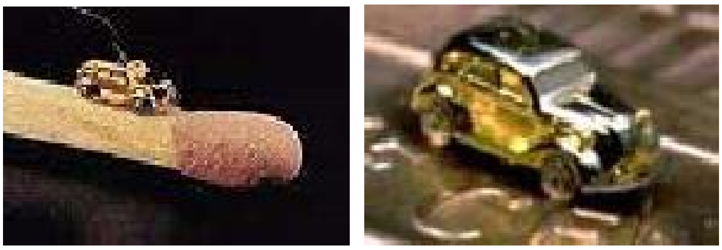


Figure 2.32 Microcar on a matchstick [75].

2.5 MEDICAL APPLICATIONS

Today in medical technology, there are microrobots that can be put in to artery to recover diseases such as heart attack, cancer, etc. In addition, microrobots can travel down the gut to look for ulcers. Therefore, they can be used in sophisticated microsurgery, remote surgery and advanced maintenance technology such as microfluidic handling for chemicals, biological and pharmaceutical applications [1].

2.5.1 MICROROBOT IN SWEDEN

These micro-robots are just over 0.5 mm tall and less than 0.25 mm. wide. They can function in different kinds of liquid, such as media used to culture cells, blood, urine and they may soon cruise through bloodstream looking for misbehaving cells, take them for inspection and cure the remaining systems as seen in Figure 2.33 [76].

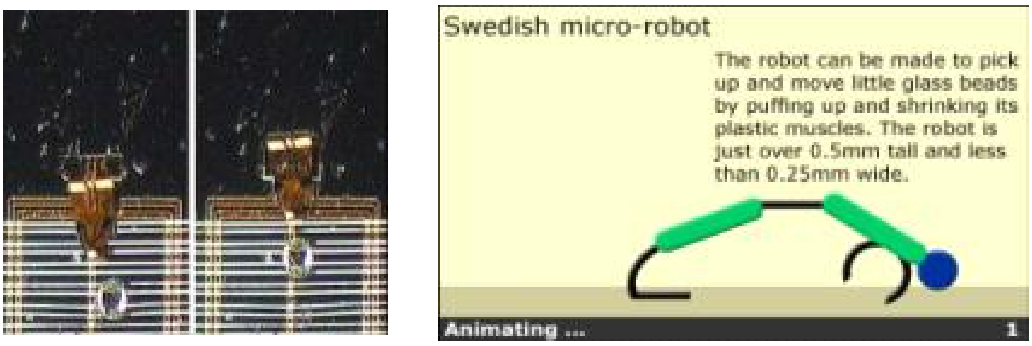


Figure 2.33 A microrobot shifts a bead to different tracks [76]

The robots also managed to transfer the glass beads from one miniature conveyor belt to another with a distance of 0.25 mm, proving their potential as tiny factory workers [76].

2.5.2 MICROROBOTS FOR ENDOSCOPY AND INSTRUMENTS

Endoscopy is a good example of Minimally Invasive Surgery (MIS) whereby only organs affected by pathological processes are treated by diagnosis and interventional operations, saving surrounding healthy organs and tissue. Unfortunately, many conventional endoscopic procedures are technically demanding for the endoscopist and cause pain and discomfort to the patient. To solve these problems, minirobots are being developed which can propel themselves into the organ of interest for diagnostic and therapeutical purposes [77].

Figure 2.34 Microrobot for endoscopy [77].

2.6 MINIATURIZATION STUDY AND DESIGN CONSIDERATION OF MICRO ROBOTIC SYSTEMS

After analyzing all these mini/micro robotic systems and their application fields in the literature, the design considerations and miniaturization effects are introduced in this section.

Mechanical miniaturization has already been investigated by Burckhardt [78] several decades ago. After that time, many studies are performed on the scaling laws for the miniaturization of the systems. Scaling laws express the scale effect dependency of physical parameters, which are defined as a function of reference or characteristic length L. Two procedures are possible to analyze the scaling effect. The first one is applying an isotropic modification of the dimensions and the second one is holding some parameters invariant with respect to the scale and study their influence on the other parameters [28 and 54].

Concentrating on mini/micro robots, which are sized between a couple of millimeters up to a couple of centimeters, scaling laws and different scaling aspects on an existing mobile micro-robot are analyzed at first, while being as general as possible. Since the mini/micro robots are composed of mechanical structures, actuators, sensors, control and power units, the scaling effects are introduced on these modules to give a better understanding [28 and 54].

2.6.1 SCALING EFFECTS ON MECHANICS OF MINI/MICRO ROBOTIC SYSTEMS

Mechanical properties of nanoscale mechanical systems are well understood and scaling effects have been investigated and verified for several decades [79]. L is the characteristic length of reference to study the scaling effects on the modules of mini/micro robotic systems. Therefore, the dimensions related to the volume (mass, inertia) are proportional to L^3, whereas dimensions related to the area (cross section) scale down only with the exponent 2. Moreover the structural stiffness and the stress related to the mass scale linearly with L as seen in the equations given in Table 2.10. This is a great advantage for smaller systems which are intrinsically more robust against destruction forces related to their own mass. Therefore in the design, thinner and less bulky structures or weaker materials are selected while still conserving a good rigidity for the mini/micro robots. An example is found in nature, if one compares the cross section of the leg of an elephant with that of an ant when the scaling considerations are taken into account. Additionally, structural eigenfrequencies increase linearly with $1/L$, thus expecting less interference with structural resonances. Surface friction depends on the normal force, which is proportional to the mass (L^3). But the energy E_μ lost by friction scales down more importantly assuming relative displacements proportional to L. This is true for small motors or gears, where one can use slider bearing instead roller bearings. However, it holds only if assuming to keep the rotational speed constant, which is not the case for many components.

Air drag and lift depend on the area and thus are proportional to L^2. This can be an advantage but also a disadvantage in some cases. Due to this effect, a flying robot might fly much slower, thus simplifying the control. However, secondary fluid effect might play a dominant role for small systems. A falling miniature robot has much better chance to survive because of the increasing ratio between air drag and mass. This effect is additionally supported by the mechanical properties mentioned above. On the other hand a small land robot is much more exposed to wind and friction with the terrain could be insufficient for staying stationary (friction ~L^3, drag ~L^2). These air drag effects become also very evident in nature. A small animal, e.g. an ant, can easily survive a fall from a multi floor building, whereas an elephant will be seriously hurt when falling from around 1 meter. Detailed analyses of scaling on mechanic quantities can be inspected in Table 2.10 [54 and 79].

Table 2.10 Scaling effects on mechanic quantities [54 and 79].

Unit	Scaling	Comments	Unit	Scaling	Comments
Volume, Mass	$Q \sim L^3$ $M \sim L^3$		Stiffness	$c \sim L$ $c \sim \frac{b.h^3}{l^3} \sim L$	Of a beam
Mass Related Force	$F \sim M \sim L^3$	Acceleration, Gravity, Impact Forces	Stress	$\sigma \sim \frac{F}{l^2}$	Beam exposed to an external force F
Friction Forces	$F_\mu = \mu.F \sim L^3$	E.g. Contact between wheel and surface		$\sigma_{max} \sim \frac{F.l}{b.h^2}$ $\sim \frac{L^3.l}{b.h^2} \sim L$	Beam exposed to its own mass
Energy Losses Due To Friction	$E_\mu = L.F_\mu \sim L^4$	Assuming that, displacement scales with L	Structural Eigen-frequencies	$f_o \sim \frac{1}{L}$ $f_o = \sqrt{\frac{c}{m}}$ $\sim \sqrt{\frac{l}{l^3}} \sim \frac{1}{L}$	Elastic Beam
Potential Energy	$E_p \sim h.m \sim L.L^3 = L^4$				
Wind, Lift, Drag Forces	$F_w \sim L^2$				

2.6.2 SCALING EFFECTS ON ACTUATORS OF MINI/MICRO ROBOTIC SYSTEMS

Actuators are one of the major problems in designing miniature robots. The main reason is the lack of commercially available micromotors and the low performance of the existing ones. For a good overview on electrostatic and electromagnetic actuators following references [80 and 81] can be revised. Most actuators such as combustion engines, pneumatic, electromagnetic, electrostatic, ultrasonic, shape memory alloy, piezoelectric or biological muscle used for large systems might also be useable in micro robots. However, some of them might be very difficult to build in small size and thus are useless for this investigation. Others are very interesting and promising but not yet well developed and present important drawbacks (low speed, high voltage, low forces etc.). One of the most promising and interesting solutions in long term might be artificial muscles that show excellent scalability in nature. However, they are still far from real applications. One of the actuators that are already available in small scale is electromagnetic motors. For scaling of electromagnetic motors, it is found for the torque *M* [82] that:

- $M \sim L^5$, assumption constant efficiency

- $M \sim L^{3.5}$, assuming similar motor temperatures.

In reality, the scaling might lay somewhere in-between the two assumptions above. Although scaling effect of the motor torque is somewhat unfavorable, electrical motors still represent one of the most interesting solutions because of their availability and ease of control. For an autonomous robot a motor with a good energetic efficiency should be preferred, but as torque scales with L^5, the mechanical power quickly becomes smaller for decreasing L. In practice the volume of the coil become predominant over the magnet, increasing significantly the overall size. On the contrary, the motor designers are mainly interested in a good power to mass ratio, and normally prefer a much lower efficiency and a higher working temperature [83]. This is allowed because the surface to volume ratio ($L^2/L^3 = L^{-1}$) responsible for heat dissipation is scaling favorably. Assuming constant surface speed on the rotor, the rotational speed of a motor scales with $1/L$. Thus small motors require gearboxes with high reduction rates which additionally reduce the efficiency [28, 54 and 79].

2.6.3 SCALING EFFECTS ON ENERGY SOURCE OF MINI/MICRO ROBOTIC SYSTEMS

Mobile micro robots (MMR) require an on-board energy source or the capability to generate energy from an external source. The most obvious energy sources are batteries, accumulators, supercaps, springs, fuel or solar cells. The scaling properties and power density of the different energy sources are presented in Table 2.11. Among the electrical energy storages, batteries have the highest power density and an excellent availability in many different sizes. Accumulators and supercaps have lower energy density but are rechargeable, thus also compatible with power generators (e.g. solar cells). The energy density of supercaps is very limited, but, compared to accumulators; they allow much higher currents for charging and discharging. Fuel has a very high energy density, but it might be a great challenge to build small size combustion engines and generators. Finally, solar panels become interesting in small size because of their advantageous downscaling effect. However, in most cases they have to be combined with accumulators or supercaps [28 and 54].

Scaling properties given in Table 2.11 are derived form real examples and some simplified models not considering the housing. Consequently the given values might be somewhat optimistic. However, taking into account current technology and availability, most promising power source for MMR are still batteries or the combination of solar cells and accumulators.

Table 2.11 Energy sources and scaling comparisons [28 and 54].

Energy Source	Scaling	Energy [Wh/l]	Energy [Wh/kg]
Battery (Silver-Oxide, Alkaline, Lithium, Zinc-Air)	L^3	230-1300	51-408
Rechargeable NiCd, NiMH, Li-ion	L^3	100-260	30-125
Rechargeable Lithium-Polymer	L^3	250-550	120-350
Supercap or Gold Capacitors	$\sim L^4$	1.8 (@ 9 cm^3)	1.6 (@ 9 cm^3)
Spring	L^3	0.66	0.1
Rubber Band	L^3	1	1
Fuel Cell: Hydrogen Densities	L^3	Encapsulated: 31000	33000
Fuel: Gasoline	L^3	9100	12300
Solar Panel	L^2	0-150 W/m^2	

2.6.4 SCALING EFFECTS ON SENSORS OF MINI/MICRO ROBOTIC SYSTEMS

Sensors for environment perception are very important for autonomous mobile robots. In relation with scaling, the power consumption of sensors might become the major issue. Generally, sensors are categorized as passive and active sensors. Passive sensors do not irradiate energy in to the environment (e.g. camera, microphone) whereas active sensors send out some sort of signals that support the measurement. In consequence, the power consumption of passive sensors is dominated by the signal conversion and processing, which is barely changing with the robot size. In contrast, active distance sensors like sonar, IR proximity sensors, triangulation (position sensitive device), light stripe, laser range finder, magnetic or radar emit energy and use the reflected beams dispersed by the object to measure.

It can be assumed that the required measurement distance is proportional to the characteristic length L, which makes sense if the robot speed scales linearly. Under this assumption, the emission power depends on L^2 (surface of the sphere where the reflection is dispersed) multiplied by an exponential factor function of L (e^{kL} representing the energy dissipation). However, even if $L^2.e^{kL}$ is favorable for small size, active sensors might have power consumption that is not feasible for mobile micro robots (MMR). Thus passive sensors or very simple active sensors are the right choice for such small systems [28 and 54].

2.6.5 SCALING EFFECTS ON CONTROL AND PROCESSING OF MINI/MICRO ROBOTIC SYSTEMS

The controller of a robot has to process information and generate adequate actions. This task might not change much with the size of the robot. However, the smaller system has a more restricted, thus less complex environment to deal with. This might allow a group of small robots to fulfill a task with lower computational power per robot. Additionally, small robots are moving slower, thus requiring less demanding sampling times for reaction. However, these effects will in most cases not compensate for the important reduction of calculation power with size. As shown above, the available energy of a MMR scales with L^3. The required power of a microprocessor, P_{CPU} is related to the number of transistors n, the clock frequency f and the power supply V_{dd}.

$$P_{CPU} \sim n \; x \; f \; x \; V_{dd}^{\;2} \tag{II.1}$$

If $f \sim velocity \sim L$ proportionalities are assumed, the power consumption scales linear with L. However, because the available power is scaling with L^3, it is still have to be admitted a reduction in calculation power by L^2, thus drastically limiting control capacity. It is therefore a must and not a choice to further reduce the calculation power by using 8-bit instead of 16 or 32-bit microcontrollers. In consequence, it is have to be admitted that the intelligence of MMR will be limited. Nevertheless, in connection with an external supervisor (computer, human, look up tables), small robots might still be able to fulfill complex tasks [28 and 54].

2.6.6 SCALING EFFECTS ON COMMUNICATION OF MINI/MICRO ROBOTIC SYSTEMS

Communication in MMR takes place between different units or between the robot and the supervisor or user. The communication can be unidirectional or bidirectional, involving a receiver, a transmitter or both / (transceiver) on the robot. The power consumption and the dimension of communication devices often depend less on the communication distance but more on the precision, the conversion technique and the communication speed. Receivers have relatively low power consumption but as they are almost always operating, it becomes an important power drain for MMRs. Transmitters irradiate power like an active sensor. Thus the power consumption depends on $L^2.e^{kL}$, where L is the communication distance that is assumed again proportional to the size of the MMR. Communication can be established through infrared, visual signaling, sound or radio. For short range, infrared becomes interesting because of the favorable $L^2.e^{kL}$ scaling and it is much simpler than radio. Moreover, clever combinations of different concepts for the sender and the receiver might reduce power consumption. For example the robot could receive infrared signals and answer with a particular movement or it could use its IR distance sensor also for communication. In any case, communication is quite power consuming for a MMR and thus should be reduced to a minimum. This favors solutions where the robot operates autonomously using its on-board capabilities only [28 and 54].

2.6.7 SCALING EFFECTS ON MOBILITY OF MINI/MICRO ROBOTIC SYSTEMS

The size of a mobile robot has strong implications on the mobility in a given environment. Wilcox introduced the "mean free path" as the average distance a robot can move before it encounters a non-traversable obstacle [84]. This distance depends on the size of the robot, the maximal surmountable obstacle height and the terrain morphology (rock distribution and size). For a given terrain there is a range of optimal dimensions. However, it should be noticed that small robots can surmount higher obstacles in relation to its size. This is due to the fact that the required energy to get on an obstacle of its own height is proportional to L^4 that is (E_{pot}~h.m~L.L^3) and thus decrease faster then the mass (volume). Evident examples from the biology are again small insects against big animals. Insects climb relatively high obstacles in their daily lives. Some of them; e.g., fleas or grasshoppers even prefer jumping. They jump over 20 cm, which is many times their height whereas kangaroos jump up to a couple of times their height. Another aspect of mobility is the speed of movement. Observations in nature and of autonomous mobile robots show that the speed scales approximately linear with L. There are of course large variations in velocity between different species/robots of the same mass, but in average the linear scaling laws hold. Since, this is related to power, energy, control and also sensors of MMR [28 and 54].

CHAPTER III

DESIGN AND PRODUCTION OF INDIVIDUAL MINI/MICRO ROBOTS

Design of mobile microrobots is still a challenge due to the restricted availability of basic components. However, the number of highly integrated microelectronic and micromechanical components (MEMS) is growing fast. Nevertheless, their integration into a microrobotic system requires a good knowledge of all the interactions between sensor, actuator, computation and energy source. In addition to that traditional machining techniques are not suitable for the microrobotic systems due to their size restrictions.

Therefore in Chapter III, first of all the major scaling effects, design considerations and their impact on microrobotic system are analyzed. Then, the scaling and size restrictions on the components of microrobots are discussed in the contents of feasibility study. After that, the detailed design architecture of the individual mini/micro mobile robots namely MinT-DB series mini/micro robots are presented. Finally, the actions and the tasks of the mobile individual MinT-DB (Made in Turkey by Dilek Başaran) series mini/micro robots are introduced.

3.1. ARCHITECTURES OF MINT-DB MINI/MICRO ROBOTS

Mini/micro robotic systems require a new design philosophy. Traditional robots are designed with a broad array of capabilities (sensing, actuation, communication, and computation). Often, the designers will even add redundant components to avoid system failure from a single fault. The resulting systems are large, complex, and expensive. For robot teams, the design can be approached from a completely different angle, namely: "Build simple, inexpensive robots with limited capabilities that can accomplish the task reliably through cooperation" [8, 65]. Each individual robot may not be very capable, but as a team they can still accomplish useful tasks. This results in less expensive robots that are easier to maintain and debug. Moreover, since each robot is expendable, reliability can be obtained in numbers; that is, if a single robot fails or any capabilities are lost, the team can still continue the task with the remaining robots. The interaction of a group of agents, even simple ones, may lead to interesting emergent collective behaviors at the group level. Common examples are given by social insects—ants, termites, bees and wasps—and by swarming, flocking, herding, and shoaling phenomena in groups of vertebrates. The main advantages of this application technique can be categorized as follows:

- Scalability: Control architecture is kept exactly the same from a few units to thousands of units;
- Flexibility: Units can be dynamically added or removed, they can be given the ability to reallocate and redistribute themselves in a selforganized way;
- Robustness: The resulting collective system is robust not only through unit redundancy but also through the unit minimalist design [10].

Other factors to keep in mind before starting the design of mini/micro robotic system implementation are simplicity, compactness and easy assembly which will influence the feasibility and afterwards the practicability of the robots. Therefore, modularity is another important issue on the mini/micro robotic systems. There are two main motivations for modular hardware architecture when building such small robots. The first is intrinsically due to restricted size not allowing to put everything on one single robot. It is instead preferable to equip some robots with some sensors and other robots with some other functionality [65], known as specialization and collaboration. The second motivation is related to the partially unknown final application and also to the research going on for future extendibility. It is therefore better to have an extension connector with as many as possible free lines and just the basic indispensable functionality on the base module. The advantage is that it is quite simple to add new features to the robot by just adapting the software and plugging on new modules. The disadvantage may be that adding many new modules tend to displace the center of gravity and thus the robot gets mechanically unstable. Therefore, other details that have to be considered carefully are the center of gravity, ground clearance (the height of the robot chassis from the ground), location of the sensors and connectors' position.

3.1.1. HARDWARE DESIGN OF MinT-DB MINI/MICRO ROBOTS

This thesis has been the first step taken towards a miniaturization of mobile robotic systems in the Mechanical Engineering Department of the Middle East Technical University. Therefore, in the content of this section, the encountered miniaturization problems were also stated in the related subtitle of hardware components.

The principal components of MinT-DB series mini/micro mobile robots (MMRs) are actuators for locomotion, microcontrollers, batteries, sensors, electronics and communication devices. The characteristic of these components, their working principles, interfaces with MinT-DB series MMRs and their miniaturization problems have been explained briefly in an itemized manner as given below:

3.1.1.1. MICROCONTROLLER / CPU

At the beginning, this thesis has not been supported financially. This situation was carried on about 1.5 Year of the thesis's period. Therefore to start the studies, the available components in METU-ME Mechatronics Laboratory were used as an initial step. As a microcontroller, OEM Basic Stamp II control cards were used in MinT-DB series MMRs due to their availability. At that time, there were two types of Basic Stamp II control cards in the laboratory, which are BS2-IC and OEMBS2 control cards produced by Parallax Inc. [85] as given in Figure 3.1 and Figure 3.2 respectively. First, the BS2-IC type was studied due to its small size. This microcontroller has the dimensions of 31x16 mm. as shown in

.

Figure 3.1 Basic Stamp II kit, BS2-IC and first prototype of MinT-DB [85].

The studies were carried out with BS2-IC microcontroller for a few months. The working steps with this microcontroller were given below:

- First the BS2-IC microcontroller was slotted into the board of education.
- Then by using the DB9 connector on the board and RS232 serial interface with the computer, the microcontroller was programmed with PBASIC computer language for the given task of a robot.
- Finally, BS2-IC was unplugged from the board of education and put on the first prototype of MinT-DB microrobot. After a lot of study with these controllers, they were damaged due to the static electricity.

Due to the limited quantity of these BS2-IC controllers (3 Units) in METU-ME Mechatronic Laboratory, the studies were carried out by using OEMBS2 microcontrollers, which are shown in Figure 3.2. Although OEMBS2 has bigger dimensions (51 x 51 mm) than the BS2-IC microcontroller, it has an advantage of onboard programming capability, i.e. the robots can be programmed without any removal or unplugging operation of the microcontrollers. In addition, this reduces the risk of damage to controllers due to static electricity while increasing the system reliability and enhancing the maintainability, modularity and debugging operations.
After the study with both of these microcontrollers, it was decided to use OEMBS2 microcontrollers on MinT-DB series mini/micro robots. However, the usage of this OEMBS2 component determined the dimensions of the robots. Since this module was the biggest part of the robot.

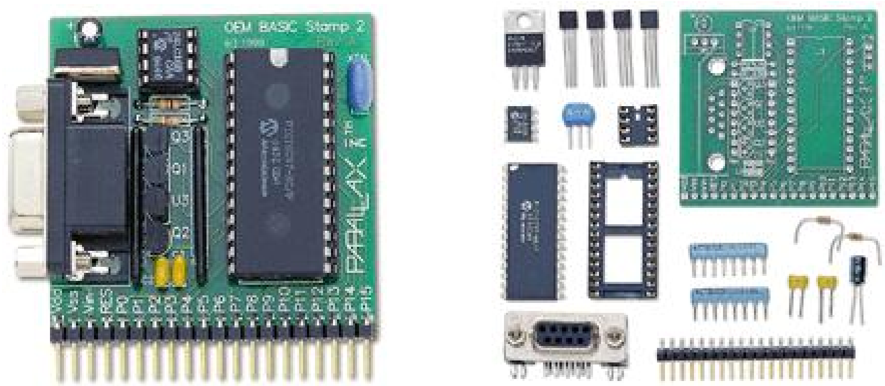


Figure 3.2 OEM Basic Stamp II (OEMBS2) control card and its components [86].

The OEM BASIC Stamp II is one version of the popular BASIC Stamp II module family [86]. These control cards are very suitable to start robotic studies due to their easy to use characteristics and easy to program capability. This card includes the PBASIC interpreter, EEPROM, resonator, DB-9 connector, the resistors and the transistors. It is presented in a 20-pin SIP module format with standard 0.1” spacing. PBASIC interpreter and EEPROM are socketed to allow for replacement. This is a fully functional BASIC Stamp card and can be programmed by using PBASIC DOS or windows editors. The properties of this card are given in Table 3.1.

Table 3.1 Properties of OEM BSII control card [86].

Dimensions : 5.1 x 5.1 cm (2x2”)
16 Fully Programmable Digital I/O Lines+ 2 Dedicated Serial Lines
RS-232 Interface to PC
5V Regulator, Resonator, Serial EEPROM
PBASIC Interpreter in OTP-ROM of PIC 16C57
Up to 500 lines of BASIC Code (2Kbyte EEPROM)
Communications to 19.2kBaud
Serial Communications on Any (or All)Pin
SPI Interface
Approximately 4000 BASIC Instructions/sec
8mA Running/100uA Sleep
Pins Sink/Source up to 20mA
24-Pin DIL Format
Windows Programming Environment

With this card, the written programs can be downloaded to the robots easily and without requiring any disassembly process as stated before. The detailed information related with this card can be found in [86]. The location of OEM BSII control card on MinT-DBs can be seen in Figure 3.3.

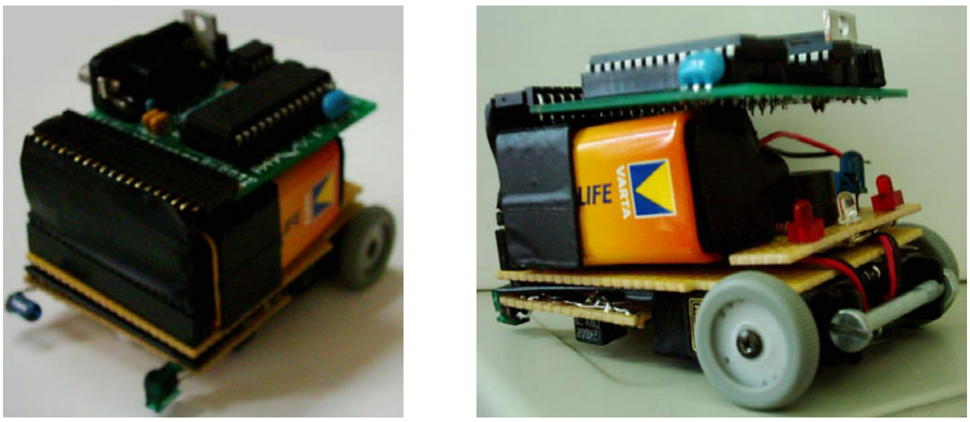


Figure 3.3 OEM BSII control card on MinT-DB mini/micro robot

3.1.1.2. CHASSIS

The dimensions of the biggest part in a system decide the physical sizes or boundaries of the whole system. As stated before, Basic Stamp II control cards are the biggest parts of MinT-DB mini/micro robots. Therefore, the dimensions of the OEMBS2 control card have determined the minimum sizes of the MinT-DB series. The dimensions of the chassis were also determined and the first prototype of chassis was manufactured in machine shop of ME department according to this card sizes. At the beginning of the chassis manufacturing, plexiglas sheets with 3 mm thicknesses and polyamide block materials were used. At first glance, this decision was suitable for small robotic applications due to the following reasons:

- Plexiglas is an insulating material. This property prevents short-cuts near the circuits.
- Plexiglas has a good appearance to use as a chassis material,
- Plexiglas can be easily manufactured and glued by adhesives,
- The cost of plexiglas is the cheaper than the other insulating materials,
- Plexiglas was widespread and available both in METU-ME and the industry.
- The same advantages are also valid for polyamide block materials.

In addition to the plexiglas chassis, polyamide material was used as a fixture to provide a contact between the cables of control card and the input pins of the electronic card, which were located on top of the chassis. Standard 3 mm bolts and nuts were also used in the structure of this chassis. Gluing was another firming technique used on the chassis manufacturing steps to combine the two plexiglas materials to each other. Therefore, the first chassis was manufactured with the stated materials for the MinT-DB1 as seen in Figure 3.4.

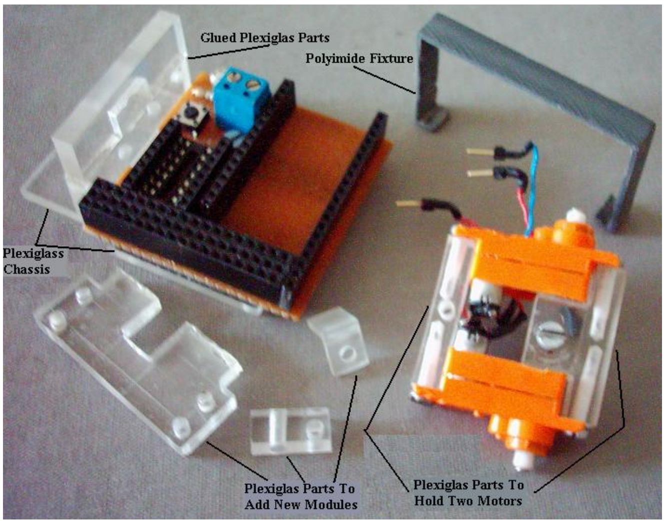


Figure 3.4 Chassis of first prototype MinT-DB mini/micro robots

But after some time, it was seen that the usage of plexiglas and polyamide materials in chassis increased the weight of the robots and prevented the easy modifications of robots, such as adding new modules and disassembly processes of the robot’s parts. In addition to that, the brittle behavior of the plexiglas material made the manufacturing ability of the small sized chassis’ components very hard.

Due to all these drawbacks, a different technique was used for the chassis production, which is the chassis made up of printed wiring board (PWB). This provided the robots more flexibility, decreased weight and easy to assembly/disassembly capability. With the isolative property, 2 mm spaced holed structure and easy to process ability, PWB chassis have been the available choice to contain all the electronic components, control card, as well as the two motors and battery on itself. In addition to that, the modification of this chassis can be easily performed even not using the traditional manufacturing techniques and huge machines, such as milling machine, sawing machine and drilling machine. Because, PWB material can be cut by hobby knife and can just be drilled by small hobby drill. Therefore, easily produced PWB chassis used on MinT-DB series mini/micro robots can be seen in Figure 3.5.

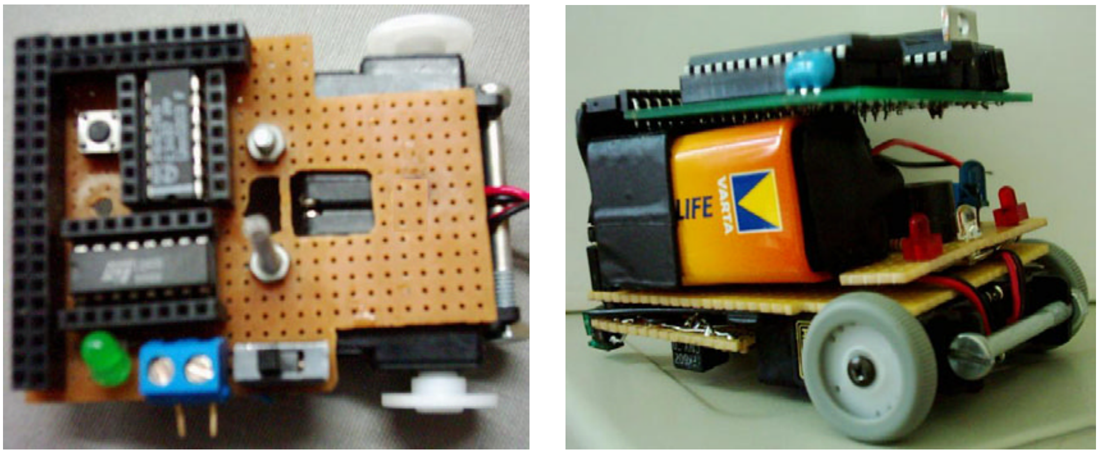


Figure 3.5 PWB chassis used on MinT-DB series mini/micro robots

3.1.1.3. ACTUATORS

Size, torque, speed and power consumption characteristics are important in choosing the motors of MinT-DB series autonomous MMRs. As stated in Table 3.2, different micro motors are inspected in the literature/markets for MinT-DB mini/micro robots.

Table 3.2 Examples of small motors (Tested in a limited temperature range, [28 and54].)

Motor Type	Gear Ratio	Torque [mN.m]	Power [mW]	Speed [rpm]	Volume [mm^3]	Mass [g]	Efficiency [%]
Smoovy ø3 mm by Myonic RMB	25	0.5	12	600	110	0.83	-
Smoovy ø3 mm by Myonic RMB	125	2.0	12	120	110	0.83	6
Minimotor ø1.9 mm	47	0.15	6.3	425	27	0.11	8.25
Wobble from SSSA	340	0.35	2.6	185	195	0.9	4.7
Watch Motor by ETA/ Swatch	180	0.35	1.4	85	210	0.8	6.3
Namiki mcn20, ø 2.4 mm	79	0.2	3.3	650	45	0.23	-
Penny MyMotor & Actuator	-	0.1	50	20000	180	1	-
Vibra DC Motor ø 4 mm	-	0.035	26	32000	160	1.3	-

Actually, DC2S6.625.R2 Smoovy micromotors (ø = 7 mm and L = 24.5 mm) are seen suitable for these robots due to their very small sizes and easier availability in the markets [87]. However, they had to be imported from the foreign country, which is a very time consuming situation. In addition to that, their costs are very expensive to use in microrobotic colony studies. Another alternative is the implementation of the very small sized piezoelectric ultrasonic motors (ø =1.6 mm. and L=6 mm), which are under development now [88 and 89]. However, these motors need some time for the final development stage due to the required complex control card electronics and the sizes of these cards. Therefore, the implementations of these two types of motors (Smoovy micro motors and piezoelectric ultrasonic micro motors) are left as a future work. Due to all these reasons, it is decided to use micro/mini motors available in the local market in Turkey. So, at the beginning of the work, two different types of small servo motors were tried as seen in Figure 3.6. But unfortunately, both servomotor types did not worked properly due to the access heating and the one motor in both pairs broke down in the robots. At the first glance, the reasons of these failures were based on the modification of servos. However, after some time it is found that the real causes of these failures were due to the excess heating of the motors. Therefore, it is observed that the heating effect is very important on the small sized miniature motors and other small electronic components. In addition to them, the required quantity of these motors for the colony study has not been provided by the local market in Turkey.

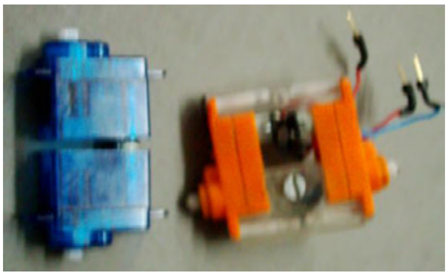


Figure 3.6 Micro motors used for initial tests of MinT-DB mini/micro robots

Therefore due to all of the above reasons, in the first prototype of MinT-DB series mini/micro robots called as MinT-DB1, two Hitech HS-60 micro servo motors were used. These were the only available smallest motors in Turkey at that time for the robotic colony studies. Although, the sizes of Hitech servo motors are bigger than the Smoovy micro motors, piezoelectric ultrasonic micro motors and the two alternative small servo motors given in Figure 3.7, the characteristics of Hitech servo motors provide more flexible and more complex task achievement ability to the MinT-DB series. The shape and the technical specifications of Hitech HS-60 motors used in MinT-DB series can be seen in Figure 3.7 and Table 3.3 respectively [90].

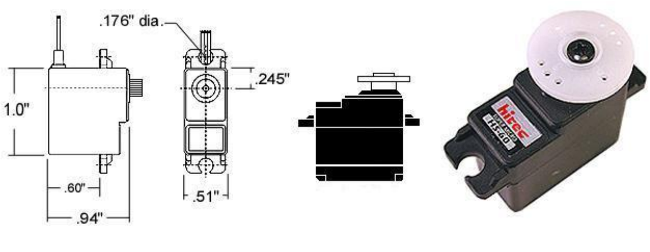


Figure 3.7 Structure and sizes of HS-60 micro servo motors [90].

Table 3.3 Specifications of Hitech HS-60 micro servo motors [90].

<table>
<tr><td rowspan="7">
</td><td>Properties</td><td>Metric Units</td><td>English Units</td></tr>
<tr><td>Size</td><td>26 x 13 x 24 mm</td><td>1.02"x 0.51"x 0.94"</td></tr>
<tr><td>Mass</td><td>14 g</td><td>0.49 oz</td></tr>
<tr><td rowspan="2">Output Torque</td><td>1.1 kg.cm @ 4.8 V</td><td>15.4 oz.in @ 4.8 V</td></tr>
<tr><td>1.3 kg.cm @ 6 V</td><td>18.2 oz.in @ 6 V</td></tr>
<tr><td rowspan="2">Operating Speed</td><td>0.21 s/60° @ 4.8 V</td><td>0.21 sec/60° @ 4.8 V</td></tr>
<tr><td>0.16 s/60° @ 6 V</td><td>0.16 sec/60° @ 6 V</td></tr>
</table>

Therefore, the reasons for the selection of Hitech HS-60 motors can be categorized as follows:

- The weights and the sizes of these motors are sufficiently small as seen in Table 3.3,
- These motors have internal gear box set with compact size,
- When considering the cost of gear sets and dc motors separately, these servo motors are cheaper than the equivalent systems,
- These motors are available in the markets of Turkey.

Mobile robot applications require continuous 360° motor rotation per cycle. Although Hitech HS-60 servomotors have advantages listed above, they have a drawback also. Because, Hitech HS-60 type servomotors are only rotates 60° due to their mechanical stops and as its name implies it has a servo control circuit and cables embedded into the motor block. Therefore, these servomotors were modified by removing these stops to get a full rotational motion like any other ordinary DC motors. The extension parts or stops, which should be removed to get a continuous rotation can be seen either on the casing of the servomotor or on the main gear depending on the servomotor type. In Hitech HS-60 servomotors; these stops were located inside the chassis of the motor block. After removing these stops, extra cables, and servo control electronic circuits from the inside of these servomotors, new dc motors with gear sets were obtained to use in MinT-DB series autonomous mini/micro mobile robots (MMRs). Detailed technical specifications of Hitech HS-60 servomotors can be seen in Appendix B. The implementation of Hitech HS-60 servomotors to the MinT-DB series mini/micro robots can be seen in Figure 3.8.

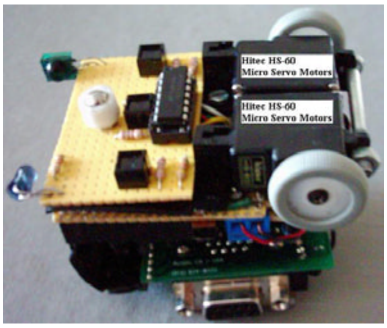


Figure 3.8 Hitech HS-60 micro servomotors on MinT-DB series mini/micro robots

Besides from HS-60 micro servo motors, SuperTec Sub-Micro PICO BB servo motors are also used in MinT-DB series mini/micro robots as an actuator. Technical details about performances of this motor can be seen in Table 3.4 [91].

Table 3.4 Characteristics of SuperTec Sub-Micro PICO BB servo motors [91].

Picture	Size [mm]	Mass [g]	Speed [Sec/60°]	Torque [Kg.cm]
	L x W x H 22.8x9.5x15.5	6	@ 4.8 V 0.12	@ 4.8 V 0.7

3.1.1.4. WHEELS

Wheels of the robots were directly embedded on the output shafts of the Hitech HS-60 micro servomotors in a right-angled way. Scrolls of the mice were used as wheels due to their treaded patterns. This pattern has provided the sticking capability of the wheels to the ground and prevented the slippage of the robots on smooth surfaces. In addition to that, a caster wheel was used. The production of a caster wheels were too hard due to their small sizes. Even a 0.5 mm has changed everything in this caster wheel. Since the outside and the inner side diameters of the wheel hub was 9 mm and 6 mm respectively and the height of the hub was 5 mm. A ball used as a wheel in this hub was 6 mm in diameter. In addition to that there was a bolt inside this caster wheel to mount this into the chassis. However there were some restrictions on the structure of the caster wheel, which were: the top of the bolt located into the hub should have not touched to the ball inside the hub and the ball must not fall from the one end of the hub. Therefore, the tolerances were very tight that, they could not even be measured by a standard caliper, which has 0.05 mm precision. This study was one of the important examples to show the difficulty of the miniaturization process with the traditional manufacturing techniques.

Besides the manufacturing study of the locomotion, different motor and wheel location techniques have been investigated in the literature for the mini/micro robots [92]. These techniques were categorized as follows:

- It is popular to fix the two motors with their axes aligned, with two casters in the front and rear sides [92].
- If this case is difficult to achieve due to lack of space, two motors with right –angled wheels [12] or with parallel wheels but not aligned [16] might be used on MMRs.
- For smooth maneuvers, aligning the wheels or adding a third motor for steering is recommended in the literature [93].

However in MinT-DB series mini/micro robots, a different motor and wheel location technique was used. According to this, two motor axes are aligned at the back side of the chassis with a right angled wheels and a caster wheel is located in the middle of the chassis' front side as seen in Figure 3.9.

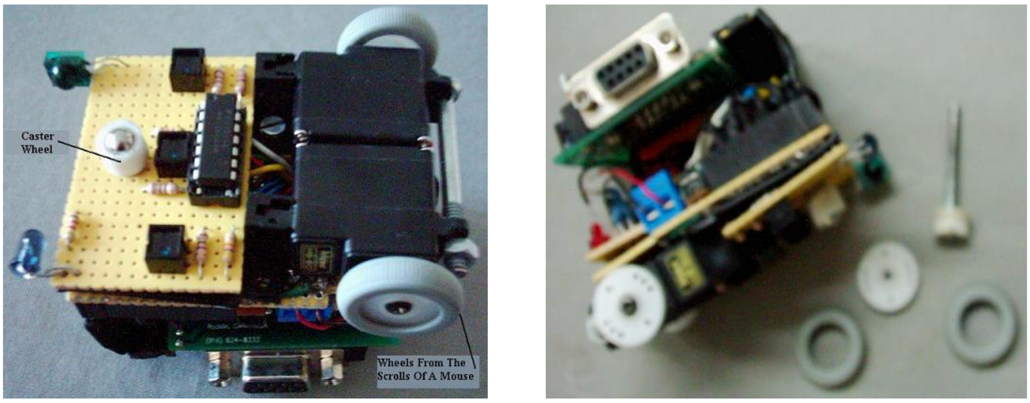


Figure 3.9 Caster wheel, two tires and two wheels of MinT-DB mini/micro robot

3.1.1.5. MOTOR DRIVERS

Hitech HS-60 servomotors require more current than the BSII control card's supply. To solve this problem and to drive these modified servomotors, H-bridge and Op-Amp motor driver types are studied in the literature. Then it is seen that L293D and L298 chips are the two most common H-Bridge motor drivers, which are used to increase the current output of controller card demanded by the circuit components such as motors and relays. The most important difference between these IC interfaces/drivers is:

- L293D, Supply current up to 600 mA per channel, while
- L298, Supply current up to 2.5 A per channel.

Both drivers have 4 channels in total, i.e. 2 motors in both directions or 4 motors in one direction can be driven as seen in Figure 3.10, which shows the working principles of H Bridge IC interfaces/drivers.

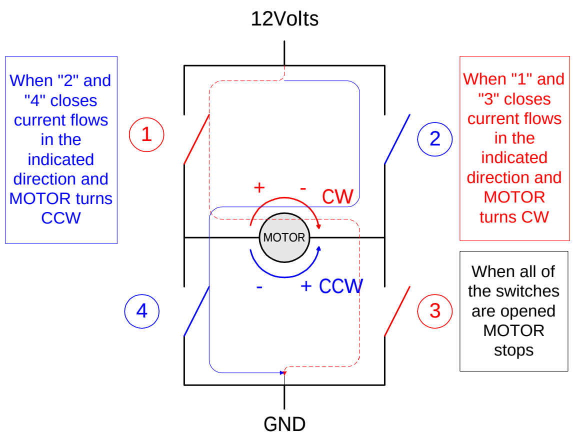


Figure 3.10 Working principle of H Bridge motor driver, L293D [94].

Therefore, L293D chip was used in MinT-DB series mini/micro robots to drive the two motors and to protect the controller card from burning up. Because L293D chip can supply current up to 600 mA per motor and with a single chip two motors can be driven. The picture of the L293D H-Bridge motor driver IC (Integrated Circuit) can be seen in Figure 3.11.

Figure 3.11 H Bridge motor driver, L293D [94].

The interface of L293D H-Bridge driver with the two motors and control card can be seen in Figure 3.12.

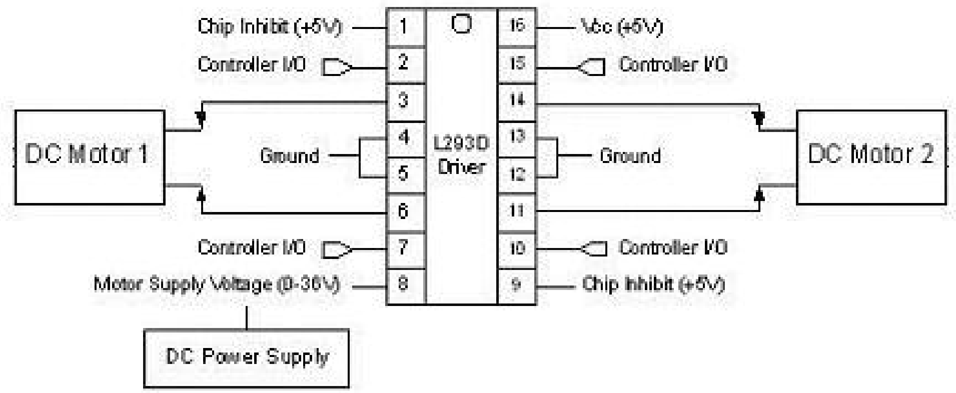


Figure 3.12 Controller – DC motor interface with L293D IC driver [94].

Other properties of L293D IC H-Bridge motor drivers are [94]:

- 600 mA output current capability per driver
- Pulsed current 1.2 A / driver
- Wide supply voltage range: 4.5 V to 36 V
- Separate input-logic supply
- NE package designed for heat sinking
- Thermal shutdown and internal ESD protection
- High-noise-immunity inputs

Detailed technical specifications of L293D IC H-Bridge motor drivers can be seen in Appendix C. Location of motor driver on the MinT-DB robots can be seen in Figure 3.13.

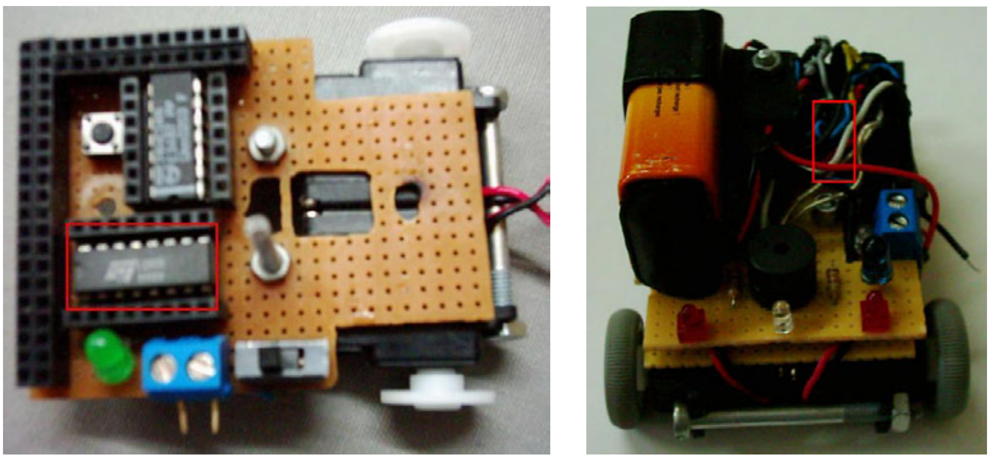


Figure 3.13 L293D IC H-Bridge motor driver on MinT-DB mini/micro robots

3.1.1.6. POWER UNIT (POWER SOURCE AND ACCESSORIES)

The autonomous mini/micro robots must carry a rechargeable power source for their operations. The power specification requirements (current and voltage), the length of operation time, the size and the weight properties are the key factors in choosing the batteries for mini robots. Other factors effecting the selection of power sources can be counted as their availability and cost in the market. Energy source alternatives were studied in the literature. Finally, battery choice was selected and different battery alternatives were studied. And then suitable battery alternatives were provided in the markets of Turkey [95]. These battery types are given in Table 3.5.

Table 3.5 Battery alternatives for MinT-DB series mini/micro robots [95].

Picture	Model	Nominal Volt [V]	Capacity 0.2C Discharge		Nominal Dimension [mm]	M [g]	Standard Charge	
			Min mA.h	Typical mA.h			Current [mA]	Time [h]
	3/V 80H	3.6	70	80	Ø 15.5 6 (H)	4	7	16
	VARTA 4922 Alkaline-Manganese Dioxide	9	550 mAh		17.5(T) 26.5(W) 48.5(H)	53	Not Rechargeable	
	GP15F8H NiMH	8.4	150	165	17.5(T) 26.5(W) 48.5(H)	42	15	16
	MN1604 Alkaline-Manganese Dioxide	9	580 mAh		17.5(T) 26.5(W) 48.5(H)	46	Not Rechargeable	
	Varta-3722 Zinc-Chloride	9	420 mAh		17.5(T) 26.5(W) 48.5(H)	38	Not Rechargeable	

There are different types of small batteries, such as watch batteries, in the markets. After the study with the watch batteries, it is seen that the characteristic of a single watch battery (current and voltage supplies) are not sufficient for the power requirements of OEMBS2 control card used on MinT-DB mini/micro robots. Since, OEMBS2 control cards need minimum 5 V voltage supply capacity for the operation. In addition to that, sensors used on

MinT-DB series mini/micro robots are also required 5V voltage and at least 150 mA.h current supplies from the power source. Therefore, 9V Duracell batteries were used on the autonomous MinT-DB series mini/micro mobile robots. Technical details of the selected battery can be found in Appendix D.

3.1.1.7. POWER JACK AND MICROSWITCH

At the development stage of MinT-DB series mini/micro mobile robots, the batteries were not used. Instead of them, power jacks and 12 V power supply adapters were used. In addition to that an on/off switch was implemented on the robot to reduce the power consumption. The order of the implementation process was as follows: first the adapter was connected to the power jacks and then the on/off switch was opened for the operation of the robot. Besides from the power jack and on/off microswitch, a reset microswitch was also used on the robot to reset the program in the control card and restart the program again at the beginning. This reset micro switches were used for the debugging operations of the robots. The power jacks, micro on/off and reset switches can be seen in Figure 3.14.

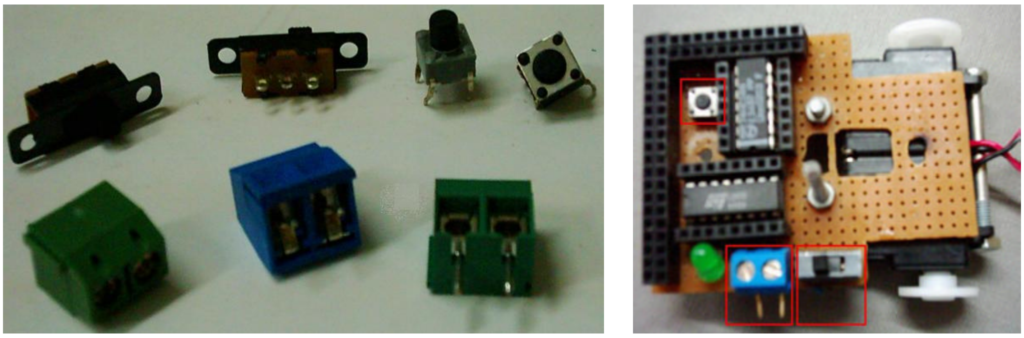


Figure 3.14 Power jacks and micro switches located on MinT-DB mini/micro robots

3.1.1.8. BATTERY STRAPS/CAPS AND BATTERY HOLDERS

Accessories for the batteries were also used on the robots as seen in Figure 3.15. These molded plastic battery caps are intended to protect the contacts of 9 V batteries when they are not being used. The non-conductive protector snaps onto the battery's male/female snap-on connector, and minimizes the likelihood of physical damage which can occur during battery handling, shipping and storage. The cap shields and protects the battery contacts from coming in contact with other conductors, thus eliminating the potential of a short circuit between the poles. In this robotic system, where sensitive electronic circuits, equipment or systems are present, the cap prevents unwanted electrical discharge. The low profile, space saving design also protects the battery from damage due to dust, dirt and contamination. In addition to the usage of battery straps, battery holders specially designed for each robot were also used on MinT-DB series mini/micro robots as seen again in Figure 3.15.

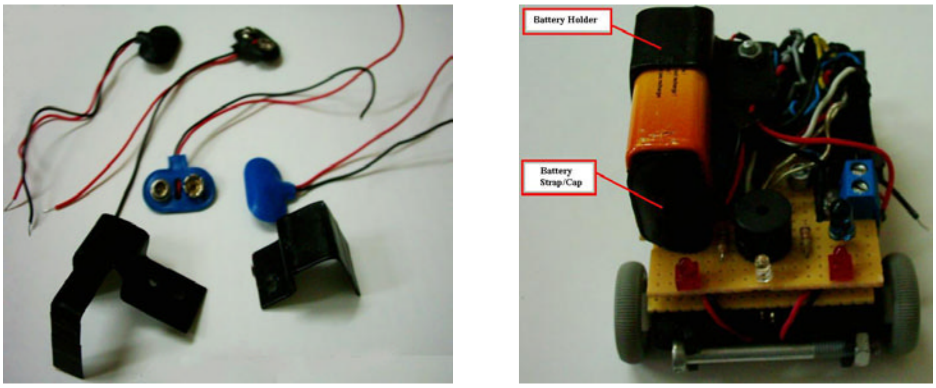


Figure 3.15 Battery straps/caps and battery holders on MinT-DB mini/micro robots

3.1.1.9. SENSORS

Sensors are the key elements of any robot. They provide the only means for a robot to observe the outside world. Sensors can measure many different kinds of information such as light intensity, temperature, and pressure as seen in Table 3.6. The most important information for a small mobile robot is its proximity to objects in the environment. This information is vital for the robot to accomplish the tasks of navigation and obstacle avoidance. A robot should be equipped with as many sensors as necessary to perceive the surrounding environment and in order to solve the given tasks. This means that a mobile robot should at least be able to detect obstacles within a range that still permits to avoid them. Other sensors to measure some environmental parameters are very desirable but depend on the application. Thus distance or proximity sensors are indispensable. At small sizes, precise distance sensors are difficult to achieve and thus only the simple proximity sensors are feasible. Ultrasound or laser use the time of flight principle and for very short range would require highly sophisticated electronics. Active infrared proximity sensors are simple to use, inexpensive and can be found in compact packages. Therefore in MinT-DB series, small size infrared proximity sensors have been used. Other possible sensors for the mobile micro robot applications can be seen in Table 3.6.

Table 3.6 Possible sensors for mobile micro robots in the markets [28 and 54].

Sensors	Principles	Outputs	Comments
Bumpers	Contact	On-Off	Easy
Compass	Magnetic	Angle	Feasible
Inclinometer	Inertia	Angle	Feasible
Barometer	Pressure	Bar	Feasible
Sensors	Principles	Outputs	Comments
Temperature	Heat	^{o}C	Easy
Microphone	Sound	Hz	Feasible
Photodiode	Light	LUX	Feasible
Camera	Light, Position and Color	Value per Pixel	Not Easy & Require Much Information
Sonar	Time Of Flight	Proximity	Not For Short Range
Infrared (IR)	Reflected Light	Proximity	Feasible
PSD	Reflected Angle	Distance	To Be Integrated
Laser Ranging	Time Of Flight	Distance	Difficult

The details of the sensors used on MinT-DB series mini/microrobots are given in an itemized manner under the following titles.

3.1.1.9.1. VISHAY CNY70 OPTICAL SENSOR

CNY70 is one of the reflective optical sensor products of Vishay Inc [96, 97 and 98]. It has a compact construction where the emitting light source and the detector are arranged in the same direction to sense the presence of an object by using the reflective IR beam from the object. The operating wavelength is 950 nm. The detector consists of a phototransistor. The output configuration of this sensor is transistor output type. With the 7 mm size square section, this sensor is very appropriate for the small robotic studies. CNY70 sensors can also be used to measure distance, that is to say it can be used also as a proximity sensor.

These sensors contain IR (infrared) LED and phototransistor (or photodiode) pairs. The working principle of CNY70 sensor can be explained as follows given in Figure 3.16.

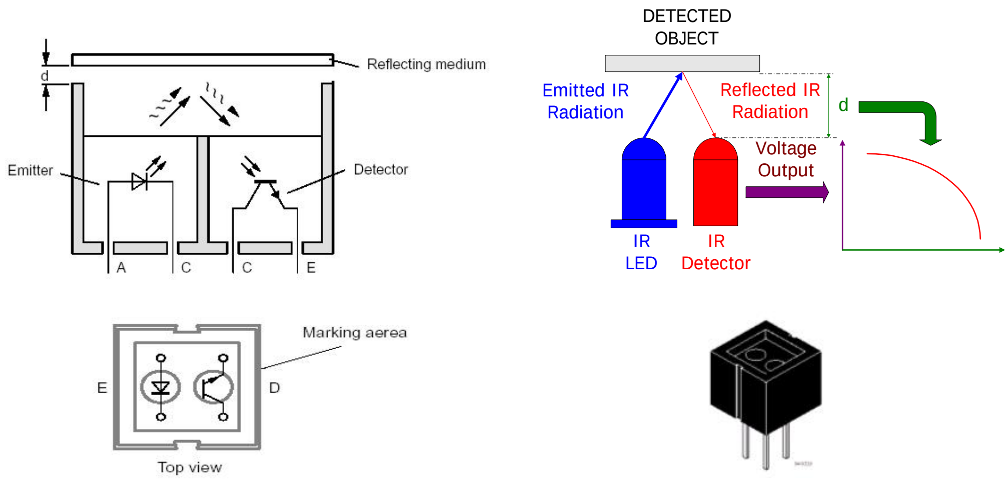


Figure 3.16 Working principle of CNY70 optical sensor [96, 97 and 98].

- CNY70 sensor consists of an IR LED and a phototransistor pair. IR LED emits (transmits) IR radiation and its photocouple (either a phototransistor or a photodiode) collects the IR radiation reflected from the surrounding.

- The voltage output of phototransistor is proportional to intensity (power/unit area) of reflected IR radiation collected by phototransistor. The intensity is proportional to distance of the object at which IR radiation is reflected. Hence the output voltage is proportional to distance.

- Output from phototransistor is analog but using 74HC14N Schmitt trigger, it can be converted to digital and after that this digital signal is send to BS II.

- Ranges of operation are from 0 to 5 mm.

In MinT-DB series mini/micro robots, CNY70 optical sensors were used in a line tracker module. With these modules, MinT-DBs have followed a black line on a white board with the lines drawn by black electrical tape. Three CNY70 sensors were used with one 74HC14N Schmitt trigger and this module was located into the bottom of the MinT-DBs for the line following task. The electronics and the location of this module were given in Figure 3.17. Detailed information about CNY70 can be found in Appendix E.

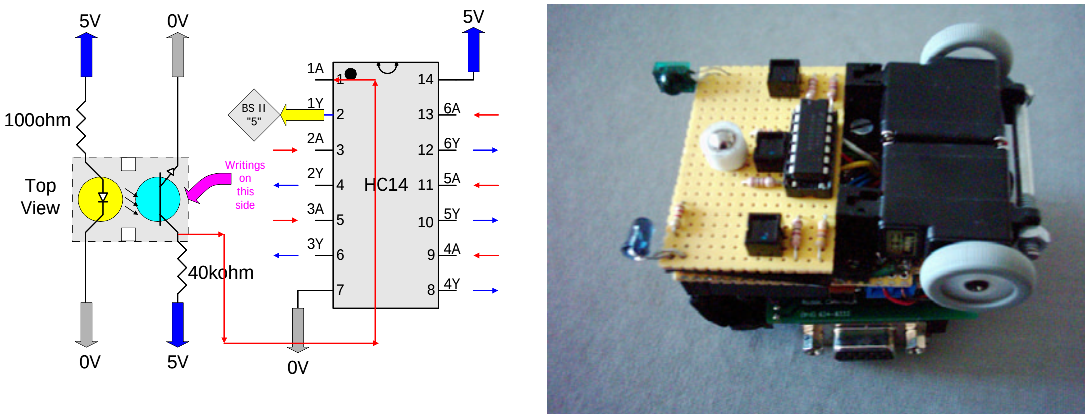


Figure 3.17 Line following module of MinT-DB series mini/micro robots

When this circuit is analyzed in detail then the following items can be figured out.

- Left circle indicates IR LED and 100 Ohm resistance is used to limit current (up to 150 Ohm may be used)
- Right circle is the phototransistor, 40 kOhm resistance is used to bias the transistor (increasing this will increase range of sensor but response time increases also)
- Output from transistor is fed to HC14 Schmitt trigger
- Schmitt trigger decreases the response time and inverts the output
- Output from HC14 is digital and is fed to microcontroller (BSII).
- Six input/output ports exist in HC14 which means that one HC14 is enough for six CNY70 optical sensors,
- Output of circuit is 0V when nothing is within 5mm of its sight vice versa output is 5V when an object is detected within 5mm.

3.1.1.9.2. VISHAY TCRT 5000 (L) OPTICAL SENSORS

Although CNY70 optical sensors works enough for the line following task, their short ranges and too much sensitivity to the surrounding light conditions decreases their operational reliability. Therefore, instead of using CNY 70 sensors, Vishay TCRT 5000 (L) optical sensors have been used in the final stages of the line following task. Due to their extended ranges to 10 mm and better operational reliability in different surrounding light conditions these sensors have been preferred for the line tracking module. The TCRT5000 reflex sensors contain IR-emitting diodes as transmitters and phototransistors as receivers as seen in Figure 3.18. The transmitters emit radiation of a wavelength of 950 nm. The spectral sensitivities of the phototransistors are optimized at this wavelength.

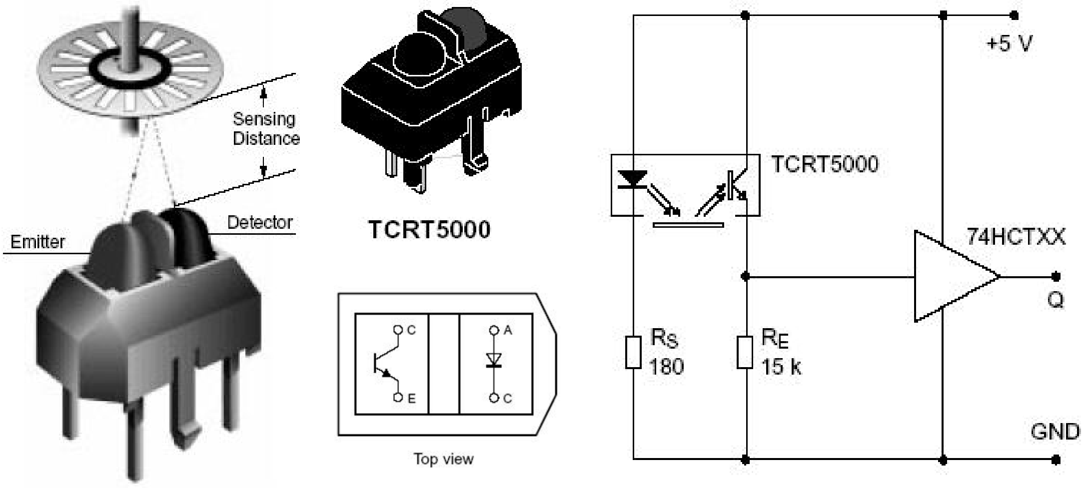


Figure 3.18 Working principle and circuit of TCRT 5000 optical reflex sensor [96].

Besides from the line tracking module, TCRT 5000 optical reflex sensors are also used in front and at the back of MinT-DB2 and MinT-DB3 mini/micro robots respectively for the local communication tasks. Location of these sensors on the robots can be seen in Figure 3.19. Detailed information about TCRT 5000(L) sensors can be found in Appendix F.

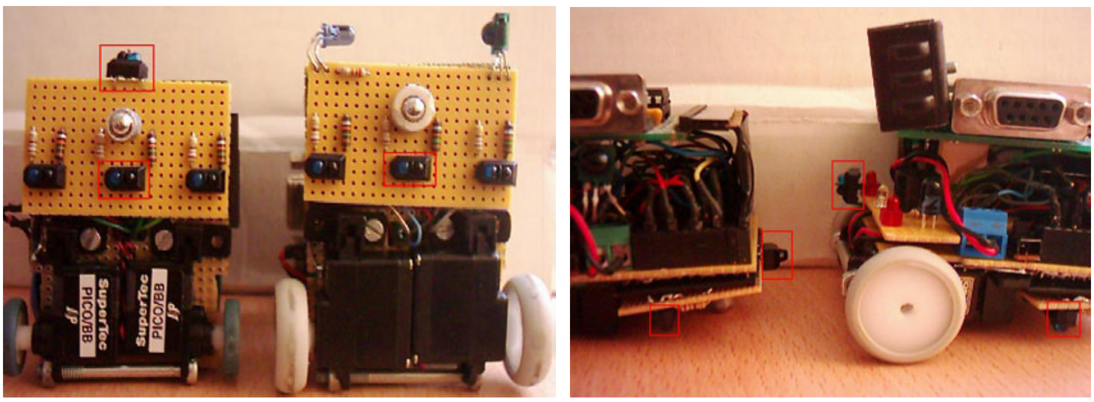


Figure 3.19 TCRT 5000 (L) sensors on MinT-DB robots for line following and local communication tasks respectively.

3.1.1.9.3. SHARP IR DISTANCE MEASURING SENSORS

The Sharp GP2D02 IR distance measuring sensors are one of the least expensive distance sensors available in small sizes (45x14x15 mm) [99 and 100]. They are designed to interface to small microcontrollers and are rated to measure distances in the range of 10 to 80 cm. Because the sensor is capable of taking measurements in varying light conditions and against a wide variety of surfaces, these sensors were used in MinT-DB series robots for the wall following task. Sharp GP2D02 sensors use a variable resistor to determine a distance threshold. The interface is 4-wire and requires a JST connector as seen in Figure 3.20. Controlling the detector is done by lowering the input line, waiting for 28-56ms, and then checking for logic 0 or 1 on the output line. One means no object is within the threshold distance, while zero means that there is an object present.

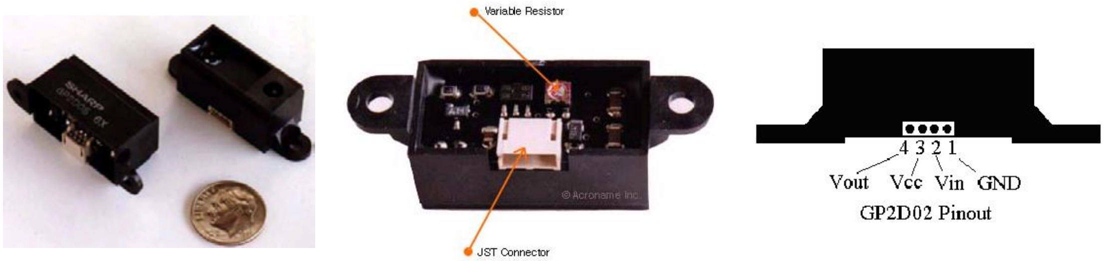


Figure 3.20 Sharp GP2D02 IR distance measuring sensor [99 and 100].

The GP2D02 has two electrical requirements: a 5 volt power supply, and a suitable clock signal. The GP2D02 has a small 4-pin connector for power, ground, and signals. The supply voltage must remain within the limits of 4.4 V to 7 V for proper operation. Sharp sensors use very little current and can therefore safely be powered by the BSII's 50 mA onboard regulator. The second interfacing requirement is the clock. The clock line (V_{in}) is intended to be driven by an open-collector (or open-drain) type output. To ensure that it is pulled down reliably, one should sink at least 100uA from it. If an open-collector output is not available, then a silicon switching diode (1N914 or 1N4148 or similar) between a normal output and V_{in} can be used. The banded end should face the output. In this configuration, the output is able to pull down, but not pull up. This output signal is then digitized to an 8-bit unsigned value and can be read out of the GP2D02 in a clocked serial format. BSII debug terminal was also used to see these readings of GP2D02.

The distance measuring technique employed by the GP2D02 is triangulation. In this process, IR light is emitted from the sensor, reflected off the target, and received again by the sensor. There are three points involved, the emitter, the reflection point, and the receiver. The points form a triangle, hence the name triangulation. The distance information is extracted by measuring the angle at which the light returns to the sensor. Because the distance between the emitter and receiver is known, the target distance can be calculated from the received angle. If the angle is large, then the target is close, because the triangle is wide. If the angle is small, then the target is far away, because the triangle is long and slim. The way triangulation is implemented in the GP2D02 can be seen in Figure 3.21. The output of the GP2D02 is proportional to the angle. GP2D02 gives very accurate results at target angles at least up to 45 degrees, and often beyond. The actual distance in feet or meters is calculated by the host microcontroller.

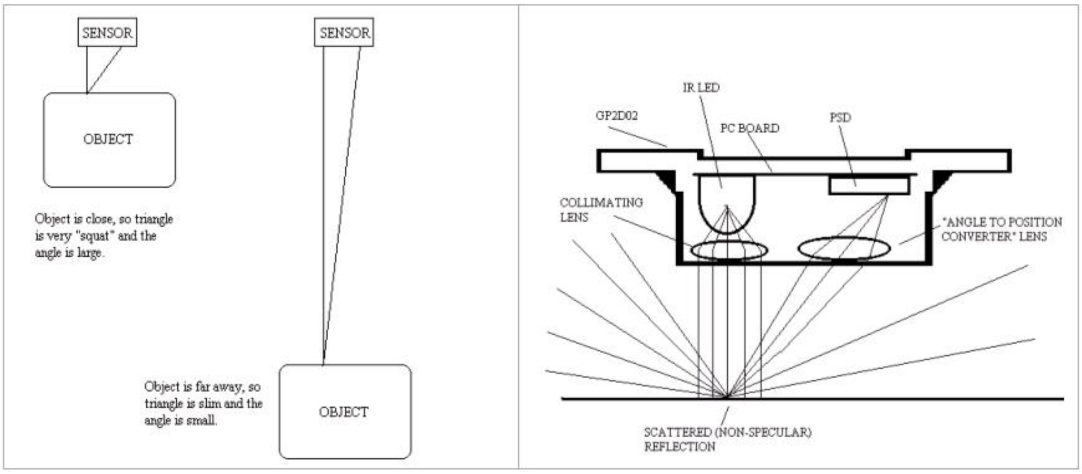


Figure 3.21 Triangulation IR distance measuring technique by Sharp sensor [100].

An excess of ambient IR and red visible light might be expected to cause the PSD difficulty in obtaining a correct reading. On the contrary, it is said that the sensor was very tolerant of light. In certain cases, quickly varying light caused more error than continuous illumination. Considering all of the sources of error, it seems that it would not be feasible to use the GP2D02 as an extremely precise distance measurement sensor. It is, however, an excellent choice for making relative distance measurements, and for measurements with an error tolerance of a centimeter or two. The GP2D02 is an excellent short-range, inexpensive robotics distance measurement sensor. It would be difficult to attain a high degree of measurement accuracy or precision using this sensor, but for simple robot navigation (wall following) and obstacle avoidance, GP2D02 sensor is very suitable. The implementation of this sensor in to the wall following module can be seen in Figure 3.22. Detailed information about Sharp GP2D02 can be found in Appendix G.

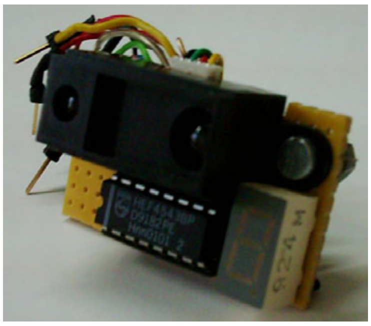


Figure 3.22 Wall following module of MinT-DB series mini/micro mobile robots

3.1.1.9.4. SEVEN SEGMENT LED AND HEF4543B BCD TO 7-SEGMENT LATCH / DECODER / DRIVER

Seven segment display LEDs were used on the wall following modules of MinT-DB series mini/micro robots as seen in Figure 3.23.

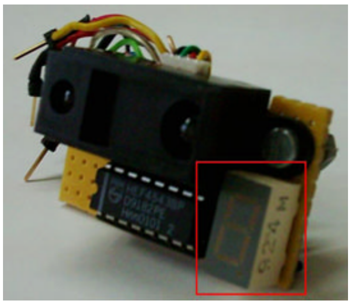


Figure 3.23 Seven segment display led on wall following module of MinT-DBs

The functions of these LEDs were to display the measured distance from the wall. As stated before, distance measurement from the wall was performed by the Sharp GP2D02 IR sensor. The measurement range of this sensor (10-80 cm) was divided into sections and according to the measured distance these sections were displayed on the seven-segment LED as a single digit (0-9). With the modification of the written PBASIC program, the intervals of the measured distances (divided sections) can be changed and then corresponding values can be shown on 7-Segment Display Led. However, to use the seven-segment display LEDs, HEF4543B chips were necessary, which were obtained from Philips semiconductors. The HEF4543B is a binary-coded decimal code (BCD) to seven-segment latch/decoder/driver for liquid crystal and LED displays. It has four address inputs (DA to DD), an active High latch disable input (LD), an active High blanking input (BI), an active High phase input (PH) and seven buffered segment outputs (Oa to Og). Functional and logic tables and detailed characteristics of HEF4543B can be found in Appendix H. Implementation of this chip into the wall following module can also be seen in Figure 3.23.

3.1.1.9.5. SHARP IS1U60 IR RECEIVER/DEMODULATOR

MinT-DB series mini/micro robots worked with small sized (8.5x7x7 mm) Sharp IS1U60 IR receiver/ demodulator detector [101 and 102] for their object detection and communication tasks as seen in Figure 3.24. This device takes an incoming IR signal, modulated at 38 kHz, strips-off the carrier and provides a clean and stable data stream that represents the originally encoded data. It is intended for IR data transfer only. This sensor is great for lots of different applications. Its primary use is to decode infrared signals modulated at 38 kHz. Most remote controls send data in this format.

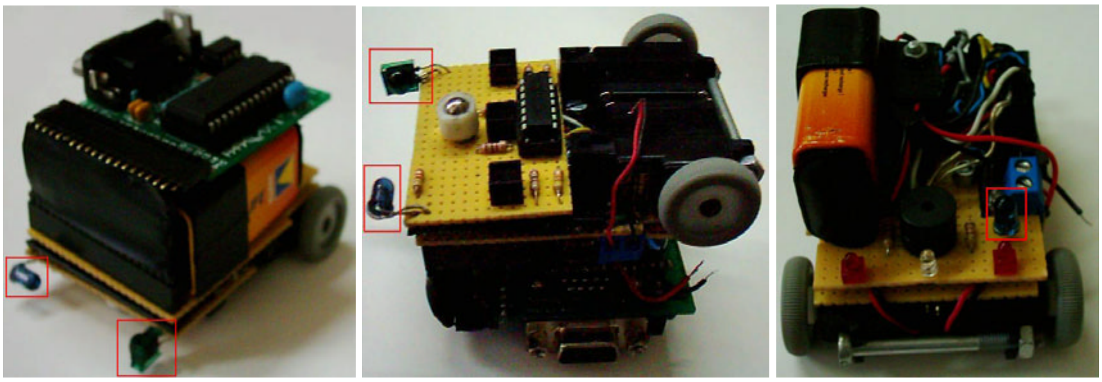


Figure 3.24 Locations of Sharp IS1U60 and Sharp GL537 on MinT-DB

The IR detector is designed to send a low signal when it sees IR flashing on and off at about 38 kHz with a 50% duty cycle, meaning that the on/of times are equal. Although the FREQOUT command only goes up to 32,768 Hz, if any filtering is leaved off, the arguments above 32,768 Hz to specify the frequency of a harmonic signal can be used. In other words, when a command like FREQOUT 7,1,37500 without the RC filter is used, a harmonic signal is broadcast at roughly 37500. The 38 kHz detectors do a good job picking up this signal. The unfiltered FREQOUT signal also causes the IR detector's output to rebound more slowly than when it sees 38 kHz at 50% duty. The result is that the FREQOUT signal out can be send to one I/O pin and it can be stopped sending the signal. In addition to that, there is still enough time to check the detector's (slowly rebounding) output.

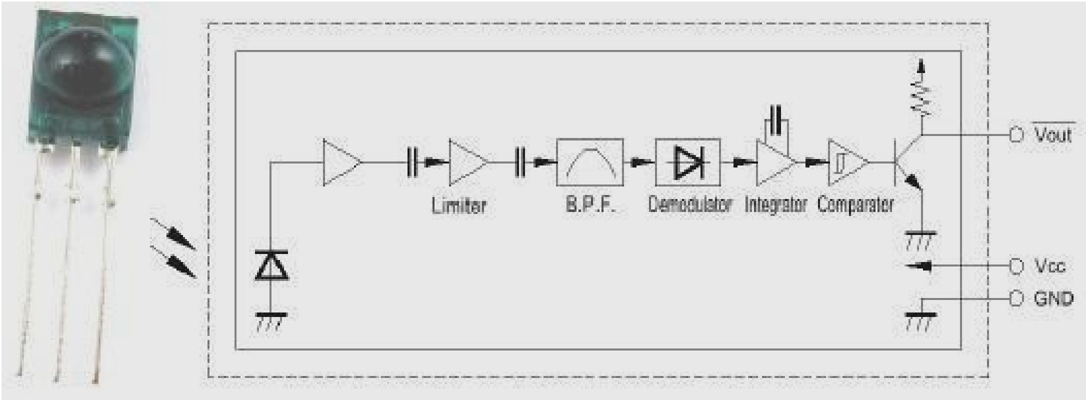


Figure 3.25 Sharp IS1U60 IR receiver/demodulator detector [101 and 102].

This unit is largely replacing the 'metal can' style of IR receiver/demodulators such as the old GP1U5x. This new generation of device is smaller, less expensive, and has better performance. While this is a 38 kHz unit, its bandpass is such that the loss at 40 kHz is only about 2 dB (relative to 38 kHz). Typical detection range is 5m (straight ahead) and 3m (30 deg. either-side of centre). The IS1U60 contains all the circuitry needed to decode IR remote signals used by most consumer electronics devices (stereos, TVs, VCRs etc.) as seen Figure 3.25. Detailed information about Sharp IS1U60 IR receiver/ demodulator detector can be found in Appendix I.

3.1.1.9.6. SHARP GL537 IR EMITTING DIODE

Sharp GL537 IR emitting diode (transmitter) is a high efficiency infrared emitting diode molded in clear, blue-grey tinted plastic packages [103]. These emitters achieve more than 100 % radiant power improvement at a similar wavelength. They are ideally suitable as high performance replacements of standard emitters. Therefore, these emitting diodes were used in MinT-DB series to be a partner to the Sharp IS1U60 IR receiver/demodulator detector for the object detection and unidirectional communication tasks. In Figure 3.24, the object detection module, composed of Sharp GL537 IR emitting diode and IS1U60 IR receiver/demodulator Detector pair, can be seen on the front side of the MinT-DB2 mini/micro robot. Some of the basic features of emitting diode can be seen in Table 3.7.

Table 3.7 Some features of Sharp GL537 IR emitting diode [103]

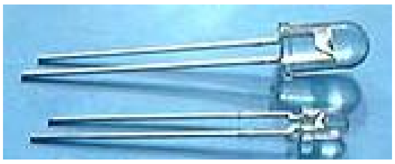
Sharp GL537 IR Emitting Diode	Features
	Extra high radiant power and radiant intensity
	High reliability
	Low forward voltage
	Suitable for high pulse current operation
	Standard (ø 5 mm) package

Table 3.8 Some features of Sharp GL537 IR emitting diode [103].

Model No.	Package, features	Absolute maximum ratings				Φ e (mW)			V_F (V)			Δ θ (°) TYP.	λ p (nm) TYP.
		I_F (mA)	V_R (V)	P (mW)	Topr (°C)	MIN.	TYP.	I_F (mA)	TYP.	MAX.	I_F (mA)		
GL537	ø5 resin	100	6	150	-25 to +85	6* 3	13* 3	50	1.3	1.5	50	±25	950
GL538		100	6	150	-25 to +85	15* 3	30* 3	50	1.3	1.5	50	±13	950

3.1.1.9.7. STATUS LEDS

MinT-DB series mini/micro robots has also included different color LEDs excluding the seven segment display LED. There are 4 LEDs with blue, white and red (x2) colors. These LEDs were used to show the states of the robots. Blue LED (white glass appearance when not activated) has indicated the power on mode of the robot. This LED was located behind the power jack and next to the on-off microswitch as seen in Figure 3.26. When the power supply has been connected to the robot and the micro switch has been opened this LED shines with powerful blue color. The other 3 LEDs, red-white-red colored respectively were used as an object or obstacle detection indication. Because when the robot has sensed the objects or obstacles in front of itself, it alarms the surrounding/ people visually by blinking these three LEDs in an order. Locations of the object/obstacle detection indication LEDs on the MinT-DB mini/micro robots can also be seen in Figure 3.26.

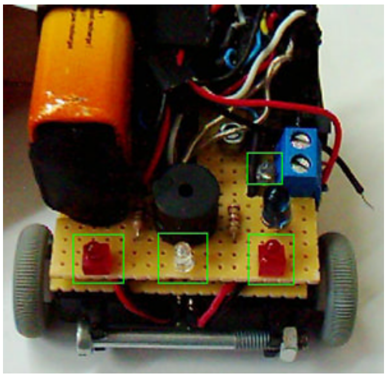


Figure 3.26 Mood LEDs of MinT-DB series mini/micro robots

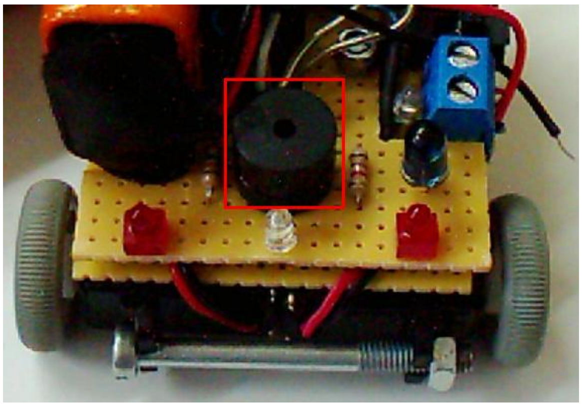
3.1.1.9.8. PANASONIC MINIATURE AUDIO TRANSDUCER (BUZZER)

Panasonic miniature audio transducer is used on the prototype of MinT-DB series mini/micro robots as a buzzer for the alarming issue. This buzzer uses straight pins as a terminal [104 and 105]. The technical specifications of the buzzer can be seen in Table 3.9.

Table 3.9 Technical specifications of Panasonic audio transducer (buzzer) [104].

Panasonic Part No.	Rated Input (mW)	D.C. Resistance (Ohms)	Impedance (Ohms)	Frequency (Hz)	Physical Size (mm)
EAF-12RF04C	50	12	35	3.8K ~ 4.3K	12 x 8.5

The operation principle of this buzzer can be explained as follows: When the object or obstacle was detected in front of the robot, then the buzzer was started to bring until the obstacle has been removed in front of the robot. This task is the same with the obstacle indication LEDs. Therefore, both these 3 LEDs and the buzzer were activated for the alarming mission at the same time. These two types of indicators have provided both visual and auditory alarming capability to the MinT-DB series mini/micro robots. Location of the alarming module (so the buzzer) on the MinT-DB2 can be seen in Figure 3.27. Detailed information about Panasonic miniature audio transducer can be found in Appendix J.



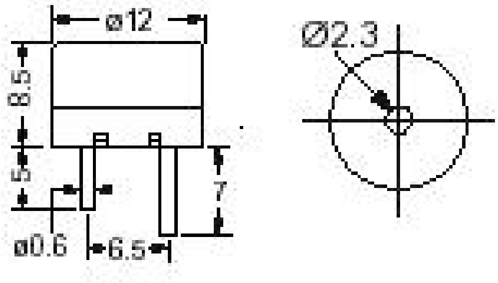


Figure 3.27 Alarming module and Panasonic audio transducer on MinT-DB2

3.1.2 SOFTWARE DESIGN OF MinT-DB ROBOTS FOR THE TASKS

Using the stated components in the hardware design part, MinT-DB series mini/micro robots have completed the following tasks/missions individually:

- Miniaturization Task
- Move Task
- Object / obstacle Detection
- Line Following Task
- Wall Following Task
- Proximity / distance Detection Task
- Display Task
- Alarming Task
- Communication Task * (Line of Sight Communication)

In addition to the above tasks, which are accomplished only by an individual MinT-DB mini/micro robot, communication task was also given to these robots. However, the detailed analysis and explanation of the communication task will be given in the next chapter (*). In this section of this chapter only the above tasks are analyzed.

3.1.2.1 MINIATURIZATION TASK

This task was achieved on the MinT-DB series mini/micro robots by taking the design considerations stated in the scalability sections into account. In addition to that, the design and manufacturing steps have also performed in the content of miniaturization phenomenon as explained in the hardware design part of these robots. Finally by taking the miniaturization considerations into account, MinT-DB series mini/micro robots with 7.5 x 6 x 6 cm have been designed, manufactured and produced successfully.

3.1.2.2 MOVE TASK

Move task is the very fundamental step for the mobile robotic systems. It is basic but it affects all the future studies on the robots such as the modification and improvement of the modules. When the miniaturization concept is included into the move task, it can not be counted as an easy and basic task any more. Since miniaturization brings the components of movement special attention, which are the small motors or actuators for the mobile robotic systems. Therefore with the study on mini/micro scale actuators, the possible smallest mini/micro motors were obtained and used on MinT-DB series. So the move task of the robots was achieved while including the miniaturization concept successfully.

3.1.2.3 OBJECT/OBSTACLE DETECTION TASK

Object / obstacle detection task was achieved using Sharp GL537 IR emitting diode (transmitter) and IS1U60 IR receiver/demodulator detector sensors as stated in the hardware design part of the MinT-DB mini/micro robots. The working principle of these tasks are based on the interruption or breaking of the IR beam between the transmitter and receiver sensors as seen in Figure 3.28. The round bump on the face of the IR detector is a lens and used to collect light. In the absence of IR flashing on and off at around 40 kHz, the IR detector sends a 5 V high signal. When IR flashing on and off at around 40 kHz enters this lens, the circuitry inside the IR detector sets its output to 0 V (active-low). The inside circuitry of the IR detector as stated earlier, can be seen in Figure 3.25. By pointing the IR LED’s output at the IR detector’s input, an obstacle can be observed if there is between the IR LED and the detector. If there is nothing to break the beam, the IR detector sends a low signal. If there is something breaking the beam, the IR detector does not see the modulated IR and sends a high signal.

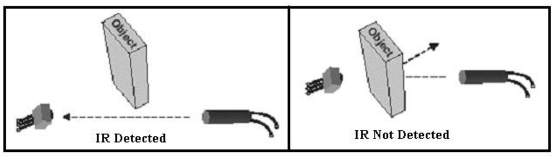


Figure 3.28 Basics of object/obstacle detection task, [101].

In other words, if there is an object in the field, then it breaks the IR beam between the two sensors and if there is no object or obstacle in the field then the IR beam can not be broken. This phenomenon was implemented into the MinT-DB series successfully. So the object / obstacle detection task have been completed.

3.1.2.4 LINE FOLLOWING TASK

Line following task is based on reflectivity differences of the black and white colors. Therefore, this line was produced by a black electrical type on a white surface. The principle is that, black color absorbs and not reflects the IR light while the white color reflects the IR light falling into the surface. Using this basic rule, the line following module was produced from the 3 CNY70 or from the 3 TCRT-5000 (L) optical sensors and a 74HC14N Schmitt trigger as stated before in the hardware design section. Both of these optical sensor types give a feedback signal to adjust and to reposition the direction of the robot on the line. When the middle CNY70 or TCRT 5000 was on the line, robot was directed straight ahead; while the left CNY70 or TCRT 5000 was on the line, the robot was directed to the left side and while the right CNY70 or TCRT 5000 optical sensor was on the line, robot was directed to the right side to perform the line following task. These directional maneuvers are provided to the robots by just stopping one of the motors for some period of time until the different feedback signal has been received from the other CNY70 sensors.

Briefly, on/off control technique was implemented on the MinT-DB series for the line following task. The critical points in this study were the adjustment of the height of CNY70 or TCRT 5000 sensor from the ground, which can be known as a ground clearance and the adjustment of the illumination conditions of the surrounding. Since, to perform the line following task successfully with CNY70 sensors, the ground clearances of the robots must be less than 5 mm and with TCRT 5000 sensors, this value must be less than 10 mm. Moreover, the suitable illumination conditions should be provided in the environment for the implementation of this task. The line following module and the picture of MinT-DB mini/micro robots performing the line following task can be seen in Figure 3.29.

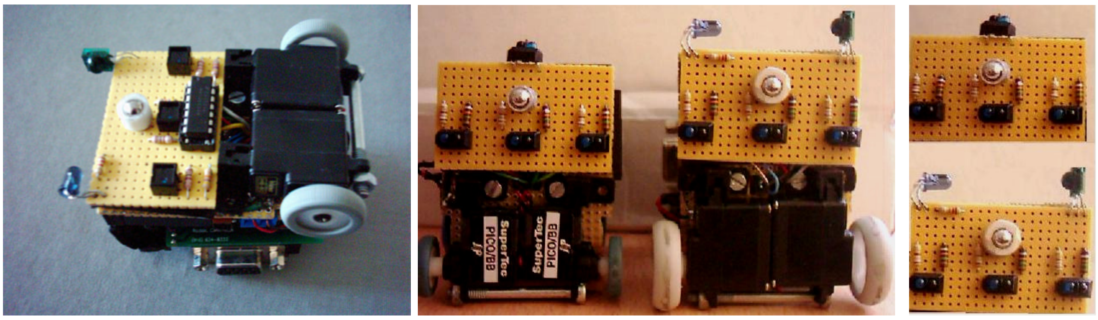


Figure 3.29 MinT-DB mini/micro robots and line following modules

3.1.2.5 WALL FOLLOWING TASK

Using the Sharp GP2D02 IR sensors, wall following task was performed successfully by the MinT-DB series. The fundamental working principle of this task was similar with the line following task. There were two main differences between those two tasks. The first difference was the detection ranges and the capabilities of the Sharp GP2D02 IR sensors and the CNY70 sensor, and the second difference was the written PBASIC code for these two tasks. Since Sharp GP2D02 IR sensor does not use background color differences. Instead of line, it only follows the wall. Sharp GP2D02 IR sensors for the wall following task has been already shown in Figure 3.22.

3.1.2.6 PROXIMITY/DISTANCE DETECTION TASK

For the proximity/distance detection task of the MinT-DB series either Sharp GP2D02 IR distance measuring sensors or Sharp GL537 IR emitting diode (transmitters) with IS1U60 IR receiver/demodulator detector pairs were used. The principle of operation was similar with the line and wall following tasks as seen in Figure 3.30 (reflection of the IR beam from the surface). That is broadcasting IR beam to the surrounding, when this beam is reflected then that indicates the presence of an object/person within certain proximity. In other words, objects which are close enough to the emitter will reflect some of the IR signal back to the detector. However, dark objects absorb IR signals very well as stated before.

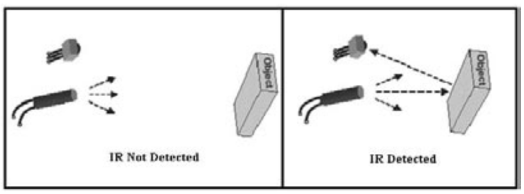


Figure 3.30 The basic principle of the proximity/distance detection task, [101].

The module used to perform this task and the working principle of the transmitter, receiver pairs can be seen in Figure 3.31. Using the GP2D02 IR distance measuring sensors, proximity/ distance detection task was achieved with the MinT-DB series.

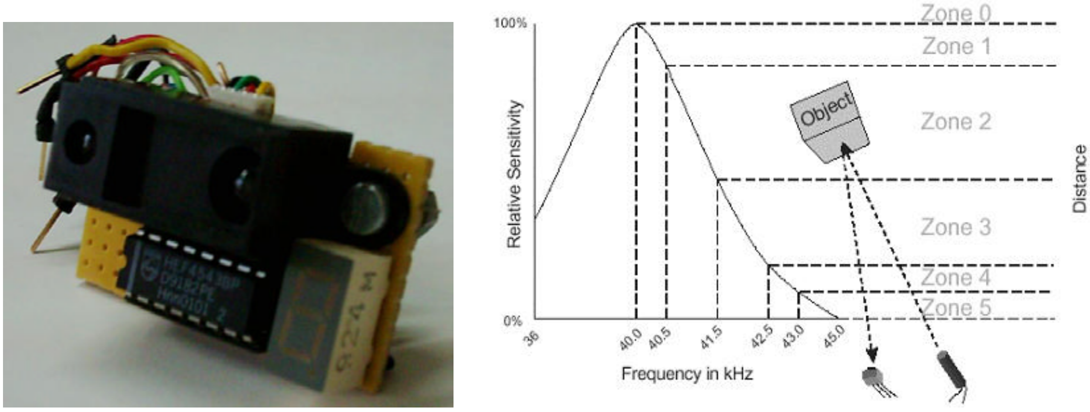


Figure 3.31 Proximity/distance detection module and the working ranges [100].

3.1.2.7 DISPLAY TASK

The measured distances by the GP2D02 IR distance measuring sensors were displayed on the 7-Segment LED. The single digits were used on the display LED for the each zone of the distances as stated in Figure 3.31. Therefore, the display task of the MinT-DB series was performed successfully with this technique.

3.1.2.8 ALARMING TASK

Both visual and auditory alarming systems were used on MinT-DB mini/micro robots. As stated before, when the objects/obstacles were detected in front of the robot then three mood LEDs and the buzzer have warned the surroundings of the robot. The picture and details of this module can be seen in Figure 3.27.

Finally achieving all the mentioned tasks given above, the individual prototype MinT-DB mini/micro robot was produced. After that, the number of individual MinT-DB mini/micro robots was increased to three and a MinT-DB mini/micro robot colony was formed from these individuals. In the next chapter, mini/micro robotic colony studies with MinT-DB series mini/micro robots are introduced and analyzed in detail. The software of MinT-DB series mini/micro robots can be seen in Appendix-K.

CHAPTER IV

COOPERATION AND COMMUNICATION OF MinT-DB MINI/MICRO ROBOTS

MinT-DB series are formed from heterogeneous small robots as seen in Figure 4.1. While some of the robots perform a line following task, some of them perform wall following task, visual and auditory alarming tasks. The nucleus of the robotic swarm system has been produced with MinT-DB series mini/micro robots and their quantities can be easily increased to work with crowded robotic systems. However for the concept of this thesis, three MinT-DB mini/micro robots are seen sufficient and suitable.

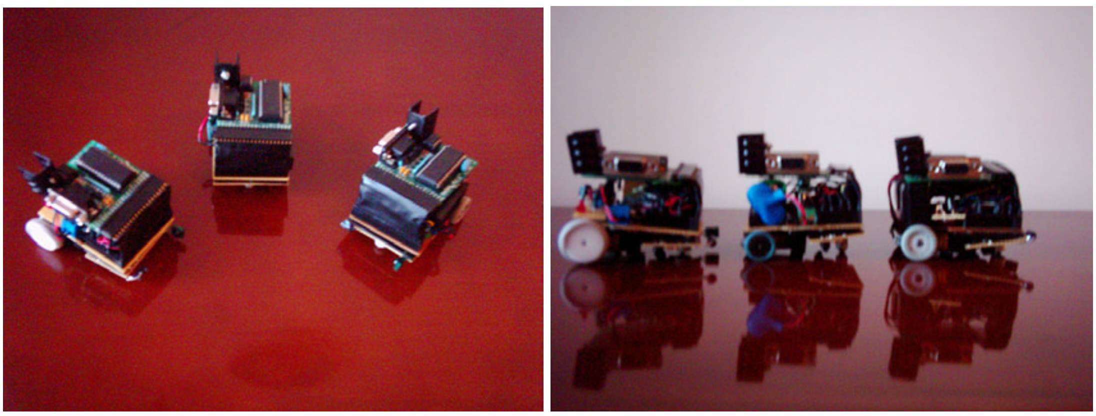


Figure 4.1 Heterogeneous MinT-DB series mini/micro robots

The software uses a behavior-based approach to form a structured community from the local interactions of simple individuals. Since the resulting actions of the robots are very closely coupled to the sensory input. The community structure for the robots is based on local interactions, with no central controller and no global communication. This type of system has advantages of both scalability and robustness.

The tasks performed by individual MinT-DB series mini/micro robots are stated in Table 4.1.

Table 4.1 Individual tasks of MinT-DB series mini/micro robots

Name	Task-1	Task-2	Task-3	Task-4	Communication Module Type
MinT-DB1	Wall Following	Object Detection	Alarming Visual & Auditory	Communication	Transmitter Module
MinT-DB2	Line Following	IR Proximity Detection	Alarming Only Visual	Communication	Receiver Module
MinT-DB3	Line Following	Object Detection	Alarming Visual & Auditory	Communication	IR Proximity Detection

4.1 COOPERATION AND COMMUNICATION TASK

As stated in Table 4.1, MinT-DB mini/micro robots can communicate and collaborate with each other using their communication modules. Local communication has been achieved within the robots by their IR communication modules. These modules are composed of the IR transmitter and the IR receiver pairs, which are Sharp GL537 IR emitting diode and Sharp IS1U60 IR receiver/ demodulator detector respectively as seen in Figure 4.2. With the help of these modules, unidirectional in-line local communication has been performed.

Figure 4.2 Communication modules on MinT-DB mini/micro robots

Two different communication techniques have been studied with these modules, which are trigger event and 8 bits data transfer event respectively. In the trigger event, one robot sends a “start to move message” to the other robots when it stops due to the obstacles or needs help. In the 8 bits data transfer event, different messages can be sent within the robots. These messages were either numbers ranging from 0 to 255 (2^8) or any other predefined sentences to visualize on the debug terminal interface of the PBasic program. Numeric messages (0-255) can have different meanings. For example, if the IR_Message is 0, the robot performs one given task, and when the IR_Message is 1 then the robot performs another given task. The examples can be diversified up to 256 different IR messages, which make also 256 separate predefined tasks.

4.1.1 MISSION

MinT-DB series as a team take a mission, which is to complete a predetermined path from the start point to the stop point on the platform cooperatively. There are randomly distributed obstacles on the platform as seen in Figure 4.3. These obstacles prevent the robot team from completing their missions. However working collaboratively and communicating with each other, one of the MinT-DB mini/micro robots in the team reaches to the target point, which means the successful completion of the given mission.

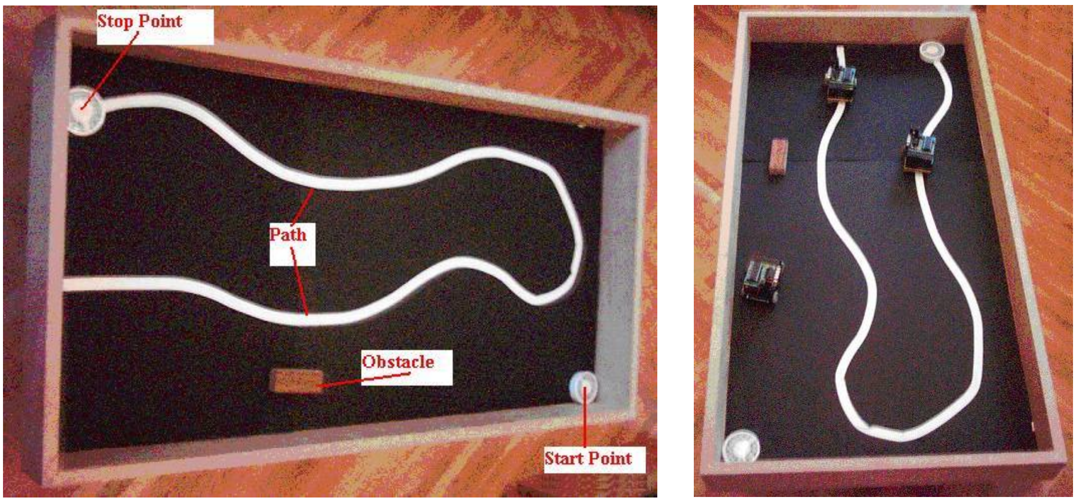


Figure 4.3 Platform used for MinT-DB mini/micro robots

4.1.2 PLATFORM

Table 4.2 and Figure 4.3 show the picture and the properties of the platform used by MinT-DB series mini/micro robots. One of the sample missions is shown on the platform to clarify the task. As seen, the start and stop points are located and the obstacles are placed on the path of the robots. However, different alternatives are possible by just changing the shape of the path and places of obstacles as well as start and stop points.

Table 4.2 Properties of the platform

Properties			
Material of the Platform	Plywood		
Color of the Platform	Wooden Colored		
Shape of the Platform	Rectangle		
Outer Dimensions	Length [cm] 103.5	Width [cm] 53.5	Height [cm] 8.5
Inner Dimensions	Length [cm] 100	Width [cm] 50	Height [cm] 8

4.1.3 SCENARIO

Following scenario has been applied to the MinT-DB series for the collaboration and communication tasks. The whole scenario can also be observed in Figure 4.4.

1. MinT-DB1 mini/micro robot starts to follow a wall on the platform beginning from the start point.
2. Suddenly an obstacle appears on the path of the MinT-DB1.
3. Then the MinT-DB1 senses the obstacle with its object detection modules using IR transmitter and receiver pairs specially located at the front.
4. When the obstacle is sensed, MinT-DB1 starts to alarm its surrounding both in visual and auditory way using its alarm module.
5. At the same time with the alarming module, the communication module of MinT-DB1 mini/micro robot is activated (in this case it is IR transmitter module) to call help from MinT-DB2 mini/micro robot.
6. MinT-DB2 takes the help message of MinT-DB1 and continues to the mission on the line to reach to the target point. MinT-DB2 starts to operate when it receives the help

message. Before the help message, it is in the ready mode, which is standing still on the located position.

7. MinT-DB2 follows the line to reach to the target point. If there is an obstacle or MinT-DB3 on the path then MinT-DB2 calls help from the MinT-DB3. If there is not, it continues until it reaches to the stop point for the achievement of the given mission.
8. If MinT-DB3 is activated then it starts to the line following task. When the MinT-DB3 comes to the target point, it stops and alarms the surrounding by visual and auditory way to explain the completion of the mission.

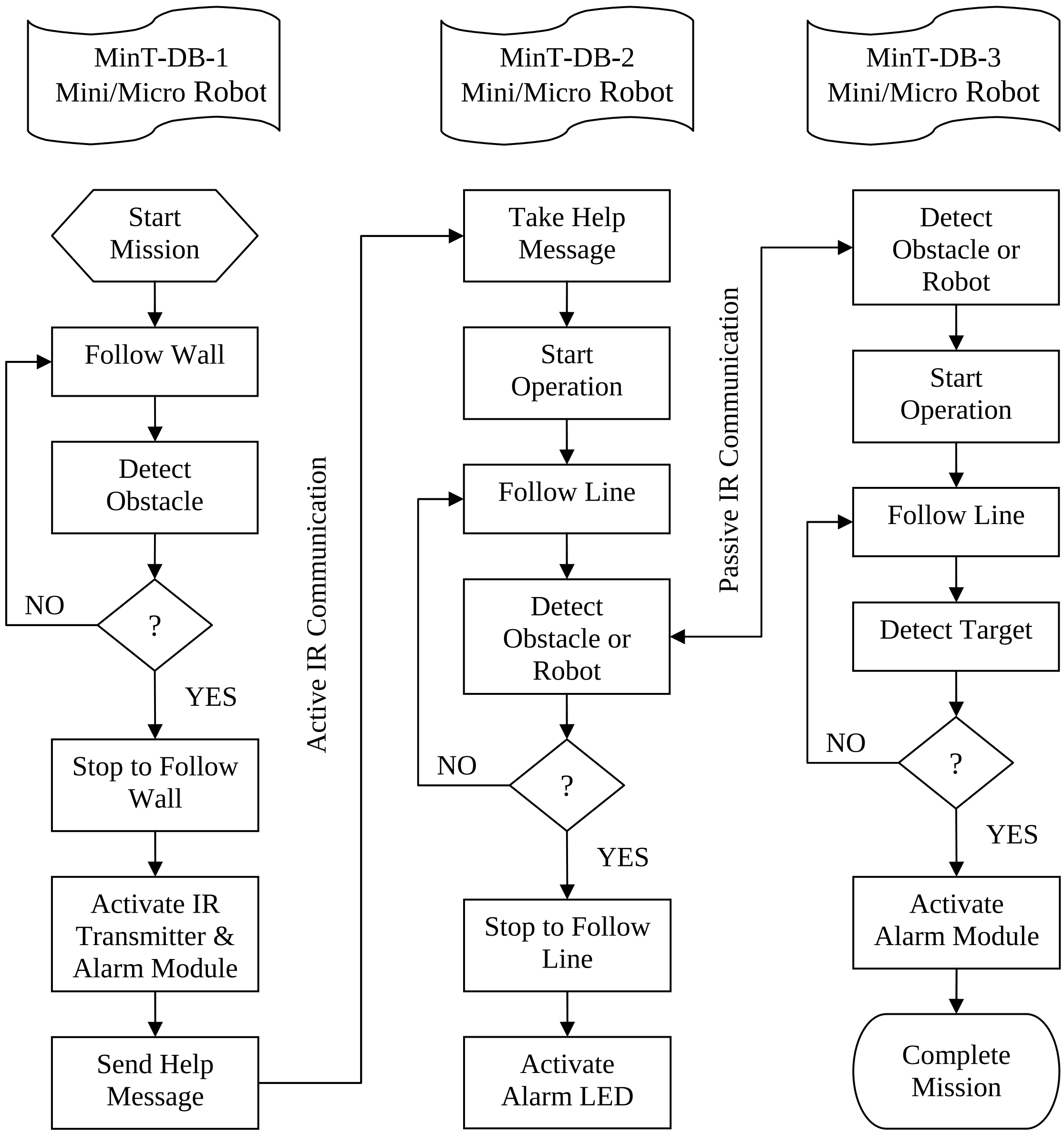


Figure 4.4 Cooperation, communication and task algorithms of MinT-DBs

4.1.4 WORKING PRINCIPLES OF COMMUNICATION MODULES

Infrared emitter has been used to send messages serially from one robot to the other. In serial communication, data is sent one by one sequentially. In general, in a serial communication, one frame of message is composed of one start bit, eight data bits and a stop bit. Sometimes a parity bit is used to check for the errors during communication. A typical RS-232 serial data byte-timing diagram is given in Figure 4.5.

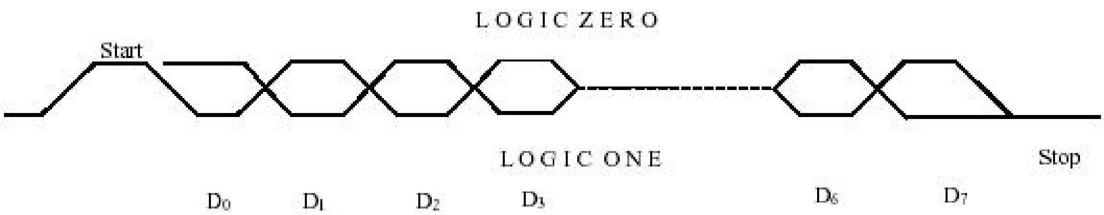


Figure 4.5 RS-232 serial data byte timing diagram [95]

The receiver wakes up when it receives the “start bit” and takes the eight “data bits” (sometimes seven “data bits”) and stops taking data when it receives the “stop bit”. When a “parity bit” is also sent with the data bits, a parity check is done in order to make a check for errors in the received data. However, in the content of this thesis parity bit has not been used.

In the communication scheme of the robotic system proposed in this thesis, the same frame format is used as in RS-232 serial communication protocol stated in Figure 4.5.

The IR detector is designed to send a low signal when it sees IR flashing on and off at about 38 kHz with a 50% duty cycle, meaning that the on/of times are equal. When the command like FREQOUT 7,1,37500 without the RC filter is used, a harmonic signal is broadcast at roughly 37500 Hz during 1 ms. from the 7th I/O pin of the control card. The 38 or 40 kHz detectors do a good job picking up this signal. The unfiltered FREQOUT signal also causes the IR detector’s output to rebound more slowly than when it sees 38 kHz at 50% duty. The result is that the FREQOUT signal out 1 I/O pin, stop sending the signal, and still have enough time to check the detector’s (slowly rebounding) output.

According to the suggested IR communication protocol by Parallax [72], following message format has been applied to the MinT-DB mini/micro robots.

Stamp-2-Stamp protocol created for communication:

– A Start Bit is 1 ms
– A Binary-1 is 3 ms (Logic One in Figure 4.5)
– A Binary-0 is 2 ms (Logic Zero in Figure 4.5)
– A Stop Bit is 4 ms
– The Delay Between Pulses is 2 ms + Any Loop Processing Overhead
– 8 Data Bits (Transmitted Bits from D0 to D7 in Figure 4.5)

This protocol states that the start pulse lasts 1 ms, which is followed by binary pulses. A binary-1 pulse lasts 3 ms and a binary-0 pulse lasts 2 ms. Time between pulses lasts 2 ms plus the loop processing overhead time for each data bit. This protocol has used within the robots to send 8 bits data message with 256 different meanings. The some part of the written code with PBasic for this communication task is given as the following to better define the formed protocol. After each line, brief explanations are given for clarity.

IR_LED_pin con 7

The 7th I/O pin of the control card is to be appointed for the IR transmitter LED.

IR_freq con 37500

37.5 KHz. IR frequency is used for the communication, which is below the working frequency of the receiver.

```
Start_Bit        con   1
Stop_Bit         con   4
Bin_1            con   3
Bin_0            con   2
Between_Pulses   con   2
```

Time period of each defined pulse is to be appointed as constant with units of ms.

```
Counter          var   nib
IR_Message       var   byte
Duration         var   nib
```

Some words are attained as variables and their sizes are defined.

IR_Message = 25

Message of 25 is send to the receiver in a decimal form, which is transferred to the binary form right there for the message processing task. The range of IR_Message is from 0 to 255

(8 Bits). In other words, 256 messages with different meanings can be sent for the communication tasks within the robots.

```
freqout IR_LED_pin,start_bit,IR_freq
pause between_pulses
for counter = 0 to 7
duration = 2 + IR_message.lowbit(counter)
freqout IR_LED_pin,duration,IR_freq
pause between_pulses
next
freqout IR_LED_pin,stop_bit,IR_freq
```

This block of code defines the formation of pulses which are start pulse, duration between the pulses, 8 data bits pulses and stop pulse respectively.

The IR led is turned on and turned off for these predefined periods of times. If these time periods are different for 8 data bit blocks then different messages are taken by the receiver. The software in the reception robot looks at these periods of pulses to decode the distinct bits from each other and directs the robot according to the processed message.

In addition to this type of data bit communication task, the triggering message formats are also used on MinT-DB mini/micro robots. According to this format, the robot waits for an infrared signal to start its mission. To determine if an IR signal is being transmitted, an if…then statement just before the main routine has been used to check over and over again to see if the IR detector’s output is active low. If yes, then it executes the rest of the program, else, it just keeps checking. When an IR broadcast is detected by the robot, it moves from standing still position performing the trigger action using its communication module. The pseudo code for the triggering action is given as follows:

```
IR_Detect_Pin   con   0
IR_Signal       var   in0
Active_Low      con   0
```

The pin number of IR detector using on the control card is defined as the 0 I/O pin, then the coming or detected signals are appointed to the IR_ Signal in the variable format. The triggering action is performed by the Active_Low variable checking as stated above.

loop:
if IR_signal = 1 then loop
display_message:
if ...then action 1

if…then action 2

if…then action 3

action 1

return

action 2

return

action 3

goto display_message

If the triggering message is taken then the robot performs its actions stated as a function given under the *display_message* section of the code.

Besides their IR communication with transmitter and receiver pairs, the robots can also communicate with each other locally using their small IR proximity sensors. For example, as given in the flow chart of the scenario, one robot senses the existence of the other robot using its small proximity sensor located in front. If the robot is sensed in the front of the other robot, then one robot stops and the other starts to perform its mission using the IR proximity sensor as a simple communication module.

Finally, three heterogeneous MinT-DB mini/micro robots have performed a basic communication task for the given sample scenario successfully using IR based sensors, transmitters and receivers. MinT-DB mini/micro robots can also be seen in Figure 4.6.

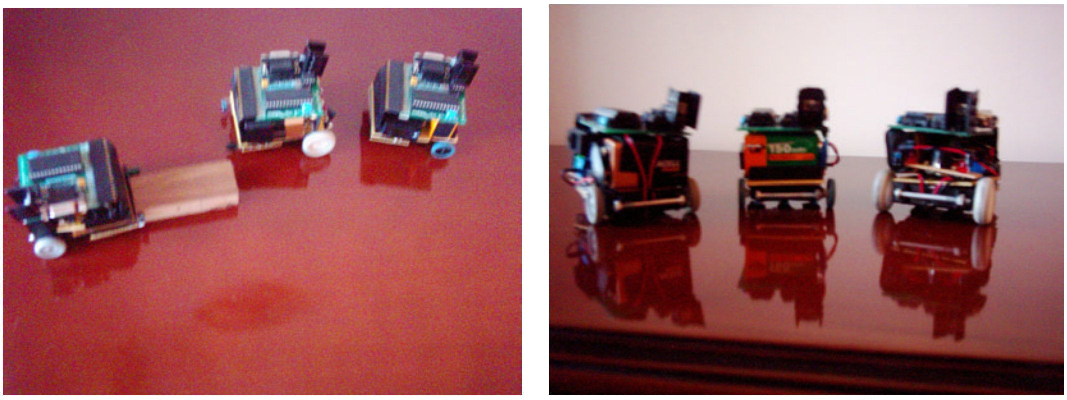


Figure 4.6 MinT-DB series mini/micro robots

CHAPTER V

EXPERIMENTS AND RESULTS

After producing each of the MinT-DB series mini/micro robots, the set-up has been produced. Then, the performances of the components and the basic characteristics of the mini/micro robot are tested. According to the measurements and observed results following categories are formed.

5.1 EXPERIMENTAL TEST SET-UP

During the experiment, a guideline with 2000 mm long and 20 mm wide is used for the line following task. The prepared platform structure for the given tasks of MinT-DB series can be seen in Figure 5.1. Different line following and wall following paths are applied to the robots to see their performances as well.

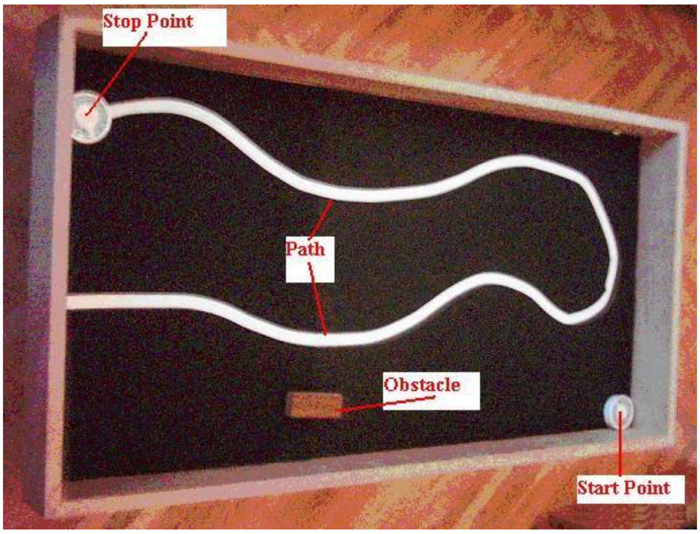


Figure 5.1 Structure of the platform

5.2 EXPERIMENMENTS ON COMPONENTS

Besides the performances of the MinT-DB series, following observations and experiments have been performed for the components of the mini/micro robots.

5.2.1 CONTROL CARD

With the experiments and studies performed by BS2-IC microcontrollers as seen in Figure 5.2, it is seen that the chips of these microcontrollers are very sensitive to the static electricity. Although the sizes of these chips (31x16 mm) are suitable for the mini robotic applications, to program these chips plug/unplug operations are needed that causes the malfunctioning due to the static electricity.

Figure 5.2 Chip of BS2-IC microcontroller

In addition to that both BS2-IC microcontrollers and OEM BSII cards have not multi tasking ability. In other words they can not process different sensor input at the same time. Therefore, this control card should not be used for the swarm studies in future.

5.2.2 CHASSIS

It is seen that plexiglas and polyamide materials are not suitable for the microrobotic applications. Because the machining processes of these materials with the traditional manufacturing techniques are very hard due to the small sizes and tolerances of the robots' parts. Therefore, printed wiring board (PWB), printed circuit board (PCB) or easily modified materials should be selected for the chassis.

5.2.3 OPTICAL IR SENSORS

It is seen that Vishay CNY70 optical sensors are not reliable for the line following task. Because the maximum sensing ranges of these sensors are stated as 5 mm if the suggested value of the resistors given in the data sheets are used. However in reality, due to the lights of the surrounding environment and the oscillations of the signals in the hardware electronics, the operational range of these sensors changes between 1 mm to 3.5 mm. This phenomenon requires and causes the changes in the design of all the parts of the robots such as the height of the caster wheel, the distance between the line following module, the chassis module and the diameter of the wheels on both of the motors etc. If the usage of 5 mm measuring range is insisted on, then the resistor values should be changed for the fixed lightening conditions, which is very time consuming and cumbersome situation.

The amount of light incident on the CNY70 sensors and the detection threshold values are critical for the line following task of the robots. Electric insulation tape is used to form the path to be followed by the robot for the optical guidance. The color of the floor on which the robot is to move has been selected as black and the color of the electric insulation tape chosen as white.

Since the CNY70 sensors are affected by the ambient light sources, the controller generates false signals and the robot is unable to follow the path determined by the guideline. In addition to that when the daylight is high, the robot conceives the entire environment as white due to reflections.

Because of all these drawbacks, Vishay TCRT 5000 (L) optical sensors are used for the line following task in the final robots. Due to their 10 mm extended range and less sensitivity to the changes of the environmental lightening conditions, TCRT 5000 (L) sensors are seen more suitable for the line following task and other small distance proximity detection applications. For the line following task, mainly two different type patterns was studied. One is the black line on the white background and the second is the white line on the black background to provide the maximum contrast. Due to the reflection principle of the black color, which is the worst in the family of colors, the second choice was selected for the line following platforms.

5.2.4 IR PROXIMITY SENSORS

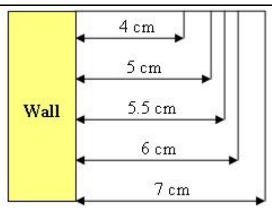
Sharp sensors are affected from the surrounding light as well as the color and pattern of the surfaces. This causes different digital output values ranging from 0 to 255 (8 bits) from the data line of the sensor. To write a reliable code for the operation of this sensor, following range testing experiment has been performed and the results found are given in Table 5.1.

Table 5.1 Sharp GP2D02 IR distance measurement test

Range From Sharp GP2D02 IR Distance Measuring Sensors [cm]	The Minimum Value Read From The Control Card (For 8 Bit)	The Maximum Value Read From The Control Card (For 8 Bit)
<10 (Non-Linear Region)	-	> 205
10	189	205
15	171	188
20	133	170
30	112	132
40	100	111
50	83	99
60	71	82
70	66	70
≥ 80 (Non-Linear Region)	-	< 65

According to these values and other experiments carried out by Sharp GP2D02 IR distance measuring sensors, it is seen that the patterns and colors of the detected objects (in this study the walls) affect the maximum and minimum values read while causing all the written program codes to change. In addition to that, due to the 10 to 80 cm working range of these sensors, it is very hard to measure the distances below 10 cm due to the non-linear properties of the sensors. However, 10 cm is a very big range for the mini/micro robotic applications when compared with the sizes of MinT-DB series and in this study the robots are run in the non-operational range of Sharp GP2D02, which is less than 10 cm. To achieve the wall following task using the non-operational range of Sharp GP2D02 sensor, the increased ranges are found in the non-linear region. The look-up table was formed with the experiments to implement into the code as seen in Table 5.2.

Table 5.2 Test performed for non-measuring range of Sharp GP2D02

<table>
<tr><td rowspan="3">
</td><td>0 - 4 cm Range</td><td>@ 4 cm</td><td>@ 5 cm</td><td>@ 5.5 cm</td><td>@ 6 cm</td><td>@ 7 cm</td><td>7-10 cm Range</td></tr>
<tr><td rowspan="2">Non-Linear Region</td><td>110 max.</td><td>165 max.</td><td>188 max.</td><td>210 max.</td><td>245 max.</td><td rowspan="2">Non-Linear Region</td></tr>
<tr><td>108 min.</td><td>160 min.</td><td>185 min.</td><td>208 min.</td><td>242 min.</td></tr>
</table>

According to the 100 measured values at each fixed distances given in Table 5.2, which are changing in the range of 0-255 (8 bit) proportional with the voltage, following pseudo code has been written using the taken maximum and minimum values at each step for the wall following task:

- If (109< Measured Value <160) then Turn Right Operation,
- If (159< Measured Value<211) then Straight Ahead Operation,
- If (209< Measured Value<246) then Turn Left Operation,

Finally, the Sharp GP2D02 distance measuring sensor has been used successfully for the wall following task both its non-working or non-operational range and operational range.

5.2.5 COMMUNICATION AND IR RANGES

For the object detection task with the IR transmitter and receiver pairs located in front of the robots as seen in Figure 5.3, the working or sensing range was evaluated first of all by the experiments to start the object detection task. According to the experimental results the reasonable range between the pairs are found as 350 mm.

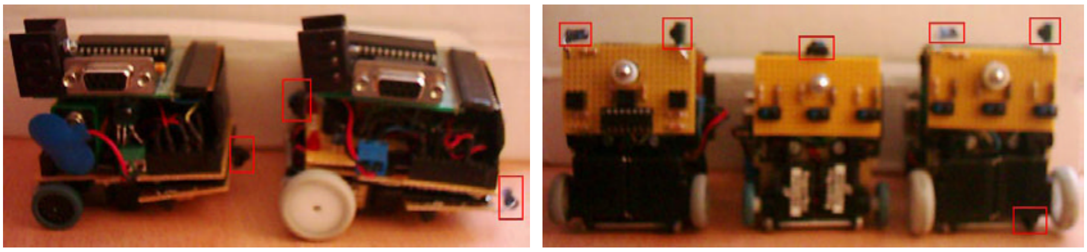


Figure 5.3 Communication modules

For the communication task within the robots using again the IR transmitter and receiver pairs, the working or sensing range was evaluated first of all by the experiments to start the communication task and to prepare the platform. According to the experimental results the allowable range between the pairs are found as 350 mm for the reliable operation of the mini/micro robots. In addition to this range, to transfer the message between the robots, the IR pairs have to be inline with each other. These restrictions limit the commands given to the robots for the communication and collaboration tasks and the shape/sizes of the used platform as a set-up.

5.2.6 POWER SUPPLY

The current and voltage ripples should be avoided in the circuits. This causes a noise in the sensors of the robots resulting in failures of the given tasks. This phenomenon was observed for all of the sensor modules on the robots. In addition to that, it is also observed that if the voltage level of the battery drops below the operational range of 5V then sensor modules work improperly. To prevent these ripples, voltage regulators, voltage level alarm modules or if possible recharging units should be used on the robots.

5.3 EXPERIMENMENTS ON PERFORMANCES

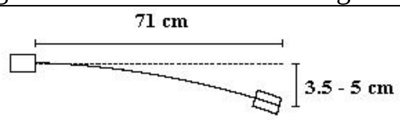
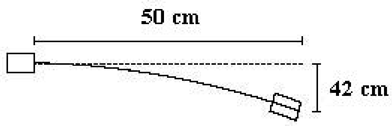
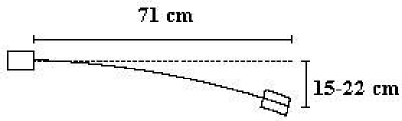
After all the prototypes of MinT-DB series mini/micro robots are produced, their performances are analyzed at different conditions.

The first experiment was performed to observe the deviations of the mini/micro robots from the straight line without using any sensors. Only the move forward task was given to the robots. After the test Table 5.3 and Table 5.4 are formed to show the performance results.

Table 5.3 Deviations from the straight line without using sensors

Name	Not Employed Task	Path	Displacement [cm]	Time [s]	Velocity [cm/s]
MinT-DB-1	Go Forward	Curved Line-1	71.2	8	~ 9
MinT-DB-2	Go Forward	Curved Line-2	65.3	6	~ 11
MinT-DB-3	Go Forward	Curved Line-3	74.3	6	~ 12.5

Table 5.4 Observed odometry errors

Name	Path	Figure of Deflection from Straight Line
MinT-DB-1	Curved Line-1	
MinT-DB-2	Curved Line-2	
MinT-DB-3	Curved Line-3	

Then, the sensors are activated and the different operational tasks are given to the robots. According to the measured performance results Table 5.5 is formed.

Table 5.5 Straight line operation using sensors

Name	Employed Task	Path	Displacement [cm]	Time [s]	Velocity [cm/s]
MinT-DB-1	Wall Following	Straight Line	50	12	4.1
MinT-DB-2	Line Following	Straight Line	50	10	5
MinT-DB-3	Line Following	Straight Line	50	9	5.6

In addition to the odometry errors, curve turning behaviors of MinT-DB-2 and MinT-DB-3 mini/micro robots are also analyzed. According to experiments, observed results are:

1. MinT-DB-2 mini/micro robot can turn a corner (i.e. 90°) however it can not turn a 45° sharp edge due to the big wheels with respect to the size of its body. It is also observed that, this robot prefers turning left when there is a junction point on the lines and it can follow a circular path of minimum 8 cm diameter.

2. MinT-DB-3 mini/micro robot can turn both 90° and 45° angled edges easily. Because, its wheel dimensions are small with respect to its body size. This robot prefers to turn right when there is a junction point on the line and it can follow a circular path of minimum 6 cm diameter.

3. Both MinT-DB-2 and MinT-DB-3 mini/micro robots are also tested in different circular paths such as 13 mm diameter path and it is seen that they can successfully follow those circular lines. Due to the wall following task of MinT-DB-1 mini/micro robot, its line following behaviors are not analyzed.

The characteristic of each MinT-DB mini/micro robots are also observed and the Table 5.6 is formed from the measured data.

Table 5.6 Performance characteristics of MinT-DB mini/micro robots

Robot Name	Size [cm]	Mass [g]	Volume [cm^3]	Motor Type	Run Time [min]	Speed [cm/s]	Year
MinT-DB-1	7.5x6x6	186	270	Modified Servo Motors	140	4.1	2003
MinT-DB-2	7.5x6.5x6	172	292.5	Modified Servo Motors	145	5	2003
MinT-DB-3	7.5x6x6	160	270	Modified Servo Motors	150	5.6	2003

Finally, after all these experiments, tests and analyses, the final state of MinT-DB series mini/micro robots are formed. These results can guide robot makers for their small robotic system studies.

CHAPTER VI

DISCUSSION AND CONCLUSION

This thesis presents the design of a distributed mini/micro robotic system consisting of very small mobile robots called MinT-DB mini/micro robots. Although the MinT-DB series are small, they still contain a full set of integrated capabilities including sensing, computation, communication and mobility as seen in Figure 6.1.

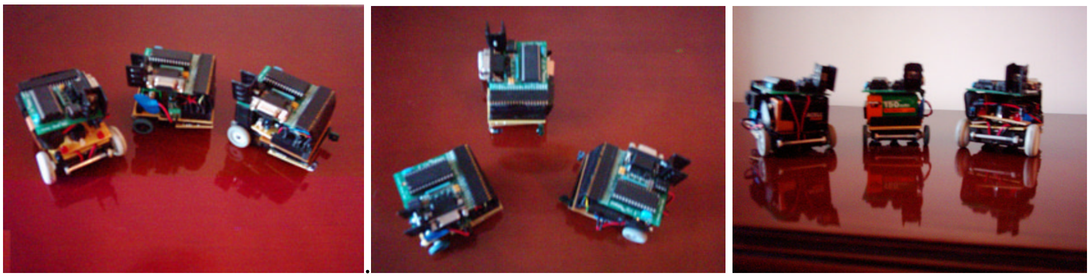


Figure 6.1 MinT-DB series mini/micro robots.

To expand the capabilities even further, the MinT-DB mini/micro robots have been designed in a modular fashion, which allows creating specialized robots with particular sensing configurations easily. In addition to that by combining several such specialized robots, a mini/micro robotic swarm or team has been created with different capabilities while still maintaining a small size of 7.5x6x6 cm.

Therefore, the aims of designing, developing, producing and testing of individual and colony mobile mini/micro robots are completed successfully using the materials at hand while providing the smallest possible robot dimensions. The mini/micro robots with low power requirements are produced as well while satisfying the light, robust, modular, flexible, and multifunctional (programmable) properties.

A small robotic community is constituted from the interactions of many simple individuals performing the given tasks cooperatively. Therefore, robotic cooperation and communication tasks are also performed in a small scale, while forming the basic colony structure for future studies such as biological systems modeling in nature etc.

In addition to that miniaturization problems in design, production and assembly processes are observed and compared with the traditional techniques. According to the findings, suggestions for future works are stated in the section of 6.2 in this chapter.

Finally, technology demonstrative cooperative multi agent mini/micro robotic system is formed and one more step is taken to contribute to the technology of intelligent robotics and mini/micro electro mechanical systems or MEMS. Some articles are also provided in the content of this thesis to speed up the studies on these technologies [107, 108 and 109].

6.1 OBSERVATIONS AND RESULTS

Different mobile robot classifications and definitions have been proposed in the literature according to the sizes of the mobile robots [80 and 106]. The words for these definitions are small, mini, micro and nano in this particular context. However, the uses of these words have been confused too much due to the variances of the miniaturization studies and the random definitions of the robot developers. For example, the effort necessary to down-scale a robot with 10 cm dimensions to a new robot with 5 cm dimensions should be appreciated. This means that the volume of the robot is reduced from 1000 cm^3 to 125 cm^3 and thus the reduction ratio is 8 not only 2. Therefore, the complexity of the work is proportional to the reduction in volume due to the effort to fit all the components of the robot in to that small volume. Based upon this idea, following classifications in Table 6.1 have been proposed by [28] to prevent the confusion in the sizes of the mobile robots:

Table 6.1 Classifications and definitions of mobile robots according to Caprari [28].

Classification	Volume [m^3]	Volume (=)
Robot	Around 1 m^3	~ 1 m^3
Mini-Robot	Around 10^{-3} m^3	~ 1 dm^3
Micro-Robot	Around 10^{-6} m^3	~ 1 cm^3
Nano-Robot	Around 10^{-9} m^3	~ 1 mm^3

The MinT-DB mini/micro robots, developed in the content of this thesis, have the maximum volume of 292.5 cm^3. This means that MinT-DB series are neither in mini-robot nor in micro-robot category. Therefore, new concepts have been suggested in this thesis and according to these proposals; Table 6.2 shows the modified version of Table 6.1.

Table 6.2 Classifications and definitions of mobile robots suggested by this thesis.

Classification	Volume [m^3]	Volume (=)
Robot	Around 1 m^3	~ 1 m^3
Mini-Robot	Around 10^{-3} m^3	~ 1 dm^3
Mini/Micro-Robot	Around 10^{-4} m^3	~ 100 cm^3
Tiny-Robot	Around 10^{-5} m^3	~ 10 cm^3
Micro-Robot	Around 10^{-6} m^3	~ 1 cm^3
Nano-Robot	Around 10^{-9} m^3	~ 1 mm^3

The MinT-DB series is put into the mini/micro-robot category, since the volumes of them are closer to the specified volume in mini/micro-robot category than the other categories.

Therefore, the most important aims of this thesis, which are the mini/micro robot and the mini/micro robotic colony development studies, have been completed successfully.

Another concept to be clarified is autonomy. When the robot has an on-board power supply (batteries) or a generator (solar panels), it is energetically autonomous. In addition, when it is able to decide alone how to react to the environment then it has an autonomous behavior. A really autonomous robot possesses both the energetic and computational autonomy.

MinT-DB series mini/micro robots have very good power autonomy and a decisional autonomy permitting them to travel independently. Therefore, all the aims of this thesis are achieved in final stage.

6.2. SUGGESTIONS FOR FUTURE WORKS

Some of the points that should be considered in the future mini/micro robotic and mini/micro robotic colony/swarm studies are itemized as follows:

- The design of the robot should be kept as simple as possible and the low cost components should be used for the robotic swarm studies.

- The mechanical design and the placement of the robot's components should be performed using CAD software programs with a great care. Although this is a very time consuming situation, it prevents the manufacturing failures due to the small dimensions and the tight tolerances.

- The chassis of the robots should be produced using stereolithography or plastic injection techniques. These techniques prevent the usage of extra connection elements such as screws, bolts and nuts on the chassis. Since, the use of these extra connection elements increase the assembly and disassembly time while bringing the robots more weight. In addition to that, due to the metallic materials of the connecting elements, there is a short-cut risk of the circuits on the robot. For example, as seen in the assembling procedure of Alice-2002 in Figure 6.2, all the components including the battery are soldered on the flat flexible PCB and it is folded in order to be placed in the holding plastic structure produced by plastic injection techniques.

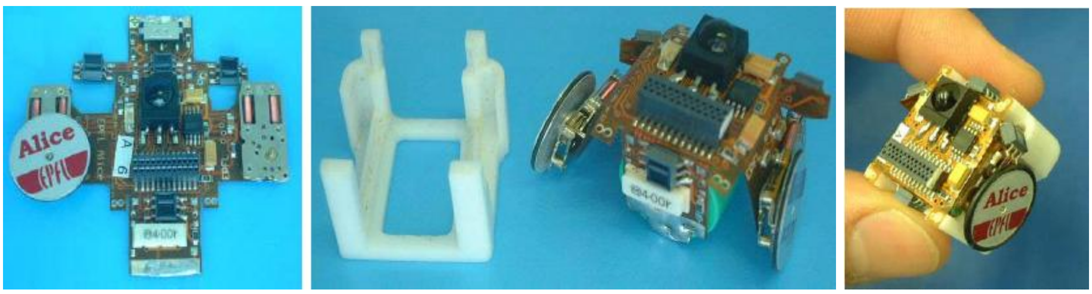


Figure 6.2 Manufacturing and assembly techniques of Alices [28].

- Traditional machining techniques and machines, such as lathe, sawing machine and milling machine should not be used for the manufacturing of the mini/micro robot components. Because their precisions are not enough for the production of the robot's components in such small sizes. Instead of these traditional machines CNC machines should be preferred if the stereolithography and plastic injection techniques are not available.

- The schematics of the circuits should be drawn with the commercial software programs such as Eagle, and the electronic cards of the robots should be PCB requiring minimum number of extra cables. If the cable must be used in the system then they should be shielded and have the twisted multi-wires form. But keep in mind that, the usage of cables affects the reliability, debugging capability and the performance of the robots in a negative way. Therefore, in the new generation of small robotic systems, there are a few or in some cases no cables as seen in Figure 6.2.

- Mini or micro robot design should be started with the selection of micro motor or actuator system. This is one of the most critical components and once this is chosen the rest steps will follow easily. In addition to that, the sizes of the motors directly determine the dimensions of the robots. Therefore very small sized motors such as Smoovy motors or piezoelectric ultrasonic motors should be preferred. However, while choosing the motors or actuator system, give attention not only to the dimensions but also to the consumed energy and torque output. Keep in mind that small actuators often require gearboxes which will increase the overall size of the micro motor dimensions.

- Instead of modified servomotors, small size dc motors with gear units should be preferred to start the small robotic study. Because the sizes of the smallest servomotor in the market is much bigger than the commercial mini/micro dc motors. But of course, there is a trade-off between the cost and the small size.

- Two or three button cells used in the watch market fit perfectly with the dimensions of small robots. The problem with this kind of batteries is the low maximal current due to the high internal resistance. This limits the functionality and the extendibility of the system. Therefore, accumulators can be used instead of them although they have a much lower capacitance/volume ratio.

- Voltage regulators should be used to stabilize the power supply and thus additional modules such as sensor modules have enough power to work properly. Nevertheless, when the system requires much more current, the voltage may decrease causing malfunctions to the motors and other electronic parts. For modules like the IR module, this may result in communication errors of non-negligible extent. For such small systems power management remains a primary issue to deal with from hardware to software.

- Energy lost by friction can be expected to be proportionally inferior then in larger systems.

- The design of the robot should use modular concept both in software and in hardware. This allows flexibility for the development and for the new applications.

- Extension connectors with as many free lines as possible should be used on the base module. The advantage is that it is quite simple to add new features to the robot by just adapting the software and plugging on new modules. The disadvantage may be that adding many new modules tends to displace the center of gravity and thus the robot becomes mechanically less stable.

- Components with low power consumption should be used. This gives the robots exceptionally long power autonomy.

- Sensors on the small scale are often not very precise and do not provide complete knowledge of the surrounding environment. The control algorithm has to cope with this. In addition, the microcontrollers available will not have the expected processing power and memory. These two aspects together will force one to favor simplified control methods.

- Instead of on/off and PWM control techniques, better control methods should be applied to the robots such as PID etc., while considering the processing power of the microcontroller.

- To increase the processing power and the memory and to have a multi-tasking capability of the robot's modules, PIC 16F877 surface mount microcontrollers or equivalent of them should be used on the robots.

- As a programming language, C or C++ high level languages should be used. Because, assembly codes are hard to understand and not easily applicable to the complex tasks of the robots, such as communication. Because, programs coded in assembly language make the things very difficult and cumbersome. In addition to that, if C high level language compilers are used then the real time control simulations with Matlab will be possible for future studies.

- Instead of IR communication, RF communication is suggested for the swarm or colony studies of the robotic systems. Because, the range of RF communication is much larger then the IR modules and the robots do not have to see each others for the communication task. In addition to that, with the developing technology RF-PIC chips have been introduced to the market. RF PICs include all the communication components in the small 16 dip socket chip packages. But if the short range local communication task is necessary, IR modules can be preferred instead of high costs of RF modules.

- Instead of unidirectional transmitter and receiver pairs, bidirectional transceivers should be used on the robots for the communication tasks. Transceivers have two main advantages over the transmitter and receiver pairs. These advantages are the bidirectional communication capability and the implementation of both transmitter and receiver components into a small sized packages.

- DC motors require high currents that can not normally be handled by microcontroller ports. In addition, the use of high currents usually generates transients on the power supply. High current spikes can easily propagate through a circuit with the help of parasitic capacitance normally found on diodes and transistors. These transients and current spikes can have adverse effects on the operation of a microcontroller. The most common problem is data and register corruption, which causes the microcontroller to enter an unknown state. These effects are seen on the operation of the sensor and the communication modules resulting with failures due to the created noise. Therefore, to prevent this phenomenon, either a separate power supply unit for compensation, or a current/voltage regulated power sources should be used on the robots. Implementation of other type power sources (Solar panels, capacitors, and mechanical springs) can also be used as seen in Figure 6.3. For example, the combination of solar panels and batteries can be applied to the small robots such as Alice as seen in Figure 6.4. Fluctuation of current and voltage should also be prevented by the special alarm modules on the robots.

If the level of the voltage drops under a predetermined level, the robots can go to recharge themselves autonomously.

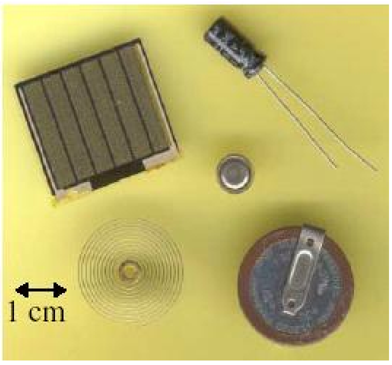


Figure 6.3 Solar panel, battery, capacitor, mechanical spring and rechargeable battery [28].

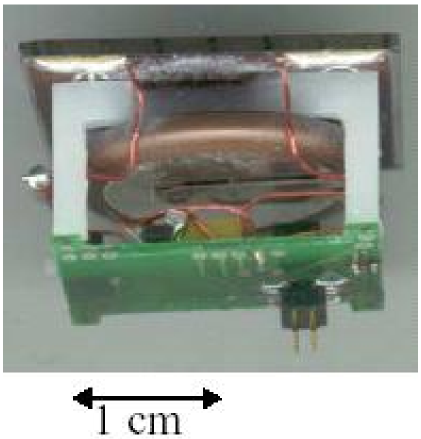


Figure 6.4 Energy module of Alice (Solar panel and rechargeable battery) [28].

- In addition to the power constraints stated above, rechargeable batteries should be preferred in the swarm robotic systems to reduce the cost.

- It is important for the robots to know their positions relative to some reference points. In communication for swarm environments, the position information is very critical. To get this data, some feedback devices should be used on the actuation system such as encoders. Using the feedback sensors, different control algorithms can be applied to the robots and better communication scenarios can be implemented to the robotic swarm systems.

- Small sized sensors produced by high-tech MEMS technology should be used on the mini/micro robots. With the precise MEMS sensors, the errors of the measured properties are reduced and the robots perform their tasks more reliably.
- At least threaded pattern wheels should be used on the small mobile robots to prevent the slippage on smooth surfaces. If the robots are required to drive on several terrains then tank like track wheels should be preferred as seen in Figure 6.5.

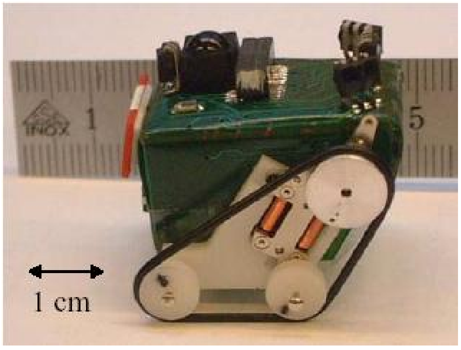


Figure 6.5 All terrain Alice, [28].

REFERENCES

[1] Hsu, C., “Micro-Mechatronics' Current Status and Future”, Micro-Mechatronics Report, *http://www.fedu.uec.ac.jp/~s99schpi/microreport.html*
Appendix-A (Included in CD - Download Date: 25.08.2003)

[2] MiTech Lab, Research at MiTech Lab, MicroEngineering, *http://www-crim.sssup.it/research/micro/default.htm*
Appendix-A (Included in CD - Download Date: 25.08.2003)

[3] *http://www.eee.metu.edu.tr/~tayfuna/whataremems.html*
Appendix-A (Included in CD - Download Date: 25.08.2003)

[4] Arkin, R.C. and Balch, T.R., “Cooperative Multiagent Robotic Systems AI-Based Mobile Robots: Case Studies of Successful Robot Systems”, Kortenkamp, D., Bonasso, R.P. and Murphy, R. (eds). MIT Press, 1998.

[5] Mataric, M., “Issues and Approaches in the Design of Collective Autonomous Agents”, Robotics and Autonomous Systems, Vol. 16(2-4), pp. 321-331, Dec. 1995.

[6] Parker, L.E., “Adaptive Heterogeneous Multi-Robot Teams, Neurocomputing”, Special Issue of NEURAP '98: Neural Networks and Their Applications, Vol. 28, pp. 75-92, 1999.

[7] Rus, D., Donald, B.R., and Jennings, J., “Moving Furniture with Teams of Autonomous Mobile Robots”, Proc. IEEE/Robotics Society of Japan International Workshop on Intelligent Robots and Systems, IROS, Pittsburgh, PA., 1995.

[8] Grabowski R., Navarro-Serment L., Paredis C., and Khosla P., “Heterogeneous Teams of Modular Robots for Mapping and Exploration,” Autonomous Robot, Special Issue on Heterogeneous and Distributed Robot, Vol. 8, No. 3, pp. 293–308, 2000.

[9] Fukuda T., "Research Trends and Methodologies in Robotics," J. of Japan Soc. for Precision Eng., (in Japanese), Vol. 60-1, pp. 20-22, 1994.

[10] Lerman, K., Galstyan, A., Martinoli, A. and Ijspeert, A. J., "A Macroscopic Analytical Model of Collaboration in Distributed Robotic Systems", Artificial Life, Vol. 7, pp. 375–393, 2001, *http://www.isi.edu/~lerman/papers/lerman-alife.pdf*

[11] Caprari, G., Arras, K.O., Siegwart, R., "Robot Navigation in Centimeter Range Labyrinths", 5th International Heinz Nixdorf Symp., Autonomous Minirobots for Research and Edutainment, pp 83-92, Germany, 2001.

[12] Mondada, F., Franzi, E., Ienne, P., "Mobile Robot Miniaturization: A Tool for Investigation in Control Algorithms", Proc. of the 3rd International Sym. on Experimental Robotics, pp. 501-513, 1993.

[13] Bonabeau, E., Dorigo, M., Theraulaz, G., "Swarm Intelligence: From Natural to Artificial Systems", Oxford University Press, July 1999.

[14] Caprari, G., and Siegwart, R., "Design and Control of the Mobile Micro Robot Alice", Proceeding of the 2nd International Symposium on Autonomous Minirobots for Research and Edutainment, pp. 23-32, (AMIRE 2003), Brisbane, Australia, 2003.

[15] Spy Robots, *http://www.robotbooks.com/spy-fly-robot.htm*
Appendix-A (Included in CD - Download Date: 25.08.2003)

[16] Microspies, *http://www.airspacemag.com/asm/mag/supp/am00/uSPY.html*
Appendix-A (Included in CD - Download Date: 25.08.2003)

[17] Fearing R.S, "Toward Micromechanical Flyers", The Bridge, Vol. 31, No: 4, 2001
http://www.nae.edu/NAE/naehome.nsf/weblinks/KGRG-4X3H2Q?OpenDocument

[18] *http://diwww.epfl.ch/w3lami/mirobots/smoovy.html*
Appendix-A (Included in CD - Download Date: 25.08.2003)

[19] Pornsin-Sirirak, T.N., Tai, Y.C., Nassef, H., and Ho, C.M., "Titanium-Alloy MEMS Wing Technology for a Micro Aerial Vehicle Application", Sensors and Actuators Vol. 89(1-2), pp. 95–103, 2001.

[20] *http://mems.caltech.edu/* , *http://mems.caltech.edu/research/microbat/microbatfr.html*
Appendix-A (Included in CD - Download Date: 25.08.2003)

[21] Dickinson, M.H., Lehmann, F.O., and Sane, S.P., "Wing Rotation and the Aerodynamic Basis of Insect Flight, Science Vol. 284(5422), pp.1954–1960, 1999

[22] Ellington, C.P., Van den Berg, C., Willmot, A.P., and Thomas, A.L.R., "Leading Edge Vortices in Insect Flight Nature, Vol. 384, pp. 626–630, 1996.

[23] Stanford University, Mesicopter Image Gallery, 2001, http://adg.stanford.edu/mesicopter/imageArchive/ , Appendix-A (Included in CD - Download Date: 25.08.2003)

[24] Nicoud, J.-D., Zufferey, J.-C.,Toward Indoor Flying Robots, http://asl.epfl.ch/aslInternalWeb/ASL/publications/uploadedFiles/Nicoud_Zufferey_IROS02.pdf , Appendix-A (Included in CD - Download Date: 25.08.2003)

[25] IMM (Institut für Mikroteknik Mainz), 2001, http://www.imm-mainz.de/images/crhubi.gif , Appendix-A (Included in CD - Download Date: 25.08.2003)

[26] SRI International, Artificial Muscle Transducers, 2001, http://www.erg.sri.com/automation/actuators.html , Appendix-A (Included in CD - Download Date: 25.08.2003)

[27] Cox, A., Monopoli, D.J. and Goldfarb, M., "Development of Piezoelectrically Actuated Elastodynamic Flapping Micro-Aerial Vehicles", ASME International Mechanical Engineering Congress and Exhibition, Adaptive Structures and Materials Systems, AD-Vol. 59/MD-Vol. 87, pp. 257–262, New York: ASME, 1999.

[28] Caprari, G., "Autonomous Micro-Robots: Applications and Limitations", Lausanne, EPFL, 2003, Appendix-A (Included in CD - Download Date: 25.08.2003) http://asl.epfl.ch/aslInternalWeb/ASL/publications/uploadedFiles/Caprari_phd2753.pdf

[29] Kim, J.-H., Jung, M.-J., Shim, H.-S. and Lee, S.-W., "Autonomous Micro-Robot 'Kity' for Maze Contest", Proc. of Int. Sym. on Artificial Life and Robotics (AROB), Oita, Japan, Feb.1996.

[30] LAMI-EPFL, Switzerland, The Microrobots Jemmy and Inchy, http://diwww.epfl.ch/lami/mirobots/1cubes.html , Appendix-A (Included in CD - Download Date: 25.08.2003)

[31] http://diwww.epfl.ch/lami/mirobots/smoovy.html , Appendix-A (Included in CD - Download Date: 25.08.2003)

[32] Meloe Micro Robots, Active Structures Laboratory, Université Libre de Bruxelles, http://www.ulb.ac.be/scmero/robotics.html#micro , Appendix-A (Included in CD - Download Date: 25.08.2003)

[33] Dario, P., Carrozza, M-C., Stefanini, C., D'Attanasio, S., "A Mobile Microrobot Actuated by A New Electromagnetic Wobble Micromotor", IEEE/ASME Transactions on Mechatronics, Vol. 3, No.1, pp. 9-16, March 1998.

[34] CRIM (Old: MiTech Lab.) *http://www-crim.sssup.it/research/micro/default.htm#Microactuators* , Appendix-A (Included in CD - Download Date: 25.08.2003)

[35] *http://www.microrobotna.com/airat2.htm* , Appendix-A (Included in CD - Download Date: 25.08.2003)

[36] *http://www.microrobotna.com/soccerrobot.htm* , Appendix-A (Included in CD - Download Date: 25.08.2003)

[37] *http://home.megapass.co.kr/~cch8960/* , Appendix-A (Included in CD - Download Date: 25.08.2003)

[38] *http://www.guinnessworldrecords.com/index.asp?id=47094* , Appendix-A (Included in CD - Download Date: 25.08.2003)

[39] *http://www.ntticc.or.jp/Calendar/1999/ROBOT/Works/emros_e.html* , Appendix-A (Included in CD - Download Date: 25.08.2003)

[40] *http://red.ntticc.or.jp/special/robot/exhibition/exh2_e.html* , Appendix-A (Included in CD - Download Date: 25.08.2003)

[41] *http://www.mobilemag.com/content/100/102/C1547/* , Appendix-A (Included in CD - Download Date: 25.08.2003)

[42] Solarbotics, *http://www.solarbotics.com* , Appendix-A (Included in CD - Download Date: 25.08.2003)

[43] Beam Online, *http://www.beam-online.com/navagation/rob.htm* , Appendix-A (Included in CD - Download Date: 25.08.2003)

[44] Mondada, F., Franzi, E., and Ienne, P., "Mobile Robot Miniaturization: A Tool for Investigation in Control Algorithms", (ISER'93), Kyoto, Japan, October 1993.

[45] K-TEAM, *http://www.k-team.com/robots/khepera/* ,

http://www.cyberbotics.com/products/robots/khepera.html ,
Appendix-A (Included in CD - Download Date: 25.08.2003)

[46] Mitsumoto, N., Fukuda, T., Shimojima, K. and Ogawa, A.., "Micro Autonomous Robotic System and Biologically Inspired Immune Swarm Strategy as a Multi Agent Robotic System", Proc. of IEEE Int'l Conference on Robotics and Automation (ICRA'95), Vol.2, pp.2187-2192, 1995.

[47] Fukuda, T., Mizoguchi, H., Sekiyama, K., Arai, F., "Group Behavior Control for MARS (Micro Autonomous Robotic System)", Proc. of the 1999 IEEE Int'l Conference on Robotics and Automation, (ICRA '99), pp. 1550-1555, 1999.

[48] Fukuda, T., Eeyama, T., Cellular Robotics and Micro Robotic Systems, World Scientific Series in Robotic and Automatic Systems, Vol. 10, 1994.

[49] Büchi R., Rohrer D., Schmid C., Siegwart R., "A Fully Autonomous Mobile Mini Robot", SPIE Photonics EAST '95, Philadelphia, pp. 50-53, 1995.

[50] Büchi R., Caprari G., Vuskovic V., Siegwart R., "A Remote Controlled Mobile Mini Robot", Int. Symposium on Micro Machine and Human Science, pp. 203-6, 1996.

[51] Caprari G., Balmer P., Piguet R., Siegwart R., "The Autonomous Micro Robot ALICE: A Platform for Scientific and Commercial Applications", Int. Symposium on Micromechatronics and Human Science, pp. 231-5, 1998.

[52] Freese M., Kaelin M., Lehky J-M., Caprari G., Estier T., Siegwart R., "LAMAlice: A Nanorover for Planetary Exploration", Int. Symp. on Micromechatronics and Human Science, 1999.

[53] Caprari, G., Arras, K.O., Siegwart, R., "Robot Navigation in Centimeter Range Labyrinths", 5th International Heinz Nixdorf Symp., Autonomous Minirobots for Research and Edutainment, pp. 83-92, Germany, 2001.

[54] Caprari, G., Estier, T., Siegwart, R., "Fascination of Down Scaling - Alice the Sugar Cube Robot", Journal of Micromechatronics, (VSP), Vol. 1, No. 3, pp. 177-189, 2002.

[55] Alice 2002 Doc Page, http://asl.epfl.ch/research/systems/Alice/alice02Doc.php, Appendix-A (Included in CD - Download Date: 25.08.2003)

[56] Caprari, G., Arras, K.O., Siegwart, R., "The Autonomous Miniature Robot Alice: From Prototypes to Applications", (IROS'00), pp. 793-8, 2000.

[57] *http://dmtwww.epfl.ch/isr/asl/publications/caprariIROS00.pdf* ,
Appendix-A (Included in CD - Download Date: 25.08.2003)

[58] *http://www.coro.caltech.edu/Courses/EE141/Labs_Hwks/Manuals/Alice_UserManu.pdf* ,
Appendix-A (Included in CD - Download Date: 25.08.2003)

[59] *http://www.mdl.sandia.gov/products/usystemsprod/rfandoptosystems/projects_surveillance.html* ,
Appendix-A (Included in CD - Download Date: 25.08.2003)

[60] Sandia National Laboratories, New Release - Mini-Robot Research, USA, January 2001, *http://www.sandia.gov/media/NewsRel/NR2001/minirobot.htm* ,
Appendix-A (Included in CD - Download Date: 25.08.2003)

[61] Byrne, R. H., Adkins, D. R., Eskridge, S. E., Harrington, J. J., Heller, E. J., Hurtado, J. E., "Miniature Mobile Robots For Plume Tracking and Source Localization Research, Journal of Micromechatronics, (VSP), Vol. 1, No. 3, pp. 253-, 2002.

[62] Mataric, M.J., 'Interaction and Intelligent Behavior', Technical Report AIM-1495, MIT Artificial Intelligence Laboratory, 1994.

[63] McLurkin, J., 'The Ants: A Community of Microrobots', MIT Undergraduate Bachelor's Thesis, unpublished, 1995, *http://www.ai.mit.edu/projects/ants/*
Appendix-A (Included in CD - Download Date: 25.08.2003)

[64] McLurkin, J. Using Cooperative Robots for Explosive Ordnance Disposal, MIT AILab, 1996, *http://www.ai.mit.edu/projects/ants/papers.html* ,
Appendix-A (Included in CD - Download Date: 25.08.2003)

[65] Navarro-Serment, L., Grabowski, R., Paredis, C., and Khosla, P., "Modularity in small distributed robots," in Proc. SPIE Conf. Sensor Fusion and Decentralized Control in Robotic Systems II, Vol. 3839, Sept. 1999, pp. 297–306.

[66] Navarro-Serment, L.E., Grabowski, R., Paredis, C.J.J., and Khosla P.K., "Millibots The Development of a Framework and Algorithms for a Distributed Heterogeneous Robot Team", IEEE Robotics & Automation Magazine, Page 31, December 2002.

[67] Brown H.B, Jr., Vande-Weghe J.M., Bererton C.A., and Khosla P.K, Fellow, “Millibot Trains for Enhanced Mobility”, IEEE/ASME Transactions on Mechatronics, Vol. 7, No.4, December 2002.

[68] McLurkin, J.,The rockettes: 10-gram microrovers for mars, MIT AI Website, 1991, http://www.ai.mit.edu/projects/mars-rovers/rockettes.html ,
Appendix-A (Included in CD - Download Date: 25.08.2003)

[69] http://robotics.jpl.nasa.gov/tasks/nrover/homepage.html ,
Appendix-A (Included in CD - Download Date: 25.08.2003)

[70] Thakoor S., Microexplorers, Final Report, JPL D-14879A, November 12, 1997, http://bees.jpl.nasa.gov/pdf/MEST998.pdf ,
Appendix-A (Included in CD - Download Date: 25.08.2003)

[71] ZDNET UK NEWS, Mon, 21 Jun 1999 15:31:35 GMT, Associated Press, http://news.zdnet.co.uk/story/0,,t269-s2079684,00.html ,
Appendix-A (Included in CD - Download Date: 25.08.2003)

[72] ZDNET UK NEWS, Fri, 28 May 1999 06:29:35 GMT, Margaret Kaneioj, http://news.zdnet.co.uk/story/0,,t269-s2072085,00.html

[73] Teshigahara, A., Watanabe, M., Kawahara, N., Ohtsuka, Y., and Hattori, T., "Performance of a 7-mm Microfabricated Car", J. Microelectromech. Sys., Vol. 4, No. 2, pp. 76-80, 1995.

[74] Denso Corporation, Micro-Inspection Robot,
http://www.densocorp-na.com/ microcar.html ,
Appendix-A (Included in CD - Download Date: 25.08.2003)

[75] Hisanaga, M., Kurahashi, T., Kodera, M., and Hattori, T., Fabrication of a 4.8 Millimeter Long Microcar, Proc. Second Int. Symp. on Micro Machine and Human Science, pp. 43-46, Nagoya, Japan, Oct. 8-9, 1991.

[76] BBC News, Thursday, 29 June, 2000, 18:00 GMT 19:00 UK,
http://www.micromuscle.com/pdf/BBC000629.pdf ,
Appendix-A (Included in CD - Download Date: 25.08.2003)

[77] Medical Micro-Instruments Competence Center, Minirobots for Endoscopy and Instruments, http://www-crim.sssup.it/research/micro/default.htm ,
Appendix-A (Included in CD - Download Date: 25.08.2003)

[78] Burckhardt C.W., “Les Lois de Similitude en Microtechnique”, Journées de Microtechnique, pp. 6-19, 1972.

[79] Drexler, E., “Nanosystems: Molecular Machinery, Manufacturing, and Computation”, John Wiley & Sons, Inc, 1992.

[80] Dario, P. et al., “Microactuators for Microrobots: A Critical Survey”, Journal of Micromechanics and Microengineering, Vol. 2, No. 3, pp.141-57, September 1992.

[81] Fearing, R.S., “Powering 3 Dimensional Microrobots: Power Density Limitations”, Tutorial on Micro Mechatronics and Micro Robotics, (ICRA’98), 1998.

[82] Jufer, M., “Electromécanique”, Traité d’électricité, Vol. IX, Presses Polytechniques et Universitaires Romandes, Lausanne, 3ème édition, 1995.

[83] ETA SA Fabriques d’Ebauches, CH-2540 Grenchen, Switzerland, A Company of Swatch Group, *http://www.eta.ch* ,
Appendix-A (Included in CD - Download Date: 25.08.2003)

[84] Wilcox, B., Nasif, A., and Welch, R., Implications of Martian Rock Distributions on Rover Scaling, Planetary Society International Conference on Mobile Planetary Robots and Rover Roundup, Santa Monica CA, 1997.

[85] Parallax Inc., *http://www.parallax.com* ,
Appendix-A (Included in CD - Download Date: 25.08.2003)

[86] *http://www.parallax.com/html_pages/products/basicstamps/basic_stamps_oem.asp*
Appendix-A (Included in CD - Download Date: 25.08.2003)

[87] Smoovy, *http://www.myonic.com/en/mps/brushed_systems/dc2s6625r2.htm* ,
Appendix-A (Included in CD - Download Date: 25.08.2003)

[88] Koc, B., Basaran, D., Akın, T., Erden, A., Design of a Piezoelectric Ultrasonic Motor for Micro-Robotic Application, 6. International Mechatronic Design and Modelling Conference, (MDM 2002), 2002.

[89] Cagatay, S., Koc, B., and Uchiho, K., “A 1.6 mm., Metal Tube Ultrasonic Motor”, (IEEE UFFC), Vol. 50, No.7, pp. 782-786, July 2003.

[90] Hitech Servomotors, Appendix-A (Included in CD - Download Date: 25.08.2003) *http://www.servocity.com/ServoCity/Products/Hitec_Servos/HS-60_Super_Micro_/hs-60_super_micro_.html* ,

[91] *http://www.aeromicro.com/Catalog/gws_pico_bb_servo__jr__804559.htm* , Appendix-A (Included in CD - Download Date: 25.08.2003)

[92] Mondada, F., Franzi, E. and Ienne P., "Mobile Robot Miniaturization".

[93] Kim, J.-H., Shim, H.-S, Kim, H.-S, Jung, M.-J and Vadakkepat, P., "Micro-Robot Soccer System: Action Selection Mechanism and Strategies", Department of Electrical Engineering, KAIST, *www.ece.nus.edu.sg/stfpage/elepv/publication/mas_mrs.ps*

[94] L293D, *http://www.hvwtech.com/pages/products_view.asp?ProductID=197* , Appendix-A (Included in CD - Download Date: 25.08.2003)

[95] *http://www.onlybatteries.com/items.asp?db=1* , Appendix-A (Included in CD - Download Date: 25.08.2003)

[96] *http://www.vishay.com/optical-sensors/* , Appendix-A (Included in CD - Download Date: 25.08.2003)

[97] *http://www.vishay.com/docs/83751/83751.pdf* , Appendix-A (Included in CD - Download Date: 25.08.2003)

[98] *http://www.vishay.com/docs/se_ant014.pdf* , Appendix-A (Included in CD - Download Date: 25.08.2003)

[99] *http://www.acroname.com/robotics/parts/R19-IR02.html* , Appendix-A (Included in CD - Download Date: 25.08.2003)

[100] *http://www.acroname.com/robotics/info/articles/sharp/sharp.html* , Appendix-A (Included in CD - Download Date: 25.08.2003)

[101] *http://www.hvwtech.com/pages/products_view.asp?ProductID=166* , Appendix-A (Included in CD - Download Date: 25.08.2003)

[102] http://www.hvwtech.com/pages/products1a.asp?CatID=10&SubCatID=47 , Appendix-A (Included in CD - Download Date: 25.08.2003)

[103] http://sharp-world.com/products/device/ctlg/esite22_10/table/077.html Appendix-A (Included in CD - Download Date: 25.08.2003)

[104] http://www.mit.edu/afs/sipb/contrib/doc/DigiKey/SECTF.pdf , Appendix-A (Included in CD - Download Date: 25.08.2003)

[105] http://www.telec.nl/cat/Zoemers%20307-311.pdf , Appendix-A (Included in CD - Download Date: 25.08.2003)

[106] Grabowski, B. Small Robot Survey, 2002 http://www.contrib.andrew.cmu.edu/~rjg/webrobots/small_robot_survey.htm Appendix-A (Included in CD - Download Date: 25.08.2003)

[107] Basaran, D., Erden, A., "Mini/Mikro Makinalar ve Mekatronik-I", Journal of Endüstri & Otomasyon, Vol. 58, January 2002.

[108] Basaran, D., Erden, A., "Mini/Mikro Makinalar ve Mekatronik-II", Journal of Endüstri & Otomasyon, Vol. 59, February 2002.

[109] Basaran, D., Erden, A., Koç B., "Mini/Mikro Robotlar", Journal of Bilim ve Teknik, Addition of Robotik-2, Vol. 428, July 2003.

APPENDICES

(INCLUDED IN CD)

APPENDIX-A: Downloads of Literature for the WEB References

APPENDIX-B: Technical Specifications of Hitech HS-60 Servo Motor

APPENDIX-C: Technical Specifications of L293D IC H-Bridge Motor Driver

APPENDIX-D: Technical Specifications of 9V Batteries

APPENDIX-E: Technical Specifications of Vishay CNY70 Optical Sensors

APPENDIX-F: Technical Specifications of Vishay TCRT 5000 (L) Optical Sensors

APPENDIX-G: Technical Specifications of Sharp GP2D02 IR Sensors

APPENDIX-H: Technical Specifications of Seven Segment Led & HEF4543B BCD to Seven Segment Latch / Decoder / Driver

APPENDIX-I: Technical Specifications of Sharp IS1U60 IR Receiver/ Demodulator Detector

APPENDIX-J: Technical Specifications of Panasonic Buzzer

APPENDIX-K: Software of MinT-DB Series Mini/Micro Robots