D2.1.1 Compiled list of recommended sensors and sensor-carriers (robots)

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Abstract.
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This document aims to identify suitable sensors and sensor-carriers (robots) to be used in the GUARDIANS system. According to the Users Requirements document, the Guardians system will be composed by a group of mobile robots able to cooperatively explore large and flat warehouses during the early phase of industrial fires.
Keyword list: mobile robot platforms, sensors for mobile robot navigation, environmental sensors.

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Executive Summary

The objective of this document is to identify suitable sensors and sensor-carriers (robots) to be used in the GUARDIANS system. According to the Users Requirements document, the Guardians system will be composed by a group of mobile robots able to cooperatively explore large and flat warehouses during the early phase of industrial fires.

Contents

Chapter 1

Introduction

Autonomous mobile robots are composed by a mobile platform and some sensors used to estimate the robot internal status and to perceive the environment around. The robot autonomy is achieved through cognition algorithms that process sensing data and actuate the platform in order to achieve the desired task.

The **locomotion architecture** depends mainly from the type of environment and from the task to be carried-out: e.g. flat or rough terrain; high speed or precise movements. The **sensing requirements** are related with the ability to move safely and accurately inside the environment and with the ability to perceive the environmental variables relevant to accomplish its mission. To navigate in its environment, a robot needs to know the following aspects:

- The robot localization. The self-localization is a basic ability for any robot intended to explore unknown environments, report the localization of potential targets and return to the starting position after accomplishing the mission or by superior request. Although outdoor environments this aspect can be solved with GPS-based systems and in normal indoor environments this aspect is commonly solved with vision-based systems, in a Guardians environment, it will exist no visibility, so other means need to be pursued to solve this challenge.

- Where it wants to go. This aspect is related with the ability of knowing in advance the localization of potential targets (e.g. positions provided by the exploration algorithm) or with the ability of detecting a target.

- How to reach the goal. This aspect is addressed by the navigation algorithms and comprises several issues, like detecting obstacles, building a map of the environment, planning a safe path to the goal and generating and controlling a trajectory until the goal.

When several robots are operating in the same environment, other issues should be considered, like knowing the localization of the neighbouring robots and guaranteeing an efficient share of the global mission among the agents involved.

Chapter 2 analyses the type of platform locomotion modes that can be used in the GUARDIANS project and proposes some types that best fit the locomotion needs. Chapter 3 deals with sensors for navigation and a set of possible sensors for helping the robots to navigate in the GUARDIANS environment is identified and some commercial models that can be bought by the partners are listed. Chapter 4 deals with mission sensors, i.e. sensors that can be used to detect target items like flames, chemically dangerous environments, victims on the ground, etc. A set of sensors appropriate to measure the relevant environmental variables are surveyed and some specific models are recommended for utilization in the project.

Chapter 2

Mobile platforms

2.1 Introduction

According to the Wikipedia, a Mobile Robot is an automatic machine that is capable of movement in a given environment. They are not fixed to one physical location. In contrast, industrial robots usually consist of a jointed arm (multi-linked manipulator) and gripper assembly (or end effector) that is attached to a fixed surface. Mobile robots are the focus of a great deal of current research and almost every major university has one or more labs that focus on mobile robot researches. Mobile robots are also found in industry, military and security environments. They also appear as consumer products, for entertainment or to perform certain tasks like vacuum cleaning or mowing. Mobile robots may be classified by the environment in which they travel:

- Land or home robots. They are most commonly wheeled, but also include legged robots with two or more legs (humanoid, or resembling animals or insects).
- Aerial robots are usually referred to as unmanned aerial vehicles (UAVs)
- Underwater robots are usually called autonomous underwater vehicles (AUVs)

Focusing on the first category, this report presents mobility configuration which has been used for land or home robots and introduces some commercial products for each configuration. It also shortly discusses the energy autonomy for such configurations.

2.2 Mobility configurations

Mobile robot Platforms may be classified by their moving system:

- human-like legs (i.e. an android) or animal-like legs.

- Wheeled robot

At the moment there are a handful of commercially available mobile robots for use in the home like the RC100 [1] or for research in the laboratory, like the Pioneer II [2], the B21 and the Magellan [3]. One thing that all of these has in common is that they get around on wheels, or perhaps tracks in the case of remote-controlled bomb disposal robots. For the environments that these robots run in, wheels are definitely the most sensible choice. Wheels are easy to control, as they act very predictably at given surface to run on. The power systems behind wheeled locomotion are well developed and understood, and they are a cheap solution. Also wheeled based robots are usually faster. However, there are some environments in which wheels are almost completely useless. In a domestic environment, the obvious problem is getting up stairs, though for the types of large buildings that presently have uses for robots, this is normally accommodated by lifts. In the outside world though, there is rarely a handy lift around. Some estimates suggest that as much as half the earth's surface is presently inaccessible to wheeled vehicles [2, 4].

Selection of wheeled based or legged base platforms for a mobile robot application highly depends on the requirements of the application. As in our case a wheeled based mobile robot fulfills the user requirements, this document rather focus on different types of wheeled based mobile configurations.

2.2.1 Typical wheeled mobility configurations

During last 2 decades many wheeled mobile robots have been developed for different applications. Many innovations were also made on mobile platforms. But according to Borenstein [5], most of the developed wheeled mobile platforms use one of the following drive system:

- Differential Drive
- Tricycle Drive
- Ackerman Steering
- Synchro Drive
- Omnidirection
- Multi-Degree-of-Freedom Vehiclesal Drive
- MDOF Vehicle with Compliant Linkage
- Robots for non flat terrains
- Wheeled walking robots

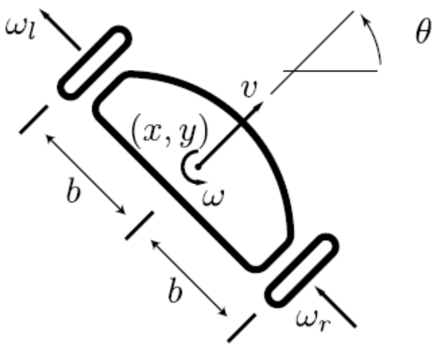

Figure 2.1: A Schematic drawing of a differential drive mobile robot platform.

Figure 2.2: Garcia is canonical differential drive platform [6].

2.2.2 Differential drive

Figure 2.1 shows the schematic of a differential drive mobile robot in which by independent velocity control of each wheel, speed and direction of the robot movement can be controlled. Incremental encoders are mounted onto the two drive motors to count the wheel revolutions. An example of a devloped platform with differential drive is Garcia (Figue 2.2). Garcia is a canonical differential drive platform focusing on simplicity, maneuverability and control [6]. Figure 2.3 shows a semi humanoid robot which moves on 2 wheels with the differential drive concept.

2.2.3 Tricycle drive

In tricycle-drive configurations the front wheel is active and includes 2 actuators to rotate the wheel and to orient the direction of the movement. The rear wheels are usually passive. Because of their simplicity they are very common in AGV applications. The main

Figure 2.3: A semi humanoid robot which moves on 2 wheels with the differential drive concept.

problem of tricycle-drive configuration is climbing an incline, where the center of gravity moves away from front wheel and because the front wheel is the only active wheel, it cause a loss of traction (Figure2.4).

2.2.4 Ackerman steering

The Ackerman Steering Principle defines the geometry that is applied to all vehicles (two or four wheel drive) to enable the correct turning angle of the steering wheels to be generated when negotiating a corner or a curve. Ackerman configuration notices an important issue in the robot movement. When a mobile platform rotates around a center, the rotation diameter of the inner wheel should be different from the outer wheel to avoid slippage on the wheels. (See Figure 2.5). In this case the inside front wheel is rotated to a slightly sharper angle than the outside wheel when turning. As it can be seen in Figure 2.5) the extended axes for the two front wheels intersect in a common point that lies on the extended axis of the rear axle. The locus of points traced along the ground by the center of each tire is thus a set of concentric arcs about this center point of rotation P and (ignoring for the moment any centrifugal accelerations) all instantaneous velocity vectors will subsequently be tangential to these arcs. Such a steering geometry is said to satisfy the Ackerman equation [7].

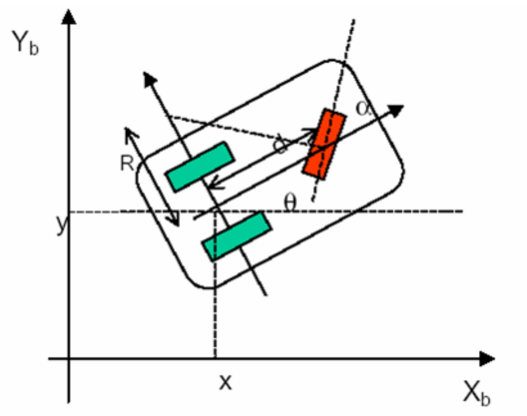

Figure 2.4: Tricycle-drive configurations employing a steerable driven wheel and two passive trailing wheels can derive heading information directly from a steering angle encoder or indirectly from differential odometry.

2.2.5 Synchro drive

Synchro drive is an innovative configuration which addresses some of the problems in traversing inclined terrains which have inclines in different directions or big obstacles which should be traversed by the robot. Usually in case of a non synchro robot traversing such obstacles, some wheels lose their contact with the terrain. In this case and many other cases, slippage may occur. An innovative configuration known as synchro drive features three or more wheels (Figure 2.6) mechanically coupled in such a way that all rotate in the same direction at the same speed and similarly pivot in unison about their respective steering axes when executing a turn. This drive and steering ”synchronization” results in improved odometry accuracy through reduced slippage, since all wheels generate equal and parallel force vectors at all times. The synchronization usually is made by mechanical devices, namely chain, belt or gear drive. But more precision can be obtained by backlash-free gear drives. Referring to (Figure 2.6), drive torque is transferred down through the three steering columns to polyurethane-filled rubber tires. The drive-motor output shaft is mechanically coupled to each of the steering-column power shafts by a heavy-duty timing belt to ensure synchronous operation. A second timing belt transfers the rotational output of the steering motor to the three steering columns, allowing them to synchronously pivot throughout a full 360-degree range [8]. The Sentry's upper head assembly is mechanically coupled to the steering mechanism in a manner similar to that illustrated in Figure 2.7 and thus always points in the direction of forward travel. The three-point configuration ensures good stability and traction, while the actively driven large-diameter wheels provide more than adequate obstacle climbing capability for indoor scenarios [5].

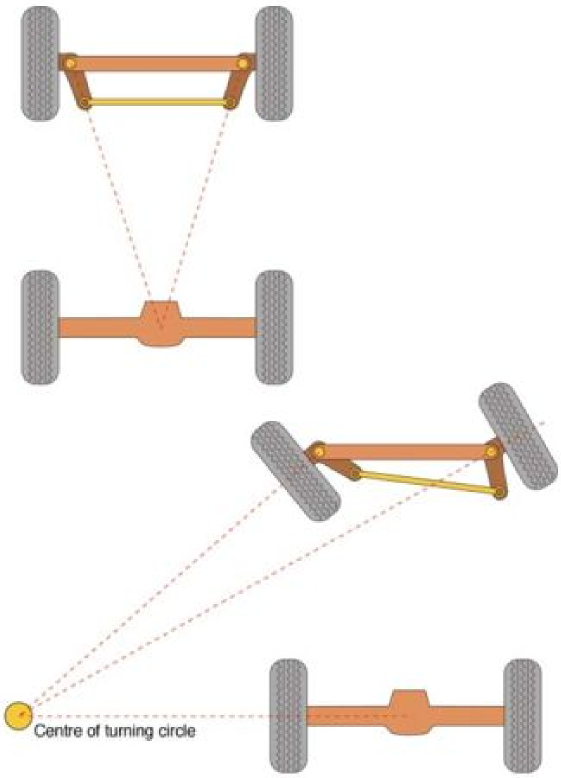

Figure 2.5: In an Ackerman-steered vehicle, the extended axes for all wheels intersect in a common point.

2.2.6 Omnidirectional drive

Omnidirectional drive is based on the Swedish wheel which has the omnidirectional property. Figure 2.9 shows a Swedish wheel.Using this concept many mobile platform have been developed which were using 3 or 4 Swedish wheels (Figure 2.10).

2.2.7 Multi-Degree-of-Freedom vehicles

Multi-degree-of-freedom (MDOF) vehicles have multiple drive and steer motors. MDOF vehicles are ideal for transport tasks in confined space. Theoretically, MDOF vehicles are extremely maneuverable; they are capable of turning in confined space, moving sideways and performing other maneuvers that would allow the vehicle to move along a mathematically optimal trajectory. A good MDOF design could significantly reduce the amount of floor space required for safe vehicle operation. Although a vehicle with more than two independently controlled axis offers exceptional advantages in terms of maneuverability, it also causes exceptional difficulties in terms of control [10]. HERMIES-III, a sophisticated platform designed and built at the Oak Ridge National Laboratory [11, 12, 13]

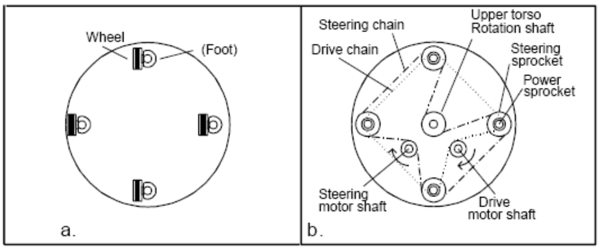

Figure 2.6: A four-wheel synchro-drive configuration: a. Bottom view. b. Top view. (Adapted from [9]

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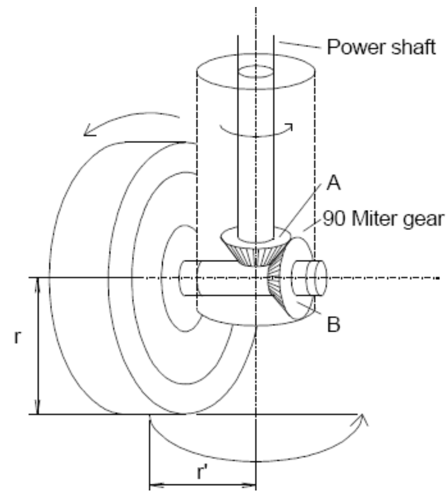

Figure 2.7: Slip compensation during a turn is accomplished through use of an offset foot assembly on the three-wheeled K2A Navmaster robot [5].

has two powered wheels that are also individually steered (see Figure 2.11). With four independent motors, HERMIES-III is a 4-degreeof-freedom vehicle. MDOF configurations display exceptional maneuverability in tight quarters in comparison to conventional 2-DOF mobility systems, but have been found to be difficult to control due to their over constrained nature [12, 14, 15, 10]. Resulting problems include increased wheel slippage and thus reduced odometry accuracy. Then [16, 17] introduced a new control algorithm based on Force Control. The researchers reported on a substantial reduction in wheel slippage for their two-wheel drive/two-wheel steer platform, resulting in a reported 20-fold improvement of accuracy. However, the experiments on which these results were based avoided simultaneous steering and driving of the two steerable drive wheels. In this way, the critical problem of coordinating the control of all four motors simultaneously and during transients was completely avoided. Unique Mobility Inc. built an 8-DOF vehicle for the U.S. Navy under an SBIR grant(see Figure 2.12) [5].

Figure 2.8: B14 is a synchrodrive mobile platform from RWI.

Figure 2.9: Swedish wheel has the omnidirectional property, Courtesy of AIRTRAX Co.

2.2.8 MDOF vehicle with compliant linkage

To overcome the problems of control and the resulting excessive wheel slippage described above, researchers at the University of Michigan designed the unique Multi-Degree-of-Freedom (MDOF) vehicle shown in 2.13 and 2.14 [5, 18, 19, 20, 10]. The two LabMates, here referred to as ”trucks” are connected by a compliant linkage and two rotary joints, for a total of three internal degrees of freedom. The purpose of the compliant linkage is to accommodate momentary controller errors without transferring any mutual force reactions between the trucks, thereby eliminating the excessive wheel slippage reported for other MDOF vehicles. Because it eliminates excessive wheel slippage, the MDOF vehicle with compliant linkage is one to two orders of magnitude more accurate than other MDOF vehicles, and as accurate as conventional, 2-DOF vehicles [5].

Figure 2.10: Uranus, CMU: Omnidirectional Drive with 4 Wheels.

2.2.9 Robots for non flat surfaces

As the working terrain of robots is not always flat and some obstacles or steps may be available, many mobile platforms were also developed for such terrains. One of the most successful platforms in this category is Packbot, which is a commercial platform available in different sizes. Figure 2.15 shows a Packbot robot [3].

2.2.10 Wheeled walking robots

Wheeled robots have the advantage of higher speeds in flat surfaces, but if they encounter an obstacle they should avoid it by changing the direction. But in some cases it is not possible to avoid the obstacle with this approach, for instance in case of existence of steps in their path. In such terrains usually walking robots are used. On the other hand non-wheeled walking robots have lower speeds in flat terrains. If a wheeled robot has also walking abilities, it may be able to pass big obstacles like steps, while maintaining its high speed in flat surfaces. Recently some wheeled robots with walking abilities have been developed. Chiba Institute of Technology developed a working prototype of the Halluc II, a robotic vehicle with eight wheels and legs designed to drive or walk over rugged terrain. Figures 2.16 and 2.17 shows the Halluc robot. Weighing in at 20 kgs the robot is 80.5 cms tall and has 4 joints for each wheel for easy movement. The Halluc II is loaded with sensors it has a camera, 13 distance sensors, two lasers for obstacle detection, one goniometer for wheel control and three axial controllers. It can move sideways, turn around in place and drive or walk over a wide range of obstacles. The operator can put Halluc II into one of three modes depending on the terrain - Vehicle, Insect or Animal mode. In Vehicle mode, Halluc II drives around on its eight wheels, and as it moves over uneven surfaces, each of the legs moves up and down in sync with the terrain to provide a smooth ride that keeps the cab at a constant height. In Insect mode, Halluc II does not use

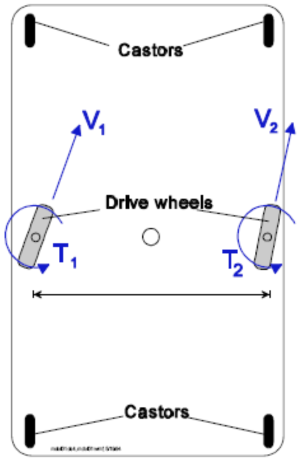

Figure 2.11: A 4-degree-of-freedom vehicle platform can travel in all directions, including sideways and diagonally. The difficulty lies in coordinating all four motors so as to avoid slippage [5]

the wheels; instead, it walks with an insect-like gait, with its legs extended outward from the cab. In Animal mode, Halluc II keeps its legs directly beneath the cab while it walks, allowing it to pass through tight spaces. With wireless LAN capabilities and a system of cameras and sensors that monitor the distance to potential obstacles, Halluc II constantly assesses how best to adjust the position of its legs and wheels[22].

2.3 Energy and power systems

In this section energy systems, batteries and energy autonomy of mobile robots are discussed.

2.3.1 Batteries

Mobile robots usually use batteries as power source. For mobile robot applications efficiency and capacity of the battery is very important. The maximum time that a mobile robot can operate without need to recharge is very important. Also the weight of the battery is of great importance as lighter batteries add less weight to the mobile platform, thus less torque is required in motors. Batteries with higher Watt-hr/kg are the most suitable batteries for mobile robots. Table 2.3.1 shows a comparison between different types of batteries. As it can be seen, Li-Ion and Li-Metal have the highest Watt-hr/kg ratio, which makes them an appropriate choice for mobile robot applications.

[23].

Figure 2.12: An 8-DOF platform with four wheels individually driven and steered. This platform was designed and built by Unique Mobility Inc. [5]

2.3.2 Fuel cell

A fuel cell is an electrochemical energy conversion device. It produces electricity from various external quantities of fuel (on the anode side) and oxidant (on the cathode side). Fuel cells are different from batteries in that they consume reactant, which must be replenished, while batteries store electrical energy chemically in a closed system. Additionally, while the electrodes within a battery react and change as a battery is charged or discharged, a fuel cell's electrodes are catalytic and relatively stable. Many combinations of fuel and oxidant are possible. A hydrogen cell uses hydrogen as fuel and oxygen as oxidant. Other fuels include hydrocarbons and alcohols. Other oxidants include air, chlorine and chlorine dioxide. Due to their scalability, new applications for fuel cells are being investigated all the time. A. Wilhelm ET. Al, evaluated using of a micro fuel cell in a mobile robot [24], but they resulted that The performance of the metal hydride was less than expected. This is partly due to the fact that its small size limited the amount of hydrogen that could be drawn at any given time due to its excessive cooling. If a mobile robot currently uses lithium batteries, weight is probably a significant factor, and cost a lesser issue. For such a situation, fuel cells, probably in tandem with capacitors or a small battery, will become attractive in the future once component weights are optimized. If long run times are important and power requirements are relatively low say, for some sort of security surveillance robot a fuel cell becomes even more attractive [24].

2.3.3 Energy autonomy

Energy autonomy of a robot can be considered like a precondition for long service free working periods, lifelong learning or surviving in hazardous environment. Mobile robots working in a human environment can be recharged using electric power, other using solar energy or gas stations [25]. The former is more common in mobile robot applications.

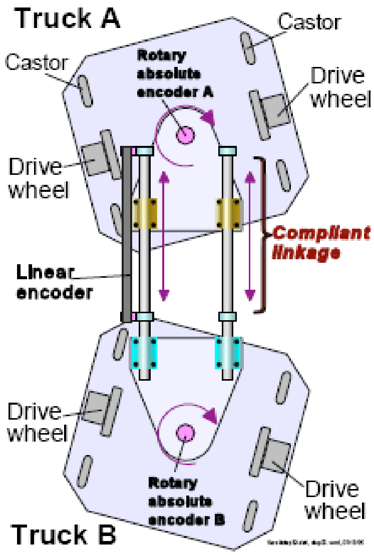

Figure 2.13: The compliant linkage is instrumented with two absolute rotary encoders and a linear encoder to measure the relative orientations and separation distance between the two trucks [5].

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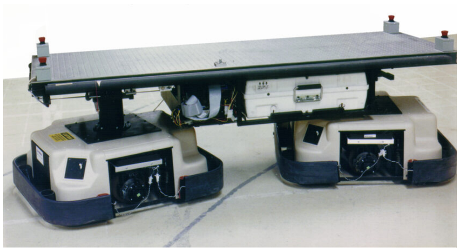

Figure 2.14: The OmniMate is a commercially available mobile robot, with omnidirectional motion capability and compliant linkage [21].

In this case some battery charger stations are considered for the robots in their working area so that they go to the station and connect the battery to the station automatically, or change their battery. A new concept in energy autonomy in large population of mobile robots is potentially distributable energy, which proposed by Trung ET. Al. [26]. They propose a new concept, potentially distributable energy, in the field of autonomous mobile robots. They present simulation results of mobile robots that are capable of not only self-recharging energy but also exchanging batteries to the other robots. They describe a simulation of multiple mobile robots, and then issue rules of battery exchange, which is formulated under constraints of workload, distance and remaining capacity. As Guardian project deals with a multi-robot system, potentially distributable energy can increase the working hours of the robots.

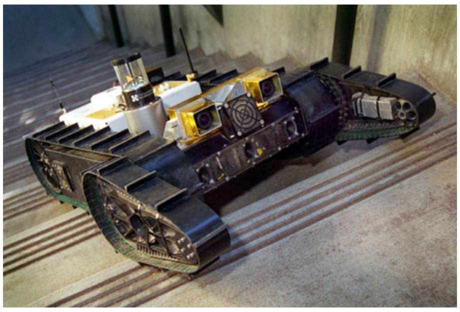

Figure 2.15: Packbot is a commercially available platform for non flat surfaces [3].

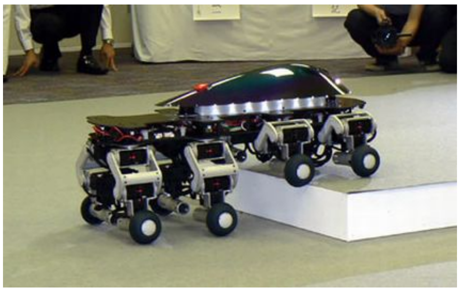

Figure 2.16: Halluc is a wheeled walking robot developed at Chiba Institute of Technology [22].

Microbial Fuel Cell

A new concept was proposed by Ioannis Ieropouloset al. [27], in their paper ”Imitating Metabolism: Energy Autonomy in Biologically Inspired Robots”. They describe the initial work to produce an artificial metabolic system for an energetically autonomous robot using a Microbial Fuel Cell (MFC). A fuel cell was developed in their laboratory and they demonstrated that it is feasible to provide sufficient power for a mobile robot platform to execute photo tactic pulsed behaviour. Their idea rise from an older and more known idea which is the idea of employing microbes to extract energy from sugars [28]. Raw substrate can be converted to sugars and then used in a Microbial Fuel Cell (MFC); a bio-

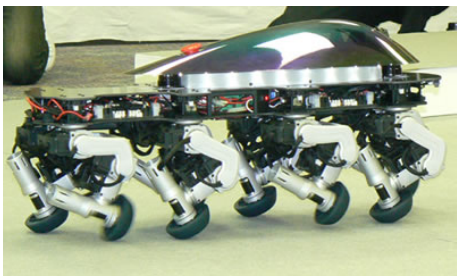

Figure 2.17: Halluc robot in walking mode [22].

Brand	Type	Chemist.	Volt.	Amp-hrs	Watt-hrs	Cycles	Watt-hr/kg	Watt-hr/liter
BYD	AA	LiIon	3.6	0.75	2.7	600+	135	365
Tadiran	AA	Li-Metal	3.0	.8	2.4	700	141	324
Gold Peak	AA	NiCad	1.2	1	1.2	–	46	200
Panasonic	AA	NiCad	1.2	1	1.2	–	46	200
JS	AA	NiCad	1.2	1	1.2	–	46	200
TopPower	AA	NiCad	1.2	0.7	0.84	1000+	32	140
BYD	AA	NiCad	1.2	0.9	1.08	800+	47	142
PowerStream	AA	NiCad	1.2	1.0	1.2	–	46	200
Sanyo	AA	NiMH	1.2	1.5	1.8	–	69	246
Varta	AA	NiMH	1.2	1.3	1.56	1000+	70	213
Panasonic	AA	NiMH	1.2	1.5	1.8	–	69	246
BYD	AA	NiMH	1.2	1.3	1.5	800+	67	205
Gold Peak	AA	NiMH	1.2	1.6	1.9	600+	72	259
JS	AA	NiMH	1.2	1.5	1.8	–	69	246
Harding	AA	NiMH	1.2	1.5	1.8	–	69	246
PowerStream	AA	NiMH	1.2	2.0	2.4	–	78	328
Evercel	Box	NiZn	1.65	24	39.6	500+	49	71
Evercel	Box	NiZn	1.65	39	64.4	500+	59	91
Evercel	Box	NiZn	12	22	264	500+	42	74
BandB	Box	SLA	12	12	144	350+	36	103
Panasonic	Box	SLA	12	12	144	–	37	99

Table 2.1: A comparison between characteristics of different type of batterie[23]

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electrochemical transducer that converts bio-chemical energy to electrical energy. MFC technology is still in its infancy and the levels of power achieved are very low. It is quite clear that the power source will, for most applications, not be in a position to provide enough power for the robot to operate in a continuous mode. Managing a variable energy resource is not a trivial task and therefore energy reserves must be employed to account for situations where the distance between the agent and the food is greater than normal and would take more than the readily available energy to be covered [27].

2.4 Commercial mobile platforms

2.4.1 Mobile robot platforms in Guardians

The mobile platforms used by Guardians are composed by:

Figure 2.18: KheperaIII is a commercially available robot[29].

1. Small platforms produced by SME partner K-Team, namely the Khepera-III robot.
2. Medium-sized commercial platforms, namely Super Scouts, Pioneer, and Erratic (recently called ERA-MOBI) platforms, owned by research partners.
3. The Rescuer tracked platform developed by SME partner Robotnik.

Small robots

Small robots will be used for real experimentation in small scale scenarios. The Khepera III robot will be used as a small platform in Guardians project. Khepera III is able to move on a tabletop but it is also designed to move on lab floor. Rough floor surfaces, carpets and even doorsteps can be overcomed by the Khepera III. The bus specification is fully open and available to enable custom extension developments for users. The robot base includes an array of 9 Infrared Sensors for obstacle detection as well as 5 Ultrasonic Sensors for long range object detection. It also proposes an optional front pair of ground Infrared Sensors for line following and table edge detection. Trough the KoreBot, the robot is also able to host standard Compact Flash extension cards, supporting WiFi, Bluetooth, extra storage space, and many others (Figure2.18)[29].

Medium sized robots

Solutions will then be implemented in medium sized platforms for testing first in real scale laboratory environments, then in user scenarios. The need for a common development environment arises from the use of different platforms. Program code developed for the small platforms should be compatible, with minor adjustments, with the bigger size platforms. Pioneer and Scout platforms will be used as medium sized commercial platforms of Guardians. According to mobilerobots website, PIONEER 3-DX8 is an agile, versatile intelligent mobile robotic platform. It is able to carry loads robustly and to traverse sills more surely with high-performance current management to provide power when it's needed. Unlike hobby robots, it will last through years of tough classroom use

Figure 2.19: PIONEER 3-DX8 is an agile, versatile intelligent mobile robotic platform [30].

and come back for more. The P3-DX stores up to 252 watt-hours of hot-swappable batteries. It arrives with a ring of 8 forward sonar and with an optional 8 rear sonar ring. 3-DX's powerful motors and 19cm wheels can reach speeds of 1.6 meters per second and carry a payload of up to 23 kg. In order to maintain accurate dead reckoning data at these speeds, the Pioneer uses 500 tick encoders. It can sense moves far beyond the ordinary with laser-based navigation options, bumpers, gripper, vision, stereo rangefinders, compass and a rapidly growing suite of other options (Figure 2.19)[30].

Packbot Scout is a mobile robot from iRobot. According to iRobot it is ideal for basic reconnaissance in theater and urban settings, this robot investigates potentially hostile areas before warfighters and first responders enter. Weighing about 18 kg and standing less than 20 cm tall, it has an impact-resistant chassis that can survive up to 400 Gs (Figure2.20) [3].

Erratic is 40cm (L) x 41cm (W) x 15 cm (H) mobile platform (Figure 2.21) developed by Videre Design Co. [31]. The robot base wights 4.5 kg, while the set of base, batteries, computer and sonar is 12.9 kg. According to [31], the ERRATIC platform (from the Latin *errare*: to wander) is compact, powerful and capable of carrying a full load of robotics equipment, including an integrated PC, laser rangefinder, pan tilt unit, sonar ring and stereo camera. Erratic is developed by Kurt Konolige, the inventor of the Pioneer robots. Erratic robot have the following characteristics:

- Industrial-strength motors and aluminum alloy base
- Large, flat top plate for mounting sensors and peripherals
- Integrated controller and motor driver for precise high-speed control of the drive system

Figure 2.20: Packbot Scout is a mobile robot from iRobot [3].

Figure 2.21: Erratic is a new mobile platform developed by Videre Design Co. [31].

- On-board low-power PC with integrated wireless networking Accepts standard PC peripherals: cameras, speakers, etc.
- Open-source networked robot software system: Player/Stage
- Efficient sensor suit (Laser rangefinder, Stereo camera, Sonar ring and IR floor sensors

Rescuer tracked platform

The Rescuer tracked platform developed by SME partner Robotnik will be also used in Guardians project. According to Robotnik website, Rescuer is a solid robot and it is very appropriate for applications in outdoor/indoor hazardous or difficult to access environments. The robot is supplied as a modular system where user components can be

Figure 2.22: Rescuer is a an appropriate platform for applications in hazardous or difficult to access environments. [32].

aggregated. The robot allows a big quantity of equipment whether it be over its platform or in the inside part of the robot (up to 200 Kg). The system offers connectivity with robotic hands, grippers, several laser scanner models, cameras and Robotniks modular arms. Also allows the immediate integration of any standard device with available Linux drivers(Figure2.22) [32].

2.4.2 Other commercial mobile platforms

Many types of commercial robots are available for different applications. There are commercial robots for cleaning, delivery, security, environmental monitoring, inspection, research application, education etc. What make these robot categorized as above is usually the type of sensors and software they use. The mobile platforms are usually among one of the categories which have been discussed in sections 2.2. They are available in different sizes and with different platforms. Some of the most famous commercial mobile robots are introduced here.

Seekur

Seekur is a sturdy, all-weather platform that can handle everything from open fields to parking garages. Its unique shape and omni-directional steering allow truly holonomic movement - meaning it can turn in its own length or even head out sideways if blocked from front and behind. It can operate in Ackermann steering mode as well as omni-directional, making it ideal for intelligent navigation research. Seekur offers space, power and networking for up to five EBX form factor PCs. This opens the way for onboard vision processing, radio-based communications, laser range finding, DGPS, and other autonomous functions. It runs up to seven hours on its nickel-cadmium batteries. Seekur's four monster wheels mounted on steel suspension are designed for speeds up to 2.2 meters per second [5mph] and slopes up to 20 percent with good response, even with a

Figure 2.23: Seekur is a sturdy, all-weather platform [30].

Figure 2.24: POWERBOT is a high-payload high-speed highly maneuverable platform [30].

70kg payload. Seekur options include laser, DGPS, stereovision, thermal sensing, an inertial measurement unit, user I/O expansion and a rapidly growing suite of other options (Figure2.23)[30].

POWERBOT

POWERBOT is a high-payload high-speed highly maneuverable platform with all the intelligence of our smaller platforms. PowerBot moves up to 6 km/h with a payload up to 100kg. PowerBot offers a full-sized PC computer option, opening the way for onboard vision processing, Ethernet-based communications, laser, DGPS and other autonomous functions. The PowerBot stores up to 2100 watt-hours of rechargeable batteries. Fourteen forward and 14 rear sonar sense obstacles from $15cm$ to $7m$. PowerBot's powerful motors and two monster wheels on steel frame with suspension is designed for higher speeds with good response. The PowerBot uses 500 tick motor encoders. Its sensing extends far beyond the ordinary with laser-based navigation options, DGPS, bumpers, 6 dof DC arm, vision and a rapidly growing suite of other options (Figure 2.24) [30].

Figure 2.25: AMIGOBOT is suitable and affordable for use in multi-robot and classroom applications [30].

Figure 2.26: Koalla is a commercially available robot [29].

AMIGOBOT

AMIGOBOT is based on an ARCS-style architecture stripped to its barest bones for affordable use in multi-robot and classroom applications. Rangefinding is handled by six forward and two rear sonar; shaft encoders track x, y and θ position. Differential drive and nearly holonomic design provide good mobility over carpet edges and small sills. Sensor, motor and power monitoring and control information is sent in packets over a wireless or tethered RS232 serial connection to your PC. Payload maximum is 1kg (2lbs). The AmigoBot is designed as a closed system to discourage internal tampering rather than encouraging extensibility as do other MobileRobots bases (Figure2.25)[30].

Koala

According to K-TEAM [29] Koala is a mid-size robot designed for real-world applications. Bigger than Khepera, more powerful, and capable of carrying larger accessories, Koala has the functionality necessary for use in practical applications (like sophisticated battery management), rides on 6 wheels for indoor all-terrain operation (Figure2.26).

Chapter 3

Sensors for Navigation

Navigation is a primary problem in mobile robotics. The local navigation problem deals with navigation on the scale of a few meters, where the major problem is obstacle avoidance. A well-known solution to this problem has been presented in the literature, where generally an occupancy grid map of the immediate surroundings of the robot is created and used to determine the navigation direction such that the robot is safely guided towards a goal. Since the map is local, and resembles a 'sliding window', mapping of the whole environment does not occur. The global navigation problem deals with navigation on a larger scale in which the robot cannot observe the goal position from its initial position. A number of solutions have been proposed by researchers to address this problem. Most rely either on navigating using a pre-specified map or constructing a map on the fly. Most approaches also rely on some technique of localization. Anyway, it is clear that most of these approaches are based on sensors. Sensors play a main role in choosing the navigation method, implementing it and also getting a good functionality. This chapter tries to introduce sensor types for robotic navigation [33] [34].

3.1 Sensors and methods for localization

One of the most general problems in mobile robot navigation can be addressed by three questions: "Where am I?" , "Where am I going?" and "How should I get there?".

here we are trying to survey the state-of-the-art in sensors, systems, methods, and technologies that aim at answering the first question, that is: robot positioning in its environment. Perhaps the most important result from surveying the vast body of literature on mobile robot positioning is that to date there is no truly elegant solution for the problem. The many partial solutions can roughly be categorized into two groups: relative and absolute position measurements. Because of the lack of a single, generally good method, developers of automated guided vehicles and mobile robots usually combine two methods, one from each category. The two categories can be further divided into the following subgroups;

3.1.1 Odometry

The classical technique especially for a wheeled robot to calculate its position is to track its location through a series of measurements of the rotations of the robots' wheels, a method often termed "Odometry". This method uses encoders to measure wheel rotation and/or steering orientation. Odometry has the advantage that it is totally self-contained, and it is always capable of providing the vehicle with an estimate of its position. The disadvantage of Odometry is that the position error grows without bound unless an independent reference is used periodically to reduce the error.

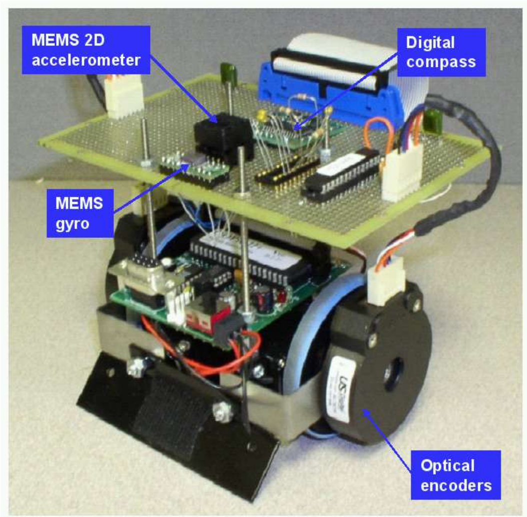


Figure 3.1: Robot, odometry, Texas University, Department of Computer Science

3.1.2 Inertial systems

An Inertial System is initially provided with its position and velocity from another source (a GPS satellite receiver, a human operator, etc.), and thereafter computes its own updated position and velocity by integrating information received from the motion sensors. The advantage of such system is that it requires no external references in order to determine its position, orientation, or velocity once it has been initialized. A robot equipped with this system can detect a change in its geographic position (for example a move west or north), a change in its velocity (speed and direction of movement), and a change in its orientation (rotation about an axis). It does this by measuring the linear and angular accelerations applied to the system. Since it requires no external reference (after initialization), it is immune to jamming and deception. Inertial systems are used in many different types of vehicles, including aircraft, submarines, spacecraft, and guided missiles and also some mobile robots.

Xsens Technologies B.V. offers small and highly accurate 3D measurement units using miniature MEMS inertial sensor technology. Xsens' products are key solutions for applications such as control, stabilization and navigation of unmanned vehicles, robots and other objects, as well as human motion capturing for character animation, training and simulation, and movement science.

3.1.3 Triangulation

This method computes the absolute position of the robot from measuring the direction of incidence of three or more actively transmitted beacons. The transmitters, usually using light or radio frequencies, must be located at known sites in the environment.

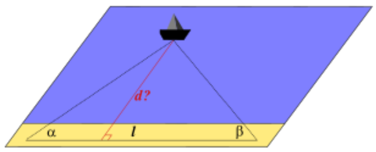


Figure 3.2: Triangulation schema

In the figure, the third angle of the triangle (θ) is known to be 180 - a - . Since, by the law of Sins, the ratio sin(θ)/l is equal to the same ratio for the other two angles (a and), the lengths of any of the remaining two sides can be computed by algebra. By given either of these lengths one can calculate the offsets in both the north/south and east/west axes from the corresponding observation point to the unknown point, thereby fining its final coordinates. Some comericial triangulation sensor systems is shown in table 3.1.

Table 3.1: Triangulation-based sensors

Constructor or designer	model	Range [cm]	Output type
Sharp	GP2D12	10 to 80	analog
Sharp	GP2Y0A02YK	20 to 150	analog
Sharp	GP2Y3A001K0F	4 to 30	analog
Sharp	GP2Y3A002K0F	20 to 150	analog
Sharp	GP2Y3A003K0F	40 to 300	analog
Idec	SA1D	20 to 50	Digital and analog
Idec	SA1L	5 to 20	Digital and analog
NAiS	UZD35	10 to 200	analog

3.1.4 Trilateration

Trilateration is the determination of a vehicle's (or robot's) position based on distance measurements to known beacon sources. In trilateration navigation systems there are usually three or more transmitters mounted at known locations in the environment and one receiver on board the robot. Conversely, there may be one transmitter on board and the receivers are mounted on the walls. The system computes the distance between the stationary transmitters and the onboard receiver. To accurately and uniquely determine the relative location of a point on a 2D plane using trilateration alone, generally at least 3 reference points are needed. Global Positioning Systems (GPS) are an example of trilateration.

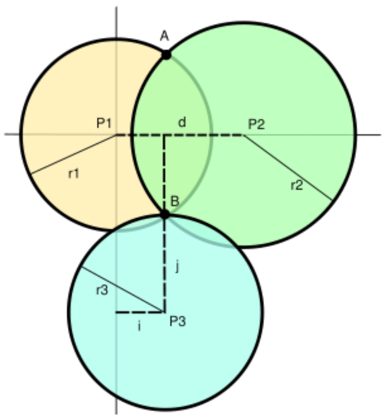


Figure 3.3: Trilateration schema

3.2 Range sensors

How is the free space around me? This is a question that a robot has to know its answer to be able to make future decisions especially for movements. In other words a robot should always have a map of surrounding world. Most sensors used for the purpose of map building involve some kind of distance measurement. There are many environmental sensing options available on mobile robots for application to localization, map building and obstacle avoidance. Active sensing approaches such as laser range finders, stripe light ranging, infra-red sensors, short wave radar and sonar offer advantages in accuracy, robustness and simplicity compared to passive sensor systems such as stereo vision and passive infra-red sensing. Some of these ranging systems will be reviewed in the following sections.

3.2.1 Contact sensors

A Contact Sensor is a generic term used to refer to an electric switch that is able to be actuated by very little physical force. They are very common due to their low cost and extreme durability, typically greater than 1 million cycles and up to 10 million cycles for heavy duty models. This durability is a natural consequence of the design. Internally a stiff metal strip must be bent to activate the switch. This produces a very distinctive clicking sound and a very crisp feel. When pressure is removed the metal strip springs back to its original state.

Micro switches

Micro switches are the most general form of contact sensors. They are commonly used in tamper switches on gate valves on fire sprinkler systems and other water pipe systems, where it is necessary to know if a valve has been opened or shut. Common applications of micro switches include computer mouse buttons and arcade game's joysticks and buttons.

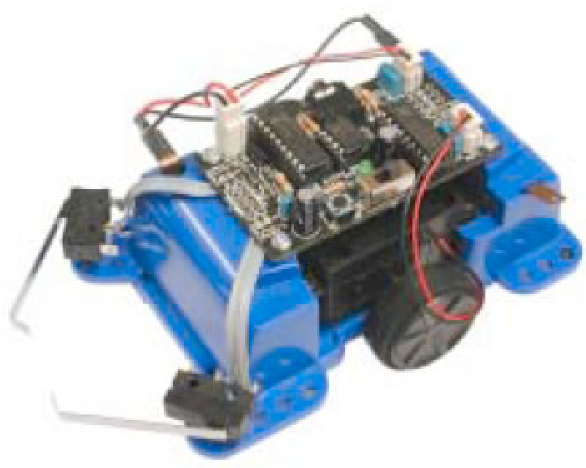


Figure 3.4: robot with microswitch

Whiskers

Whiskers are versatile sensors for short-range navigation and exploration that are widespread in many animal species, especially in rodents. In fact whiskers are another type of contact switches and very similar to micro switches in functionality. The defining feature of whisker is that a relatively small movement at the actuator button produces a relative large movement at the electrical contacts, which occurs at high speed. There are some researchers that try to make a very sensible artificial whisker, and even some of them are working of whiskers arrays [35].

Tactile

Engineers at Northwestern University have developed an array of artificial whiskers that can sweep over an object to render a 3-D mapping of its shape. They have also developed a similar set of whiskers that can measure the velocity profile of a fluid flowing past the array. They constructed the arrays in attempt to mimic the functionality of mammalian whiskers.

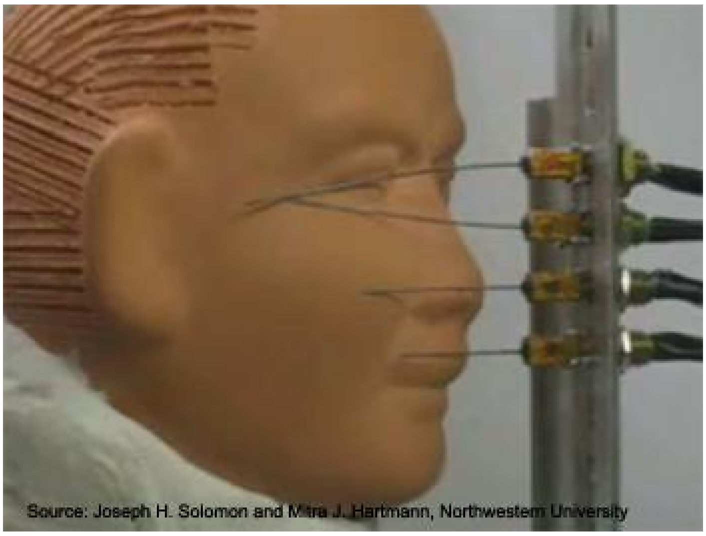


Figure 3.5: Northwestern University, Tactile system

The idea of artificial whiskers is not itself new. Work on the AMOUSE project (ETH, Zurich, Switzerland), has focused on developing robotic arrays of whiskers that can determine surface texture. Work on the Whiskerbot project (Sheffield, England), has focused on using whiskers for navigation and spatial mapping tasks. Other research teams in the US, Japan, Australia and Korea have constructed whiskers that extract some aspects of object shape, but have been limited by bulky sensors and complex movement strategies, making the transition to multi-whisker arrays problematic. The Northwestern researchers looked to the rat vibrissal (whisker) system as an inspiration to overcome these obstacles. Rats have approximately thirty whiskers on each side of their face, each of which is exquisitely sensitive to tactile information. Rats move their whiskers back and forth over objects between five and twenty times a second in order to determine object size, shape, orientation and texture. Because there are no sensors along the length of the whisker (which is a hair-like structure), all information must be collected at the base. The basic premise of the Northwestern work was to keep the artificial whisker array as simple as possible, while retaining the fundamental sensing strategies employed by the rat and using firmly-grounded principles of engineering.

The result is an average array of four straight spring-steel whiskers, vertically aligned and actuated by a single motor. The sensor at each whisker's base measures bending moment - often called torque - to estimate how much the whisker has bent and at what angle. To make sense of this information, the whiskers are modeled as rotating beams, thus allowing the use of equations from classical elasticity theory. The system works by estimating the angle and radial distance at which each whisker touched the object. Because each whisker's height is fixed, this amounts to sensing the point of contact for each whisker in three-dimensional space. Building up multiple contact points over multiple whisks leads to three-dimensional feature extraction. The ability to sense vertical "slip" of the whiskers is an important component of the research, as it permits sweeping in any direction along the object. In final result, the whiskers slip up and down when they hit differently angled surfaces of the object [36].

The Northwestern researchers also tested another array design, this one with the goal of modeling the sensing capabilities of harbor seals. Seals are renowned for their ability to follow the wakes of their prey, capable of detecting and tracking the wake caused by a fish up to minutes after it has swum by. The whiskers of the seal-inspired sensobot are thicker to allow greater sensitivity to fluid flow, and remain fixed while sensing fluid flow velocity. Again, by measuring the bending moment at the base of each whisker, the velocity profile of a fluid can be accurately estimated. Tracking a wake may be as simple as keeping a given flow pattern centered along the array, an idea that the researchers hope to test in future experiments [37].

Solomon and Hartmann expect that the whiskers could have a variety of applications, ranging from use on small and efficient robots capable of exploring dark, confined environments, to use on autonomous rovers to determine times of wheel slip and locking. The researchers are particularly interested in using these whiskers as a research tool in neuroscience. The whiskers will help to predict the signals that may exist in the primary sensory neurons of animals that use their whiskers for exploration. In addition, the whisker sensobots will help elucidate the benefits and drawbacks of different whisking and exploratory strategies, and aid as a "bottom-up" approach towards studying neural coding. The researchers are currently creating a full three-dimensional model of the rat's head and whiskers to quantify the spatiotemporal variations in moment across the whisker array s the rat explores different types of objects[38].

3.2.2 Sonars

SONAR (SOund NAvigation and Ranging) - or sonar - is a technique that uses sound propagation to navigate, communicate or to detect other vessels. There are two kinds of sonar systems; active and passive. The frequencies used in sonar systems vary from infrasonic to ultrasonic, but chiefly for reducing beside effects, ultrasonic frequency is more popular. In a sonar system, range is estimated by measuring the time of flight of a transmitted acoustic signal. Ultrasonic ranging is today the most common technique employed on indoor mobile robotics systems, primarily due to the ready availability of low-cost systems and their ease of interface. In the automotive industry, BMW now incorporates four piezoceramic transducers (sealed in a membrane for environmental protection) on both front and rear bumpers in its Park Distance Control system. table 3.2 compares some commercial ultrasonic range sensors that are already in the market.

Table 3.2: Ultrasonic sensors

Constructor or designer	model	Range [cm]	Output type
Maxbotics	EZ0, EZ1, EZ2, EZ3, EZ4	up to 645	serial, analog and pulse width
Robotic Electronics (Devantech)	SRF10	3 to 600	I2C
Robotic Electronics (Devantech)	SRF08	3 to 600	I2C
Robotic Electronics (Devantech)	SRF04	3 to 300	I2C
Robotic Electronics (Devantech)	SRF235	10 to 120	I2C
Idec	SA6A	5 to 30, 10 to 100, 20 to 200	analog
ASL (Seiz-Viscarret)	Usonic	100, 200, 400	digital (I2C or RS232)
Sonaswitch	MiniA	15 to 180	analog
Sonaswitch	MiniS	15 to 180	Digital

Two of the most popular commercially available ultrasonic ranging systems will be reviewed in the following sections.

Massa Products, Ultrasonic Ranging Module Subsystems

M-300

Massa Products Corporation introduces the M-300 Family of RoHS Compliant Low Cost Ultrasonic Sensors that produce detection ranges from as close as 4 inches (100 mm) to greater than 15 feet (4.5 meters).

Incorporating state-of-the-art ultrasonic technology, the sensors provide precision non-contact distance measurement for factory automation or industrial process control. The M-300 Family of Sensors stand out over all other systems because of their affordability, extraordinary ease of operation, genuinely user-friendly software, versatility in user-

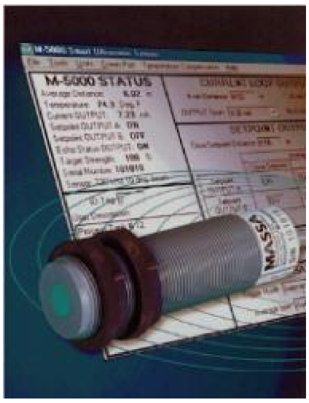


Figure 3.6: MassaSonic ultrasonic sensor

controlled outputs, and the ability to be set up without using a target. They transmit narrow beam sound pulses at a user-selected rate (or they can be software triggered), process return echoes, and produce several outputs dependent on the position of the target.[39].

The user-friendly M-300 Software operates with MS Windows operating systems using an RS-232/RS-485 or USB/RS-485 converter. This data link allows up to 32 sensors to be connected in parallel onto the same multidrop communication network using the supplied protocol. This network also allows users to remotely program their sensors and read target distances for quick integration into their process control application.

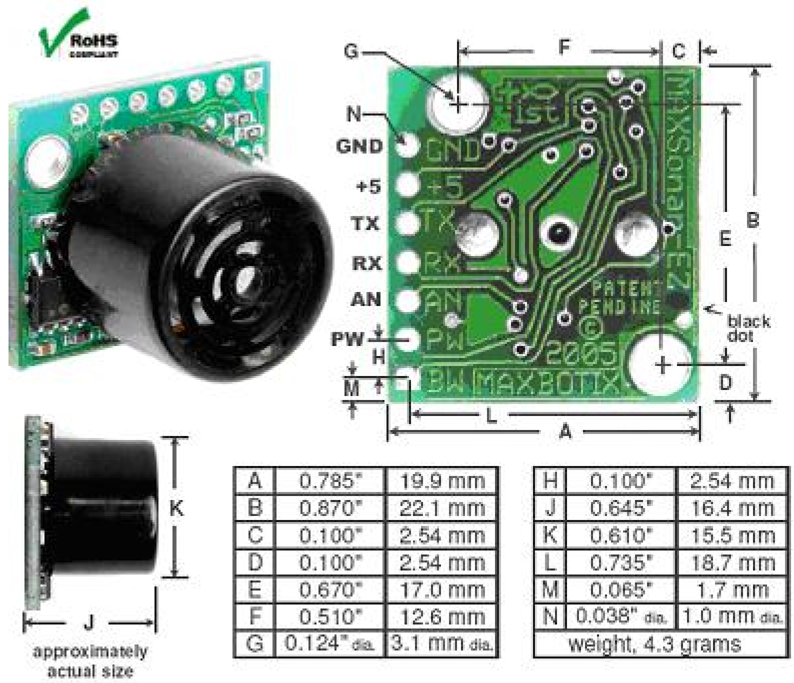
LV-MaxSonar-EZ0,High Performance Sonar Range Finder

MaxBotix Inc has provided a very short to long range detection in an incredibly small package. The LV-MaxSonar-EZ0 detects objects from 0-inches to 254-inches (6.45-meters) and provides sonar range information from 6-inches out to 254-inches with 1-inch resolution. Objects from 0- inches to 6-inches range as 6-inches. The interface output formats included are pulse width output, analog voltage output, and serial digital output [40].

Beam Characteristics:

The LV-MaxSonar-EZ0 has the most sensitivity of the MaxSonar product line, yielding a controlled wide beam with high sensitivity. Sample results for measured beam patterns are shown below on a 12-inch grid. The detection pattern is shown for:

- A) 0.25-inch diameter dowel, note the narrow beam for close small objects,
- B) 1-inch diameter dowel, note the long narrow detection pattern
- c) 3.25-inch diameter rod, note the long controlled detection pattern



A	0.785"	19.9 mm
B	0.870"	22.1 mm
C	0.100"	2.54 mm
D	0.100"	2.54 mm
E	0.670"	17.0 mm
F	0.510"	12.6 mm
G	0.124" dia.	3.1 mm dia.

H	0.100"	2.54 mm
J	0.645"	16.4 mm
K	0.610"	15.5 mm
L	0.735"	18.7 mm
M	0.065"	1.7 mm
N	0.038" dia.	1.0 mm dia.
weight, 4.3 grams		

Figure 3.7: LV-MaxSonar-EZ0 High Performance Sonar Range Finder

- D) 11-inch wide board moved left to right with the board parallel to the front sensor face and the sensor stationary. This shows the sensor's range capability.

ZigBee

ZigBee is a low-power wireless communications technology and international standard protocol for the next-generation wireless network, reducing data size and allowing for lower-cost network construction with simplified protocol and limited functionality. ZigBee uses the PHY and MAC layers defined by IEEE 802.15.4, which is the short-distance wireless communication standard for 2.4 GHz band[41].

ZigBee Key Features

- Low Power

“ The benefits of simple, cost-effective, low-power wireless connectivity that ZigBee technology provides address a variety of markets, including industrial and home monitoring, control and automation, as well as health care diagnostics. Freescale provides all the building blocks used in a complete ZigBee-compliant platform solution: the RF transceiver, MAC and ZigBee software, microcontrollers and sensors. The development hardware and reference designs provide developers with the tools they need to easily and

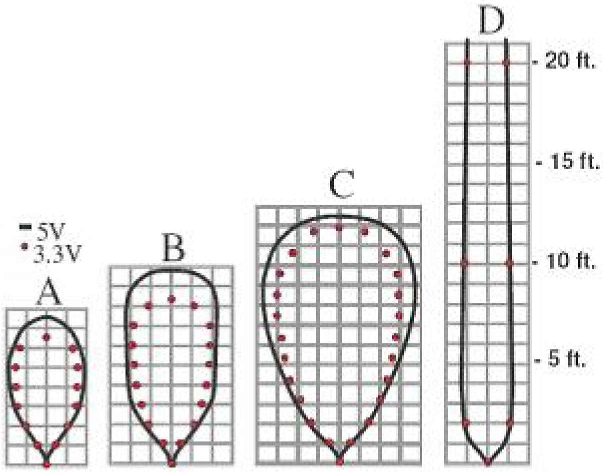


Figure 3.8: beam characteristics that are approximated

quickly implement these building blocks. One solution, one provider-built, tested, compatible and ready for integration.

- Robust

“ 802.15.4 provides a robust foundation for ZigBee, ensuring a reliable solution in noisy environments. Features such as energy detection, clear channel assessment and channel selection help the device pick the best possible channel, avoiding other wireless networks such as Wi-Fi. Message acknowledgement helps to ensure that the data was delivered to its destination. Finally, multiple levels of security ensure that the network and data remain intact and secure.

- Mesh Networking

“ The ability to cover large areas with routers is one of the key features of ZigBee that helps differentiate itself from other technologies. Mesh networking can extend the range of the network through routing, while self healing increases the reliability of the network by re-routing a message in case of a node failure

- Interoperability

“ The ZigBee Alliance helps ensure interoperability between vendors by creating testing and certification programs for ZigBee devices. Users can be assured the devices that go through certification testing and use the ZigBee logo will work with other devices based on the same applications. This provides end customers with the customers with peace of mind while creating brand awareness of products with the ZigBee logo.

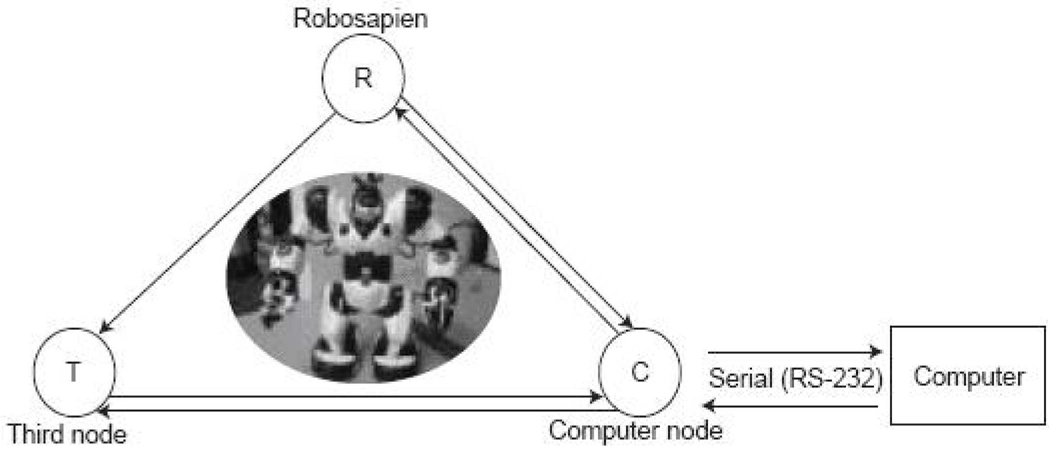


Figure 3.9: WowWee Robosapien's localization schema

Robot Localization using ZigBee

There are a lot of works that try to use ZigBee in localization field. Ethan Leland and his colleagues have developed a localization idea for robotic applications. They used a ZigBee evaluation kit from Freescale Semiconductor to implement a proof-of-concept network for a WowWee Robosapien 1.0, which is a humanoid robot. They implemented the prototype using the kit's three ZigBee nodes to simultaneously localize the robot with signal strength measurements while controlling it with a minimal command set. Their localization and control system features a Freescale MC13192 evaluation board with three accelerometers (MMA6261Q for the x- and y-axes and MMA126OD for the z-axis) mounted on the Robosapien robot (see 3.9). The system also includes an MC13192 SARD board connected to a PC via an RS-232 serial connector and another MC13192 evaluation board in the environment[42].

3.2.3 Laser Range sensors

Laser range finders are in different types. Table 3.3 is comparing some of most popular laser range finders, and we have described one of them in more details. Table 3.4 presents some recently commercial products in details.

THE SICK LMS 200 LASER SCANNER

The Sick LMS 200 is a laser scanner based on the measurement of time-of-flight (TOF). As depicted in Figure 3.11, a pulsed infrared laser beam is emitted and reflected from the object surface. The time between the transmission and the reception of the laser beam is used to measure the distance between the scanner and the object. The laser beam is deflected by a rotating mirror turning at 4500 rpm (75 rps), which results in a fan-shaped

Table 3.3: Laser range finders

Constructor or designer	model	Range [cm]	Output type
Idec	MX1C	60 to 160	Digital and analog
Baumer electric	OADM	5 to 25 or 10 to 50	analog or digital (RS485)
Leuze	ODS 96	10 to 60 or 20 to 200	Digital (RS232) and analog
LAMI (Lamon)	Laser Range Finder	5 to 80	digital (I2C, RS232)
Sick	any type	100 to 900	many types

scan pattern. The angular resolution of the scanner is selectable at l, 0.5, or 0.25 degrees. However, the 0.5 and 0.25 resolutions are achieved only by interlaced scanning, i.e., a complete frame of data is acquired by 2 or 4 interlaced scans, espectively[43].

Figure 3.10: LMS 200

For each individual scan, the physical resolution is 1 degree. We limited our interest to the 1" resolution setting, where a full scan of 180 degrees produces 181 measured range values. The data transfer rate can be programmed to be 9.6, 19.2,38.4, or 500 Kbaud. We used the 500 Kbaud rate, at which data of a full scan is transferred to the user's computer within 13.3 ms. A high-speed RS422 interface card is needed for this transfer rate (unfortunately Sick's support for this high baud rate is very limited and caused us

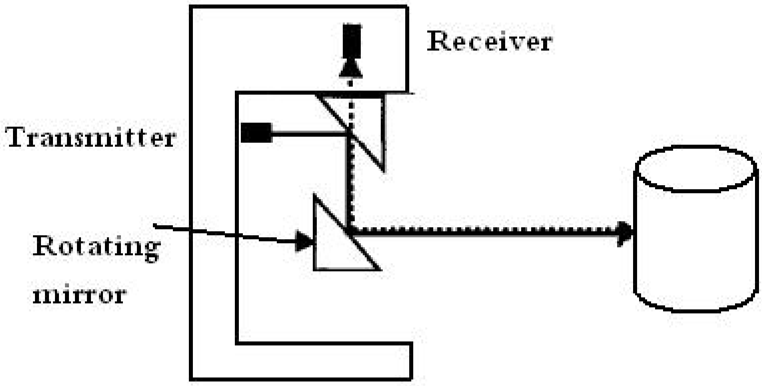


Figure 3.11: Operating principle of the LMS 200

substantial problems). According to the manufacturer's specifications the scanner can measure ranges up to 8 m with 15 mm system error and 5 mm standard deviation.

3.2.4 MW radars

Radar is an apparatus and a method that uses electromagnetic waves to measure the distance to an arbitrary target that includes a radiation source producing a beam of coherent radiation the frequency of which is continuously varied. it can identify the range, altitude, direction, or speed of both moving and fixed objects such as aircraft, ships, motor vehicles, weather formations and also robots.

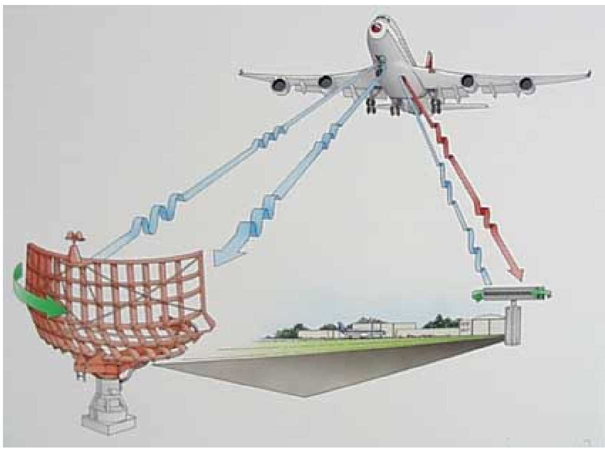


Figure 3.12: Radar schema

The beam is divided into a ranging beam and a reference beam. The ranging beam is coupled to a ranging interferometer, which directs a portion of the ranging beam at the tar-

Table 3.4: Laser Range Finders' Specifications [44]

Sensor	Sick LMS200	Hokuyo URG-04LX	Sick DT60	IFM O1D100
Dimensions (mm)	155x210x156	50x50x70	38x99x104	42x52x59
Total Weight (g)	4500	160	202	203
Scanning Range (°)	180	240	punctual	punctual
Angular Resolution	1/0.5/0.25°	0.36°	–	–
Range (m)	80	0.2 - 4	0.2 to 5.3	0.2 to 10
Max. Error (mm)	±7.5	±10 or 1% of range	±10	±15
Wavelength (nm)	905	785	655	650
Interface	RS422/RS232	USB/RS232	$4-20\,mA$; $0-10\,V$	$4-20\,mA$; $0-10\,V$
Power consumption	650mA@24V	550mA @5V	$< 170\,mA$ @ 11 to 30V	$< 150\,mA$ @ 18 to 30V
Operating temperature (°C)	0 to +50	-10 to +50	-25 to +55	-10 to +60
Approximated Cost (Euro)	4000	2500	750	250

get. The ranging interferometer produces a first signal indicative of the phase difference between a portion of the ranging beam directed at and scattered by the target and another portion of the ranging beam which has traveled over a path of fixed length. The reference beam is coupled to a reference interferometer. A portion of the reference beam is directed by the reference interferometer along a reference path of a predetermined length, and the phase difference between the portion of the reference beam directed along the reference path and another portion of the reference beam which has traveled over a path of a fixed length is measured. The number of fringes resulting from the wave interference produced in the ranging interferometer and the number of fringes in the wave interference pattern produced by the reference interferometer are counted and used, together with the known length of the reference path, to determine the distance of the target from the ranging interferometer. In the other words, a transmitter emits waves which are reflected by the target and detected by a receiver, typically in the same location as the transmitter. Although the signal returned is usually weak, it should be amplified. This enables radar to detect objects at ranges where other emissions, such as sound or visible light, would be too weak to detect. Radar is used in many contexts, including meteorological detection of precipitation, measuring ocean surface waves, air traffic control, police detection of speeding traffic, and military applications.

Figure 3.13: robot using radar in military, Foster-Miller Inc

One of the applications of microwave radar is obstacle detection in robotic path planning. The new generation of radar prototype systems detects stationary obstacles up to the braking distance. In these cases an obstacle is located and identified at around 200 m. A 77 GHz scanning radar has been developed by the AWARE project for collision warning and avoidance (CW/A) vehicle systems. The CW/A system is intended to be applicable in motor- and highway traffic (urban traffic is not covered at this stage). Moving and stationary obstacles in front of the vehicle are detected and tracked, post-processing modules analyze the radar tracks, and when necessary the driver is alerted. The main limitations of microwave radars in this project is related to the detection of objects not belonging to the road, like bridges, to the difficulty to extract road geometry, and to the relatively rough classification of objects types[45]. The human machine interface of a radar system is typically based on visual (like icons on a LCD changing color to red if the obstacle comes so close as to become an imminent danger) and/or acoustic warnings. Some robots also have a vision part for analyzing the radar output.

RF Systems

Recently, RF systems gain increasing attention, since the radio frequency can eliminates the need for an optical line of sight and transmits a relatively large amount of information. Moreover, it can be used for the bi-directional information flow. Thus, if we embed RFID tag in every object and localize the tagged object precisely, this can be a powerful solution for the robot environment recognition and localization. For this purpose, many methods using RFID have been developed so far.

One of the methods is based on RF signal strength analysis. The RF signal strength is inversely proportional to the square root of the distance, so the distance can be calculated

Figure 3.14: RF robot, www.EvoSapien.com

from the signal strength. But at least three reference points are needed to find the exact position of the transponder. Also, the wave strength is reduced by not only the distance, but also the scattering and reflection of the wave. So it is impossible to determine the distance precisely by this approach. Another method is using an ultrasonic wave together with RF signals. It measures the distance using time of flight techniques of ultrasonic wave from the transmitter to the receiver. RF signals are used to wake up the receiver and transmit the information to the receiver. But it also needs at least three base stations to measure the exact position of the object. Also, the ultrasonic wave reflects off the surface of an object, so the system requires line of sight between receivers and the transponder. One of the ways for overcoming to these problems is determining the signal phase shift.

phase shift:

The position can be determined by the direction and the distance. The distance from a reader to a transponder in RFID systems can be measured from the phase shift by time of flight techniques of the RF signal. The direction from the reader to the transponder is measured by the power change upon the distance and direction angle between the antenna plane and the transponder. If an electromagnetic wave passes through a loop coil, a voltage V is generated as

$$V \propto SBsin\theta$$

where S is the surface area of the loop coil,B is the arrival signal magnetic flux density passing through the loop, and θ is the angle between the loop coil plane and the wave direction. But at least two time scanning processes, up to down, and left to right direction, are required to know the exact direction in 3 dimensions. With a 3-axis orthogonal array antenna, we can determine the direction of the transponder only with a single time scanning process. The 3-axis array antenna is a set of antennas having the same three loop antennas those are orthogonally arranged in one another as shown in Fig. 1. When an electromagnetic wave from the transponder passes through the three orthogonal antennas, three different voltages proportional to the sine function of the angle between each axis and the transmitted wave are induced as follows:

$$V_{x-axis} \propto SB_0 sin\theta_x = SB\frac{a}{r} \propto a$$
$$V_{y-axis} \propto SB_0 sin\theta_y = SB\frac{b}{r} \propto b$$
$$V_{z-axis} \propto SB_0 sin\theta_z = SB\frac{c}{r} \propto c$$

where a , b , and c are the elements of the transponder position vector, respectively and r is the distance that equals

$$\sqrt{a^2 + b^2 + c^2}$$

As the direction to the transponder can be related directly to the voltage induced in each axis given by

$$\overrightarrow{r} = (a, b, c) \propto (V_{x-axis}, V_{y-axis}, V_{z-axis})$$

Thus one can determine the position of the transponder in 3 dimensions.

MMW Radar in localization application

Manjari Chandran and Paul Newman have presented a good approach for motion estimation with millimeter wave radar. Millimeter wave radars have been successfully used in the area of outdoor autonomous navigation. Radars are long range sensors and hence are well suited for outdoor applications and large scale mapping. They are also known to be little affected by weather and lighting conditions. Some researchers have implemented the navigation of autonomous guided vehicles designed to transport standard cargo containers in port environments using millimeter-wave (MMW) radar sensors. The sensors are used to detect the range and bearing of a number of fixed known beacons located in the environment. Two radar units, at 77GHz, are mounted at the front and rear of the vehicle. The navigation system works by detecting the range and bearing to a set of beacons placed at known, mapped locations about the environment. The beacons are radar trihedrals, effectively internal corner reflectors. Also some other researchers have used the radar either for location determination, or to build a terrain map in front of the vehicle. Location determination is achieved by matching and triangulating pre-placed beacons to a map of their known co-ordinates polarization information is used to distinguish location beacons from terrain reflections. Dissanayake and his colleagues use MMW radar to implement the simultaneous localization and mapping algorithm on a vehicle operating in an outdoor environment. The radar returns the range and bearing to a landmark. The number and location of the landmarks is not known a priori. Landmark locations need to be initialized and inferred from observations alone.

Figure 3.15: The MDARS robot, using MMW radar

The radar receives reflections from many objects present in the environment but only the observations resulting from reflections of stationary point landmarks should be used in the estimation process. In their implementation landmark quality implicitly tests whether the landmark behaves as a stationary point landmark. Range and bearing measurements which exhibit this behavior are assigned a high quality measure and are incorporated as a landmark. Those measurements that do not are rejected. Foessel and Bunting have used the evidence grid approach for three dimensional map building with a radar sensor model. The evidence grid approach divides the space of interest, which can be two-dimensional or three-dimensional, into regular cells. Each cell stores the accumulated evidence of occupancy for the corresponding area or volume as provided by the sensor observations. The technique takes into account the uncertainty of sensor data through a probabilistic sensor model. The framework of evidence grid or occupancy grid has been used in the area of adaptive robotic exploration to maximize map accuracy. The spatial representation of the environment is used to calculate the entropy of the map and hence the accuracy. The disadvantage of this metric is that the method is highly dependent on accurate estimation of the robot's location. Since the observations are taken in sensor space which is relative to the robot's absolute location, the correct cells can be updated only when the correct location of the robot is known[46].

3.2.5 Vision and IR cameras

As a scientific discipline, computer vision is concerned with the theory and technology for building artificial systems that obtain information from images. The image data can take many forms, such as a video sequence, views from multiple cameras, infra red cameras or even multi-dimensional data from a medical scanner.

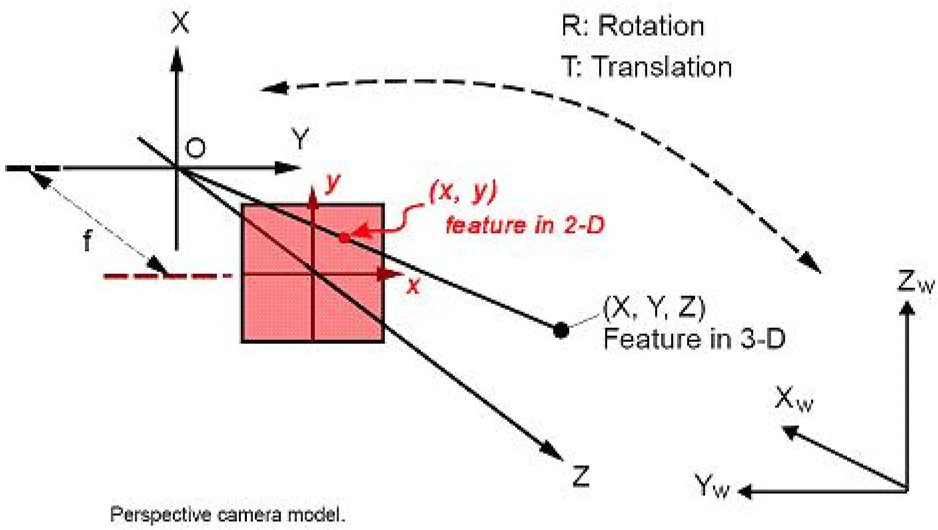


Figure 3.16: Perspective camera model

A core problem in robotics is the determination of the position and orientation of a mobile robot in its environment. The basic principles of landmark-based and map-based positioning also apply to the vision-based positioning or localization which relies on optical sensors in contrast to ultrasound, dead-reckoning and inertial sensors. Common optical sensors include laser-based range finders and photometric cameras using CCD arrays. Visual sensing provides a tremendous amount of information about a robot's environment, and it is potentially the most powerful source of information among all the sensors used on robots to date. Due to the wealth of information, however, extraction of visual features for positioning is not an easy task. Most localization techniques provide absolute or relative position and/or the orientation of sensors. Techniques vary substantially, depending on the sensors, their geometric models, and the representation of the environment. The geometric information about the environment can be given in the form of landmarks, object models and maps in two or three dimensions. A vision sensor or multiple vision sensors should capture image features or regions that match the landmarks or maps. On the other hand, landmarks, object models, and maps should provide necessary spatial information that is easy to be sensed. When landmarks or maps of an environment are not available, landmark selection and map building should be part of a localization method.

Geometric models of photometric cameras are of critical importance for finding geometric position and orientation of the sensors. The most common model for photometric

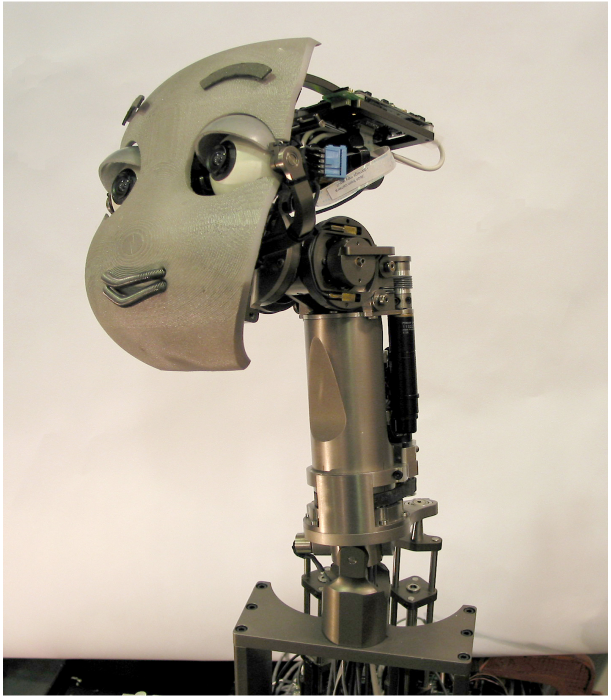


Figure 3.17: MERTZ: An active vision head robot for exploring social learning

cameras is the pin-hole camera with perspective projection as shown in Figure below. Photometric cameras using optical lens can be modeled as a pin-hole camera. The coordinate system (X, Y, Z) is a three-dimensional camera coordinate system, and (x, y) is a sensor (image) coordinate system. A three-dimensional feature in an object is projected onto the image plane (x, y).

As it has shown in 3.17 robots are using vision more than only simple localization. MERTZ is an active vision head robot, designed for exploring scalable learning in a social context. Inspired by how human infants learn by observing and imitating other people, we plan to have MERTZ be placed in a public venue for long periods of time, continuously interacting with people and incrementally learning about various correlations. For example, the robot may learn to correlate objects and people with frequently uttered phoneme sequences, differentiate among people and their interaction habits, learn to dislike some people who tend to annoy the robot, etc. MERTZ has recently gone through a series of experiment where it interacted with many people at different public spaces in the Stata Center[47].

3.3 Internal status sensing

The first requirement for physical autonomy is the ability for a robot to take care of itself. As an example, many of the battery powered robots on the market today can find and connect to a charging station, and some toys like Sony's Aibo are capable of self-docking to charge their batteries. Self maintenance is based on "proprioception", or sensing one's own internal status. Status sensing usually includes "self energy measuring", "heat measuring" and "current, velocity and position measuring for each actuator". Nowadays robots can measure the sinking current, heat, position and velocity of each actuator, even sometimes as a feedback for control system. In addition, as the work places of robots increases, it is difficult to prepare a knowledgeable human worker to manipulate the robots when it is needed. Therefore, the robot system which can work for a long time without maintenance is required essentially. Scientists aim to realize self-maintenance robot system which can be maintained the working ability for a long time without maintenance by the worker. Actually a robot that has the ability of self maintenance needs to have some special sensors for determining its status. It should gather some data like heat, current, position and etc sensors to analyze them and have some information about its standing. Actually there are two common different type of these systems; Gyroscopes and Accelerometers.

Gyroscopes

Gyroscopes measure the angular velocity of the system in the inertial reference frame. By using the original orientation of the system in the inertial reference frame as the initial condition and integrating the angular velocity, the system's current orientation is known at all times. Gyroscopes can be classified into two broad categories: mechanical gyroscopes

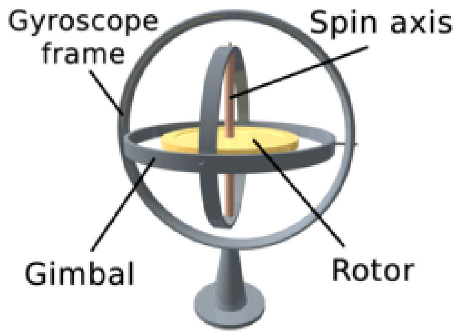


Figure 3.18: typical two-axis mechanical gyroscope configuration

and optical gyroscopes. Above figure is showing how a mechanical gyroscope works. The basic optical gyroscope consists of two laser beams traveling in opposite directions (i.e., counter propagating) around a closed-loop path. The constructive and destructive interference patterns formed by splitting off and mixing parts of the two beams can be used to determine the rate and direction of rotation of the device itself.

Accelerometer

Accelerometer measures the linear acceleration of the system in the inertial reference frame, but in directions that can only be measured relative to the moving system since the accelerometers are fixed to the system and rotate with the system, but are not aware of their own orientation. The suitability of accelerometers for mobile robot positioning was evaluated at the University of Michigan. In this informal study it was found that there is a very poor signal-to-noise ratio at lower accelerations. The results obtained from the tilt-compensated system indicate a position drift rate of 1 to 8 cm/s (0.4 to 3.1 in/s), depending on the frequency of acceleration changes. This is an unacceptable error rate for most mobile robot applications. Nonetheless, inertial sensors are thus unsuitable for accurate positioning over an extended period of time. Another problem with inertial navigation is the high equipment cost. For example, highly accurate gyros, used in airplanes, are so expensive. Recently fiber-optic gyros (also called laser gyros), which are said to be very accurate, have fallen dramatically in price and have become a very attractive solution for mobile robot navigation.

Figure 3.19: nBot, two-wheeled robot [48]

Accelerometers are also used for balancing. nBot is a two-wheeled robot that uses this concept. The basic idea for a two-wheeled dynamically balancing robot is pretty simple: drive the wheels in the direction that the upper part of the robot is falling. If the wheels can be driven in such a way as to stay under the robot's center of gravity, the robot remains balanced. In practice this requires two feedback sensors: a tilt or angle sensor to measure the tilt of the robot with respect to gravity, and wheel encoders to measure the position of the base of the robot. Four terms are sufficient to define the motion and position of this "inverted pendulum" and thereby balance the robot;

1. the tilt angle
2. its first derivative, the angle velocity

3. the platform position
4. its first derivative, the platform velocity

These four measurements are summed and fed back to the platform as a motor voltage, which is proportional to torque, to balance and drive the robot. It uses a accelerometer and a rate gyro for balancing. The gyroscope and accelerometer are combined with complementary filters to provide an inertial reference sensor. The accelerometer provides accurate static tilt information, when the robot is not accelerating. The gyroscope can be integrated to provide accurate dynamic tilt information, but the integration tends to drift over time. Combining the two sensors provides a robust inertial measurement[48].

Chapter 4

Environmental Sensors

This chapter describes the sensors used to help perceiving the environmental conditions regarding the mission to be performed by the system, in this case - a firefighting mission.

4.1 Gas sensing

Gas sensing is very important on a firefighting environment, bringing a better characterisation of the hazardous environment that fireman's has to face.

4.1.1 Metal oxide gas sensors

When a metal-oxide crystal is heated at a certain high temperature in air, oxygen is adsorbed on the crystal surface and a surface potential is formed that inhibits electron flow. When the surface is exposed to reducible gases, the surface potential decreases and conductivity measurably increases. The relationship between the film's electrical resistance and a given reducible gas concentration is described by the following empirical equation:

$$R_s = A[C]^{-\alpha}$$

where R_s is the sensor electrical resistance, A is a constant specific for a given film composition, C is the gas concentration, and α is the characteristic slope of the R_s curve for that material and expected gas. Metal-oxide devices change the resistivity as a function of the presence of reducible gases, and as such, they require an additional electronic circuit to operate. Figure 4.1 shows a metal oxide gas sensor schematic where R_H is the heating element and R_S the sensors resistor.

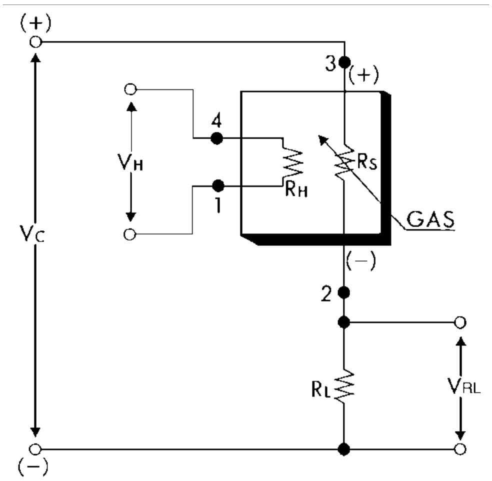


Figure 4.1: Metal oxide gas sensor electrical connections [49].

Figure 4.2: Alphasense gas sensors.

4.1.2 Electrochemical cells

The electrochemical can be divided by their operation mode into sensors which measure voltage (potentiometric), those which measure electric current (amperometric), and those which rely on the measurement of conductivity or resistivity (conductometric). Special electrodes are used, where either a chemical reaction takes place or the charge transport is modulated by the reaction. Because electric current flow essentially requires a closed loop, the sensor needs at least two electrodes, one of which is called a return electrode. The electrodes in these sensing systems are often made of catalytic metals such as platinum or palladium or they can be carbon-coated metals. Electrodes are designed to have a high surface area to react with as much of the analyte as possible, producing the largest measurable signal. A simple liquid electrochemical sensor (cell) uses two electrodes immersed in an electrolyte solution. Gas analytes such as CO react at the working electrode and produces CO_2 and free electrons. Charges and charged species migrate to the other (counter) electrode where water is produced if oxygen is present. The reaction converts CO to CO_2. If the electrodes are connected in series to a resistor and the potential drop across the resistor is measured, it will be proportional to the current flowing, making it a function of analyte gas present.

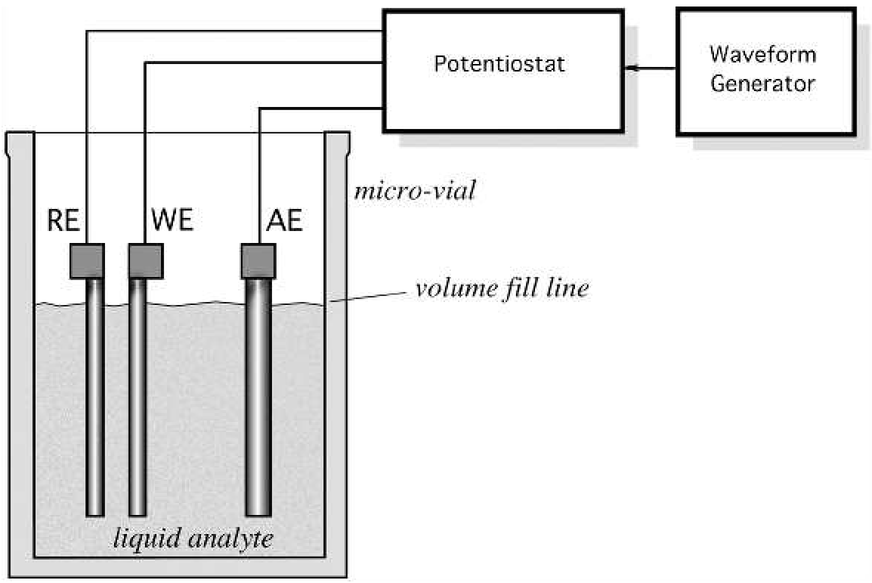


Figure 4.3: Electrochemical sensor electrode set [49].

4.1.3 Optical methods

Optical sensors are based on the interaction of electromagnetic radiation with matter, which results in altering (modulating) the intensity, polarisation, and velocity of light in the medium. Examples of such modulations are variations in intensity, polarisation, and velocity of light in the medium. In a general arrangement, the monochromatic radiation passes through a sample (which may be gas, liquid, or solid), and its properties are examined at the output. Alternatively, the sample may respond with a secondary radiation (induced luminescence), which is also measured. Chemiluminescence devices (reaction produces measurable light) phosphoresce when light hits them and that emission of light is an indication of chemical species presence. Nondispersive infrared (NDIR) absorbance involves the absorption of specific wavelengths of light and, when tuned through experimental methods, can be used for single-analyte target gases such as CO_2. Spectroscopic absorption optical sensors are useful for UV and IR wavelengths and can be used to target O_3 detection by producing a more complex absorbance signature versus a simple attenuation. In all strategies, the wavelength of the light source is routinely matched to the reactive energy of the optrode indicator to achieve a best possible electronic signal. The detection of the original and resultant light is obtained with a photodiode or photomultiplier tube.

Figure 4.4 shows a simplified configuration of a CO_2 sensor that consists of two chambers which are illuminated by a common LED. Each chamber has metallised surfaces for better internal reflectivity. The left chamber has slots covered with a gas-permeable membrane. The slots allow CO_2 to diffuse into the chamber. The bottom parts of the chambers

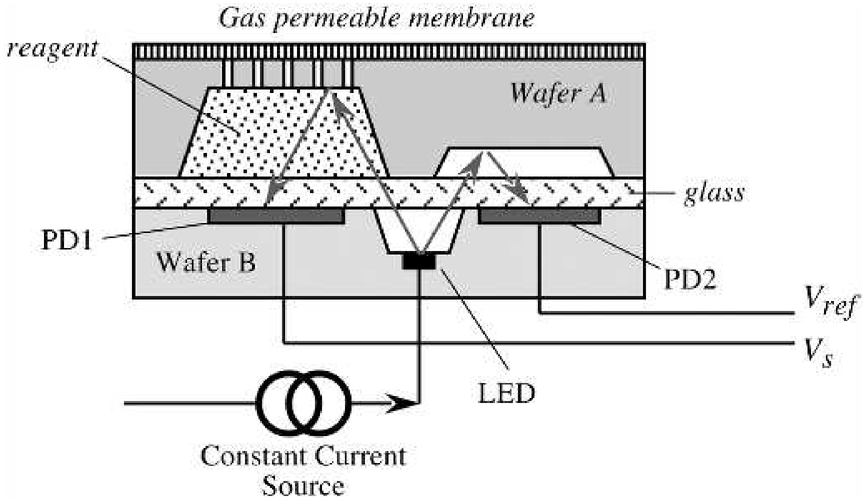


Figure 4.4: Simplified configuration of an optical CO_2 sensor [49]

are made of glass. Both wafers, A and B, form optical waveguides. The test chamber is filled with a reagent, and the reference chamber is not. The sample part of the sensor monitors the optical absorbency of a pH indicator in a dilute solution, where the optical absorbency changes in accordance with the BeerLambert law:

$$I = I_0^{-\alpha(\lambda,pH)dC}$$

where I is the transmitted intensity, I_0 is the source intensity, α is the molar absorptivity, λ is the wavelength, C is the concentration, and d is the optical path length.

4.1.4 Gravimetric methods

Chemical sensors that utilise the very small mass change from adsorbed chemical molecules to alter mechanical properties of a system are referred to as mass, gravimetric, or microbalance sensors. These are physically active devices, as no chemical reaction takes place. An acoustic gravimetric sensor can be used because it operates at ultrasonic frequencies. The idea behind the oscillating sensor is the shift in the resonant frequency of a piezoelectric crystal when an additional mass is deposited on its surface.

Another type of a gravimetric detector is a surface-acoustic-wave (SAW) sensor. The SAW is a phenomenon of propagating mechanical waves along a solid surface which is in a contact with a medium of lower density, such as air. These waves are sometimes called Reyleigh waves. As with a flextural plate, the SAW sensor is a transmission line with three essential components: the piezoelectric transmitter, the transmission line with a chemically selective layer, and the piezoelectric receiver. An electrical oscillator causes the electrodes of the transmitter to flex the substrate, thus producing a mechanical wave. The wave propagates along the transmission surface toward the receiver.

4.1.5 Conductometric sensors

An electrochemical conductivity sensor measures the change in conductivity of the electrolyte in an electrochemical cell. An electrochemical sensor may involve a capacitive impedance resulting from the polarisation of the electrodes and faradic or charge-transfer process. In a homogeneous electrolytic solution, the conductance of the electrolyte, G(Ω_{-1}), is inversely proportional to L, which is the segment of the solution along the electrical field, and directly proportional to A, which is the cross-sectional area perpendicular to the electric field: $G = \frac{\rho A}{L}$

Table 4.1 list several models of gas sensors and their target detection gas.

Table 4.1: Gas Sensors Listing by Gas Type

Gas Type	Manufacturer	Model	Optimum sensing
Oxygen	Figaro	KE50	Oxygen
	City Technology	4OX-1	Oxygen
Fuel vapours	Figaro	TGS813	Propane
	Figaro	TGS2611 (Fig. 4.5)	Methane
	Nemoto	NAP-67A	Propane
	FIS	SP-12A-00	Methane
	FIS	SP-15A-00	Propane
	City Technology	4P90M	Methane
	City Technology	IRcel CH4	Methane
Toxic Gases	Figaro	TGS2442	Carbon monoxide
	Figaro	TGS4161	Carbon Dioxide
	Membrapor	CO MF-1000	Carbon monoxide
	Membrapor	NH3 MR-1000-2E	Ammonia
	Figaro	TGS826	Ammonia
	FIS	SB-500-12	Carbon Monoxide
	City Technology	IRceLCO2	Carbon Dioxide
	City Technology	Eco-Sure (2e)	Carbon Monoxide

Other companies that produce gas sensors are :

- E2V

Figure 4.5: Figaro TGS2611 methane sensor.

- Hanwei Electronics
- Edinburgh Instruments
- Perkin Elmer
- ICXphotonics
- City Technology
- Alphasense

4.2 Smoke

The smoke inside an area where a fire is present, makes firefighting a impossible mission, since firemen can't see through the smoky areas.

4.2.1 Photoelectric detectors

Opacity is the state of being impenetrable to light. When light strikes an interface between two substances, some of the light is reflected, some is absorbed, and the rest is transmitted. An opaque substance transmits very little light, and therefore reflects or absorbs most of it.

4.2.2 Ionisation detectors

Ionisation smoke detectors use an ionisation chamber and a source of ionising radiation to detect smoke. It can detect particles of smoke that are too small to be visible. An ionisation smoke detector has a small amount of radioactive material that ionises the air in the sensing chamber, rendering the air conductive and permitting a current flow through the air between the charged electrodes. This gives the sensing chamber an effective electrical conductance. When smoke particles enter the ionisation area, they decrease the conductance of the air by attaching to the air particles.

4.2.3 Semiconductor detectors

Semiconductor detectors principle is defined in Subsection 4.1.1.

A brief survey of the commercial smoke sensors available nowadays is listed in Table 4.2.

Table 4.2: Smoke Sensors Listing

Manufacturer	Model	Type
Nemoto	NIS-5A	Ionisation
	NIS-09C	Ionisation
Hanwei Electronics	MQ-2	Semiconductor
Bosch Security	F220-P	Photoelectric
	F220-PTHC	Photoelectric
Afriso	61151	Photoelectric
Shinyei	PPD4NS (Fig 4.6)	Photoelectric

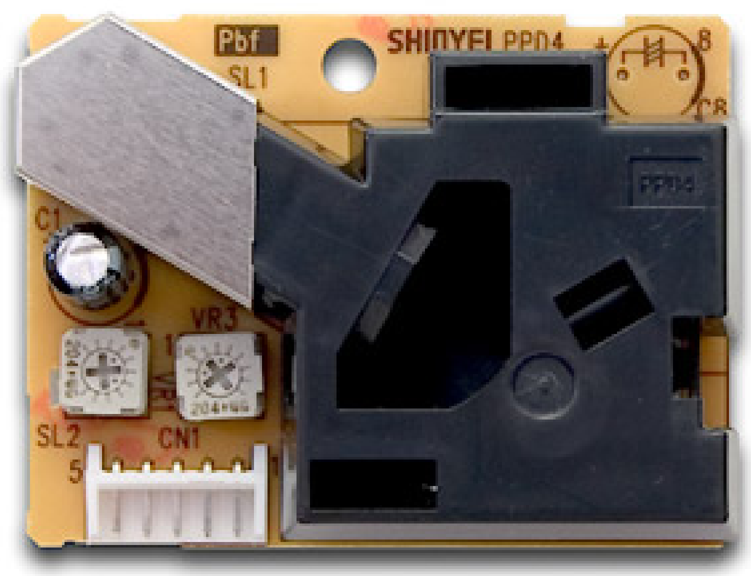


Figure 4.6: Smoke sensor - Shinyei PPD4NS

4.3 Airflow

The measurement of the airflow is usually made by anemometers. Inside a fire area it's necessary to know the flow of the air in order to know it's possible propagation.

4.3.1 Anemometers

An anemometer is an instrument used to measure wind speed / airflow. In this Deliverable we will describe some of methods able to be used in this project.

Figure 4.7: Some examples of sensors used to measure airflow - (A) Sensor from a Testo 435 anemometer; (B) Hibrid integrated circuit and sensor from Shibaura F6201-1 anemometer; (C) Commercial thermistors and signal condition circuit; (D) Tungsten wiring from a low voltage incandescent light bulb; (E) Thin film sensor from E+E Elektronik. [50]

Ultrasonic anemometer

The Ultrasonic Anemometer consists of at least 2 ultrasonic transducers which are opposite each other at known distance. The transformers act both as acoustic transmitters and acoustic receivers. When a measurement starts, a sequence of 2 individual measurements in 2 directions of the measurement paths is carried out at maximum possible speed. The measuring directions (acoustic propagation directions) rotate clockwise. Mean values are formed from 2 individual measurements, and are used for further calculation.

The speed of an air flow superposes the propagation speed of the sound in silent air. An air flow in the propagation direction of the sound supports its propagation speed, and leads to its raise. An air flow against the propagation direction, however, leads to a reduction of the propagation speed of the sound. The propagation speed resulting from the superposition leads to different running times of the sound at different air flows, and directions over a fixed distance of measurement. As the sound speed is much depending on the air temperature, the running time of the sound is measured in both directions, thus avoiding any effect of the temperature on the measuring result.

Thermal / Hot-wire anemometer

Thermal anemometers are based in the change of the heat transfer coefficient from a heated surface to its surrounding environment when the velocity of the fluid around the surface changes [51]. Sensitivity of the sensors is derived from temperature equilibrium in steady state, when electrical energy delivered to the sensor is the same as heat energy lost for cooling of the sensor, see Figure 4.8. The energy loss depends on speed of flow of the cooling medium (wind). Power delivered for the sensor heating is used for the flow speed measurement [52].

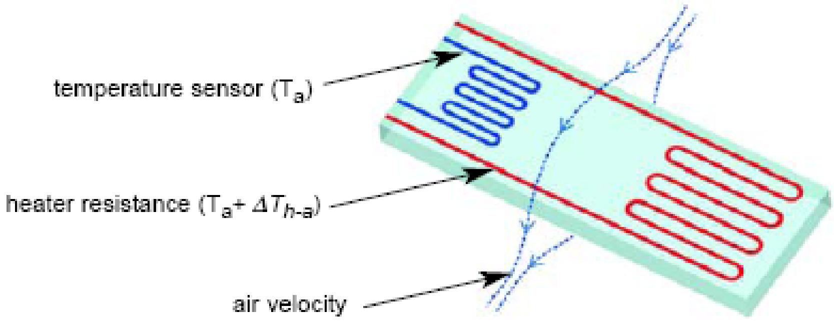


Figure 4.8: Hot-wire operating principle.

Rotating vane anemometer

This consists of a disc of angled vanes attached to a rotating spindle and is usually mounted within a protective ring and supporting bracket. The speed at which the vane assembly rotates is a measure of the air velocity acting upon it. This speed may be sensed either electronically or by a counter mechanism.

Some of the commercial sensors are listed in Table 4.3.

4.4 Temperature

Fire it's a synonym of heat. If the heat is too much, firemen cannot enter the fire area.

Table 4.3: Airflow Sensors Listing

Manufacturer	Model	Type
Vaisala	WMT50	Ultrasonic
	WS425	Ultrasonic
Shibaura	F6201-1	Thermal anemometer
Testo	435 probes	Various
Airflow Instruments	LCA301 (4.9)	Rotating vane

A variety of devices are available to measure temperature, the most common of which are thermocouples, thermistors, resistance temperature detectors (RTD), and infrared types. Thermocouples are the most versatile, inexpensive, and have a wide range ^{o}C. A thermocouple simply consists of two dissimilar metal wires joined at the ends to create the sensing junction. When used in conjunction with a reference junction, the temperature difference between the reference junction and the actual temperature shows up as a voltage potential. Thermistors are semiconductor devices whose resistance changes as the temperature changes. They are good for very high sensitivity measurements in a limited range of up to 100^{o}C. The relationship between the temperature and the resistance is nonlinear. The RTDs use the phenomenon that the resistance of a metal changes with temperature. They are, however, linear over a wide range and most stable. Infrared type sensors use the radiation heat to sense the temperature from a distance. These noncontact sensors can also be used to sense a field of vision to generate a thermal map of a surface.

4.4.1 Thermocouples

There is a relationship between the temperature of a conductor and the kinetic energy of the free electrons. Thus, when a metal is subjected to a temperature gradient, the free electrons will diffuse from the high temperature region to the low temperature region where they have a lower kinetic energy. The electron concentration gradient creates a voltage gradient since the lattice atoms that constitute the positive charges are not free to move. This voltage gradient will oppose the further diffusion of electrons in the wire and a stable equilibrium will be established with no current flow.

4.4.2 Resistance Temperature Devices (RTDs)

Some metals have a very predictable change of resistance for a given change of temperature; these are the metals that are most commonly chosen for fabricating an RTD. A precision resistor is made from one of these metals to a nominal ohmic value at a specified

Figure 4.9: Model LCA301 from Airflow Instruments.

temperature. By measuring its resistance at some unknown temperature and comparing this value to the resistor's nominal value, the change in resistance is determined. Because the temperature vs. resistance characteristics are also known, the change in temperature from the point initially specified can be calculated. We now have a practical temperature sensor, which in its bare form (the resistor) is commonly referred to as a resistance element (see Figure 4.11).

4.4.3 Thermistors

Thermistors are bulk semiconductors made from an oxide of nickel, cobalt, manganese, or other metal. The oxide is ground to a fine powder and then sintered to produce the actual thermistor material that is then incorporated into a sensor. Thermistors are resistance temperature sensing devices with several notable differences from RTDs such as their large negative temperature coefficients, and extreme nonlinear response. The resistance of a thermistor is usually so large (several thousand ohms) that lead wire resistance is rarely a concern. Thus, they are inevitably two-wire devices unless multiple thermistors or components are included in the probe. All thermistors are divided into two groups: NTC (negative temperature coefficient) and PTC (positive temperature coefficient). Only

Figure 4.10: Eltec 442-3 Pyroelectric Detector.

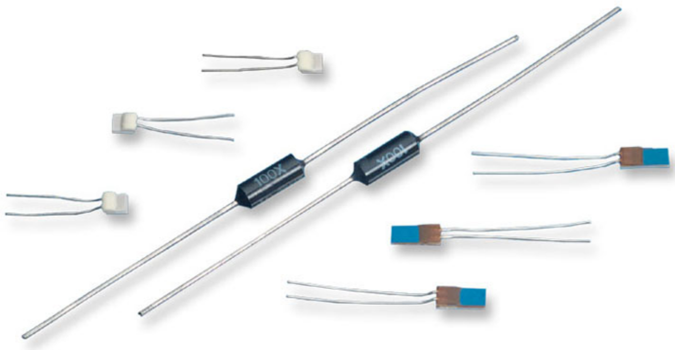


Figure 4.11: Resistant temperature devices.

the NTC thermistors are useful for precision temperature measurements.

4.4.4 Integrated Circuit Temperature Sensors

The base-to-emitter voltage drop of a transistor operating at a constant current is a simple function of absolute temperature. Thus, any transistor can be used as a temperature sensor. In reality, this is much more of a problem with building thermally stable electronics than a convenient means of measuring temperature. We can see Texas Instruments TMP102 in Figure 4.12.

4.4.5 IR Emission Thermometers

Any object above absolute zero emits electromagnetic radiation whose spectrum is related to its surface temperature and surface emissivity. By characterising the spectrum,

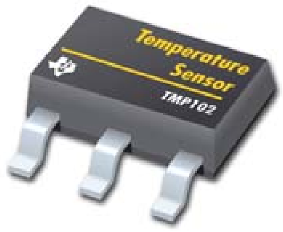


Figure 4.12: TMP102 temperature sensor in a tiny SOT563 package.

the temperature of the object can be determined directly and absolutely. The microwave background of the universe at 3K, and the temperature dependent colour of stars are extreme examples of this phenomena. Temperature can still be determined from the emitted surface without using a spectrometer. If two bodies are allowed to come into thermal equilibrium with each other and the temperature of one body is known, the temperature of the other is also known. The radiation heat transfer is also valid when two bodies are coming into thermal equilibrium. The radiant energy is a function only of the temperature of the surface.

Table 4.4 lists several temperature sensors.

Table 4.4: Temperature Sensors Listing

Manufacturer	Model
Maxim	DS60
	DS600
	MAX6605
	MAX6612
Texas Instruments	TMP102
	TMP106
	TMP175
Honeywell	HEL-705-T-0-12-00
Eltec	442-3 IR-EYE
Kube	6192
	C172
Roithner-Laser	OTC-236
	OTC-237
Melexis	MLX90614
	MLX90247

4.5 Flame

The presence and the size of the flames have to be taken in account by the firemen squad.

A flame detector responds either to radiant energy visible to the human eye or outside the range of human vision.

4.5.1 Ultraviolet detector

A Ultraviolet(UV) detector detects the presence of UV radiation. After passing through the atmosphere, sunlight loses a large portion of its UV spectrum located below 250 nm, whereas a gas flame contains UV components down to 180 nm. This makes it possible to design a narrow-bandwidth element for the UV spectral range which is selectively sensitive to flame and not sensitive to sunlight or electric lights.

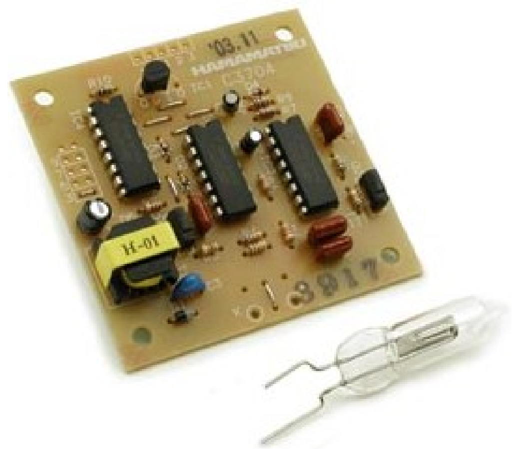


Figure 4.13: Hamamatsu UV TRON board and UV Flame Sensor.

4.5.2 Infrared detector

An infrared (IR) detector basically is composed of a filter and system used to screen out unwanted wavelengths and focus the incoming energy on a photovoltanic or photoresistive cell sensitive to infrared radiation. IR flame detectors can respond to the total IR component of the flame alone or in combination with flame flicker in the frequency range of 5 to 30 Hz.

Table 4.5 lists some of the commercial sensors able to detect flames.

Table 4.5: Flame Sensors Listing

Manufacturer	Model	Type
Devantech	TPA81	IR
Perkin Elmer	TPAM166L3.9	IR
Hamamatsu	UV Tron	UV
Spectrex	SharpEye Mini 20/20ML	UV and IR
Maier Electronics, Inc	PX series	UV

Chapter 5

Interfacing standards

5.1 Common Standards

Line drivers and receivers are commonly used to exchange data between two or more points (nodes) on a network. Reliable data communications can be difficult in the presence of induced noise, ground level differences, impedance mismatches, failure to effectively bias for idle line conditions, and other hazards associated with installation of a network.

The connection between two or more elements (drivers and receivers) should be considered a transmission line if the rise and/or fall time is less than half the time for the signal to travel from the transmitter to the receiver.

Standards have been developed to insure compatibility between units provided by different manufacturers, and to allow for reasonable success in transferring data over specified distances and/or data rates. The Electronics Industry Association (EIA) has produced standards for RS485, RS422, RS232, and RS423 that deal with data communications. Suggestions are often made to deal with practical problems that might be encountered in a typical network. EIA standards where previously marked with the prefix ”RS” to indicate recommended standard; however, the standards are now generally indicated as ”EIA” standards to identify the standards organization. While the standards bring uniformity to data communications, many areas are not specifically covered and remain as ”gray areas” for the user to discover (usually during installation) on his own [53].

Table 5.1 shows some of the major characteristics of the previously described standards.

5.1.1 Recommended Standard 232

Electronic data communications between elements will generally fall into two broad categories: single-ended and differential. RS232 (single-ended) was introduced in 1962, and despite rumors for its early demise, has remained widely used through the industry. The specification allows for data transmission from one transmitter to one receiver at relatively slow data rates (up to 20K bits/second) and short distances (up to 50Ft. @ the maximum data rate).

Independent channels are established for two-way (full-duplex) communications. The RS232 signals are represented by voltage levels with respect to a system common (power / logic ground). The ”idle” state (MARK) has the signal level negative with respect to common, and the ”active” state (SPACE) has the signal level positive with respect to common. RS232 has numerous handshaking lines (primarily used with modems), and also specifies a communications protocol. In general if you are not connected to a modem the handshaking lines can present a lot of problems if not disabled in software or accounted for in the hardware (loop-back or pulled-up). RTS (Request to send) does have some utility in certain applications [53].

RS232 was designed to single device connection, but is one of the most used communication protocols.

5.1.2 Recommended Standard 485

The 485 standards title is Electrical Characteristics of Generators and Receivers for Use in Balanced Digital Multipoint Systems. 485 is commonly used, rather than its official title. If more than one driver is required, devices conforming to 485 are recommended. 485 specifications allow only one driver to send data at a time, and up to 32 unit loads (U.L.) can be placed on the bus. The U.L. concept is described in this application report in the Selected 485 Electrical Specifications section [54].

5.1.3 I^2C - Communication Protocol

The I^2C-bus is a de facto world standard that is now implemented in over 1000 different IC's manufactured by more than 50 companies. Additionally, the versatile I^2C-bus is used in a variety of control architectures such as System Management Bus (SMBus), Power Management Bus (PMBus), Intelligent Platform Management Interface (IPMI), and Advanced Telecom Computing Architecture (ATCA) [55].

Here are some of the features of the I^2C-bus:

- Only two bus lines are required; a serial data line (SDA) and a serial clock line (SCL).
- Each device connected to the bus is software addressable by a unique address and simple master/slave relationships exist at all times; masters can operate as master-transmitters or as master-receivers.

Table 5.1: Specifications for RS232, RS423, RS422 and RS485 [53].

SPECIFICATIONS	RS232	RS485
Mode of Operation	SINGLE-ENDED	DIFFERENTIAL
Total Number of Drivers and Receivers on One Line	1 DRIVER 1 RECVR	32 DRIVER 32 RECVR
Maximum Cable Length	50 FT.	4000 FT.
Maximum Data Rate	20kb/s	10Mb/s-100kb/s
Maximum Driver Output Voltage	+/-25V	-7V to +12V
Driver Output Signal Level (Loaded Min.) Loaded	+/-5V to +/-15V	+/-1.5V
Driver Output Signal Level (Unloaded Max) Unloaded	+/-25V	+/-6V
Driver Load Impedance (Ohms)	3k to 7k	54
Slew Rate (Max.)	30V/uS	N/A
Receiver Input Voltage Range	+/-15V	-7V to +12V

- It is a true multi-master bus including collision detection and arbitration to prevent data corruption if two or more masters simultaneously initiate data transfer.
- Serial, 8-bit oriented, bidirectional data transfers can be made at up to 100 kbit/s in the Standard-mode, up to 400 kbit/s in the Fast-mode, up to 1 Mbit/s in Fast-mode Plus, or up to 3.4 Mbit/s in the High-speed mode.
- On-chip filtering rejects spikes on the bus data line to preserve data integrity.
- The number of IC's that can be connected to the same bus is limited only by a maximum bus capacitance. More capacitance may be allowed under some conditions.

5.1.4 SPI - Communication Protocol

The Serial Peripheral Interface is used primarily for a synchronous serial communication of host processor and peripherals. However, a connection of two processors via SPI is just as well possible and is described at the end of the chapter.

In the standard configuration for a slave device, two control and two data lines are used. The data output SDO serves on the one hand the reading back of data, offers however also the possibility to cascade several devices. The data output of the preceding device then forms the data input for the next IC.

There is a MASTER and a SLAVE mode. The MASTER device provides the clock signal and determines the state of the chip select lines, i.e. it activates the SLAVE it wants to communicate with. CS and SCKL are therefore outputs.

The SLAVE device receives the clock and chip select from the MASTER, CS and SCKL are therefore inputs.

This means there is one master, while the number of slaves is only limited by the number of chip selects [56].

5.1.5 CANopen

CANopen is a CAN-based higher layer protocol. It was developed as a standardised embedded network with highly flexible configuration capabilities. CANopen was designed for motion-oriented machine control networks, such as handling systems. By now it is used in various application fields, such as medical equipment, off-road vehicles, maritime electronics, railway applications or building automation. CANopen unburdens the developer from dealing with CAN-specific details such as bit-timing and implementation-specific functions. It provides standardised communication objects for real-time data, configuration data as well as network management data.

Standardised CANopen device and application profiles simplify the tasks of integrating a CANopen system. Off-the-shelf devices, tools, and protocol stacks are widely available at reasonable prices. For system designers, it is very important to reuse application software. This requires not only communication compatibility, but also interoperability and interchangeability of devices. CANopen device and application profiles enable device manufacturers to provide their products with standardised interfaces to achieve CANopen devices with ”Plug and Play” capability in CANopen networks. CANopen is flexible and open enough to enable manufacturer-specific functionality in such devices as well.

5.1.6 USB - Universal Serial Bus

The Universal Serial Bus (USB) peripheral interface has become ubiquitous across all personal computing platforms as well as many industrial and infrastructure platforms.

The release of the USB 1.1 specification combined with the native operating system support offered by Microsoft enabled the rapid adoption of USB hosts in the PC. It also drove the conversion of many peripheral devices from legacy interfaces such as serial (RS-232), PS-2 (mice and keyboards), and parallel ports (Centronix and IEEE-1284 for printers) to this common interface standard. With the release of the USB 2.0 specification enabling a higher speed connection, an even greater explosion in the number of USB peripherals available greatly enhanced the end-user experience.

The USB is a host-centric bus. In other words, the host must initiate all transfers, both outbound and inbound. The specification defines three basic types of devices: host controllers, hubs, and functions (peripherals or targets are also used interchangeably with the word function). The physical interconnect is a tiered-star topology with a hub at the center of each star. Each wire segment is a point-to-point connection between the host and a hub or function, or a hub connected to another hub or function. The addressing scheme used for devices in a USB system allows for up to 127 devices to be connected to a single host. These 127 devices can be any combination of hubs or peripherals. A compound or composite device will account for two or more of these 127 devices.

USB 2.0 is the current revision of the specification and it fully superseded USB 1.1. The beauty of USB 2.0 is that it maintained full backwards compatibility to USB 1.1 devices. However, it added a much needed third speed node, high-speed (480 Mbps), along with keeping both low-speed (1.5Mbps) and full-speed (12 Mbps) support. In July 2003, the USB On-the-Go (OTG) addendum was released defining a new class of devices aimed at portable, battery-powered devices.

USB On-The-Go (OTG)

USB OTG is an addendum to the USB 2.0 Specification that defines a new class of devices. This class of devices is intended to extend the functionality of a peripheral product to include limited host capabilities. As the name implies, the original target of the specification was portable devices with which end-users may have wanted to share data when a computer was not available. Usage examples include sharing contact information between two PDAs or cell phones, sharing pictures from one DSC or camera phone with another, or printing directly from a DSC or PDA.

Like standard USB, OTG is a point-to-point, host-centric bus and is not intended as a peer-to-peer networking connection. OTG Products must act as a standard peripheral when connected to standard USB host such as a PC. The OTG addendum mainly addresses how a device must act when it is acting as the host. Just like a standard USB host port (or downstream-facing hub port), an OTG host must supply power. However, the required supply current is limited to 8 mA. Unlike a standard USB host in a PC, an OTG device may not have a simple way to add drivers for "unrecognized" devices. Therefore, an OTG device must supply what is called a Targeted Peripheral List. This allows the device manufacturer to specify exactly what devices they will support. The specification also requires some type of messaging display to enable communicating to the end-user that an unsupported device has been plugged in and that it will not work. This messaging can be as simple as an LED or as complex as a text display. In addition, two new protocols were defined as part of the OTG addendum. Host Negotiation Protocol (HNP) defines a method for dynamic switching between host and device roles. Session Request Protocol (SRP) enables a method for bus power to be turned off/on at the discretion of the host device.

5.1.7 Protocol Comparison

Table 5.2 presents a brief comparison between various communication protocols.

Table 5.2: Comparison of popular computer interfaces [57].

Interface	Format	Number of Devices (max)	Distance (max, feet)	Speed (max, bits/sec.)	Typical Use
USB	asynchronous serial	127	16 (up to 96ft. with 5 hubs)	1.5M, 12M, 480M	Mouse, keyboard, drive, other standard and custom peripherals
Ethernet	serial	1024	1600	10G	General network communications
IEEE-1394b	serial	64	300	3.2G	Video, mass storage
I^2C	synchronous serial	40	18	3.4M	Microcontroller communications
Microwire	synchronous serial	8	10	2M	Microcontroller communications
drives					
RS-232	asynchronous serial	2	50-100	20k (max. 115k)	Instrumentation
RS-485	asynchronous serial	32 (max. 256)	4000	10M	Data acquisition and control systems
SPI	synchronous serial	8	10	2.1M	Microcontroller communications

5.2 IEEE 1451.x - A Standard for Smart Sensors

An IEEE 1451 smart transducer is defined as a smart transducer that provides functions beyond those necessary for generating a correct representation of a sensed or controlled quantity. This functionality typically simplifies the integration of the transducers into applications in a networked environment. This means IEEE 1451 smart transducers would have capabilities for self-identification, self-description, self-diagnosis, self-calibration, location-awareness, time-awareness, data processing, reasoning, data fusion, alert notification (report signal), standard-based data formats, and communication protocols [58].

The IEEE 1451 set of standards was developed to unify the diverse standards and protocols by providing a base protocol that allows interoperability between sensor/actuator networks and buses [59].

In the IEEE 1451 family, the IEEE 1451.0 standard defines a common set of commands for accessing sensors and actuators connected in various physical configurations, such as point-to-point, distributed multi-drop, and wireless configurations, to fulfill various application needs. There are three possible ways to access sensors and actuators in the Transducer Interface Module (TIM) from a network.

They are :

- IEEE 1451.1 Network Capable Application Processor (NCAP) Information Model Description,
- IEEE 1451.0 Hyper Text Transfer Protocol, and
- the proposed Smart Transducer Web Services.

The physical interfaces between the Network Capable Application Processor and TIM include the following:

- the point-to-point interface that meets the IEEE Standard 1451.2-1997,
- the distributed multi-drop interface that meets the IEEE Standard 1451.3-2003,
- the wireless interface that meets the IEEE Standard 1451.5-2007 (WiFi, Bluetooth, and ZigBee),
- the CANopen interface that meets the proposed IEEE P1451.6 standard, and
- the Radio Frequency Identification (RFID) interface that meets the proposed IEEE P1451.7 standard.

A brief description of the IEEE 1451 Standards that concern communication will follow.

5.2.1 IEEE 1451.2

The IEEE 1451.2 standard defines a transducers-to-NCAP interface and TEDS for point-to-point configurations. Transducers are part of a Smart Transducer Interface Module. The original standard describes a communication layer based on the Serial Peripheral Interface, with additional hardware lines for flow control and timing resulting in a total of 10 lines for the interface. This standard is being revised to interface with IEEE 1451.0 and to support two popular serial interfaces: UART and Universal Serial Interface.

5.2.2 IEEE 1451.5

The IEEE 1451.5 standard defines a transducer-to-NCAP interface and TEDS for wireless transducers . IEEE 1451.5 specifies radio-specific protocols for achieving this wireless interface. Wireless standards such as 802.11 (WiFi), 802.15.1 (Bluetooth), 802.15.4 (ZigBee), and 6LowPAN are adopted as the IEEE 1451.5 wireless interfaces. The NCAP is a device that contains one or more wireless radios (802.11, Bluetooth, and ZigBee) and that can talk to one or more Wireless Transducer Interface Module (WTIM). Each WTIM contains one wireless radio (802.11, Bluetooth, or ZigBee), signal conditioning, A/D and/or digital-to-analog conversion, and the transducers. The NCAP can wirelessly talk to each WTIM using different wireless protocols, such as 802.11, Bluetooth, or ZigBee, and it may also be connected to an external network.

5.2.3 IEEE P1451.6

The IEEE P1451.6 standard defines a transducer-to-NCAP interface and TEDS using the high-speed CANopen network interface. Both intrinsically safe and nonintrinsically safe applications are supported. It defines a mapping of the 1451 TEDS to the CANopen dictionary entries, as well as communication messages, process data, a configuration parameter, and diagnostic information. It adopts the CANopen device profile for measuring devices and closed-loop controllers.

5.2.4 IEEE P1451.7

The IEEE P1451.7 standard defines an interface and communication protocol between transducers and RFID systems. By providing sensor information in supply-chain reporting, such as identifying products and tracking of their condition, the standard opens new opportunities for sensor and RFID system manufacturers [58].

Chapter 6

Conclusions

Given the GUARDIANS mission and target operating environment, three platforms and a limited set of navigation and mission sensors were selected and their characteristics are summarised below. The platforms considered in this report were more or less defined before the beginning of the project. These are the Khepera III for tests in small scale scenario, and the Erratic and the Rescuer platforms for operation in realistic scenarios.

6.1 Platforms

The target Guardians environment is made by flat terrain, large corridors defined by mainly regular obstacles.

6.2 Sensors for navigation

Given the problems placed by the smoke encountered in the GUARDIANS environment, several sensors should be added to improve the navigation capabilities of the platforms employed. This problem of reduced visibility is not yet solved, but is being address with some of the non-optical sensors described in chapter 3.

6.2.1 Odometry

The three platforms employed by the project consortium are equipped with optical encoders attached to the driving motors. With this, it will be possible to estimate the platform displacement.

6.2.2 Inertial systems

An inertial measuring unit (IMU) can be an useful sensor system to improve the odometry results. Considering this aspect, Xsens Technologies produces some inertial sensors that are useful for the Guardians purpose. The MTx is a small and accurate 3DOF Orientation Tracker. It provides drift-free 3D orientation as well as kinematic data: 3D acceleration, 3D rate of turn (rate gyro) and 3D earth-magnetic field.

6.2.3 Laser Range Finders

Laser Range Finders can be useful to test some navigation concepts inside the project. Given its size and wide availability of drivers, the Hokuyo LRF can be a useful sensor to test navigation concepts.

6.2.4 Sonars

Sonars can be very useful for the project, since they are not affected by smoke and so, they can be the obstacle sensors of choice. Both the Khepera III and the Erratic platforms come equipped with an array of Murata-based sonars.

6.2.5 Microwave radars

It seems that there are no MMW radar systems commercially available to be used in the Guardian project. Even though, there are huge efforts being spent in the development of MMW radar for driving assistance in cars and so in the near future it is expectable that those systems appear on the market.

6.2.6 Contact sensors

Micro switches, whiskers, and tactile sensors are described in chapter3. Only the Erratic platform carries micro-switch-based bumpers, but this option can be very useful and its utilization is advisable in the future. Artificial whiskers can be very useful sensors for the Guardians platforms. There are no commercial devices of this type, but during the project development this type of sensors should be researched and developed in order to allow using them in the project (e.g. for wall following).

6.3 Mission sensors

Several target analytes need to be detected by the mission sensors as described in the Deliverable 1.1/2 - Description of the Warehouse Search Scenario and User Requirements Document.

The following devices will be developed in order to cover some of the User Requirements Document needs.

6.3.1 kheNose

kheNose (Figure 6.1) is a Smart Transducer developed by ISR - University of Coimbra. It includes five gas sensors, three anemometers for air flow estimation and one sensor capable of measuring the temperature and the humidity of the environment. It is able to actuate four output ports for general purpose actions.

This device is intended to be used in Khepera III mobile robots and includes the I^2C communications protocol.

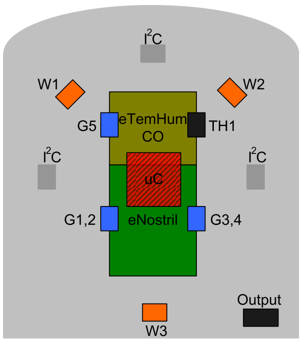


Figure 6.1: Diagram of the kheNose device.

The developed Smart Transducer, according to the IEEE 1451 Standards for a Smart Transducer Interface for Sensors and Actuators, intends to firstly interact with a Khepera III mobile platform and after to be compliant with other NCAP's, like Erratic platform.

6.3.2 ISRNose

ISRNose is an upgrade of kheNose. This upgrade will maintain the best characteristics of the kheNose and add more communication capabilities in order to be used with the Erratic and Rescuer mobile platforms.

6.3.3 Smoke

Smoke detection will be carried using the Shinyei PPD4NS photoelectric detector. Some of it's major characteristics are:

- stable and sensitive
- dual output for particles over 1 micron and 2.5 micron
- pulsed output

6.3.4 ThermalSkin concept

ThermalSkin is a biomimetic thermal anemometer to measure airflow intensity and direction around solid structures. The common thermal anemometers are point devices that only allow to measure the airflow intensity. On the other way, the surfaces of solid structures disturb the fluid flow in such a way that usually, measuring the velocity in different points around those structures allow to estimate an average airflow vector around the structure.

This device behaves like a directional anemometer that could be easily added to the robot surface without changing too much the robot shape and aerodynamics.

The ThermalSkin airflow sensing system is based on the information provided by a network of small thermal anemometers (thermal ”scales”) placed around an airflow deflecting structure [51].

6.3.5 Temperature/Flame Detection

The temperature, and consequently the flame detection, will be carried by a TPA81 Thermopile Array sensor that detects infra-red radiation in the 2um-22um range. This sensor has a very wide detection angle/field of view of 100 degrees and it can measure the temperature of 8 adjacent points simultaneously.

6.4 Interfacing standards choice

The chosen mobile platforms for the GUARDIANS system include the following protocols listed in Table 6.2.

As we can see, all the platforms are able to communicate through USB and Wi-Fi, wich means that the interfaces chosen for this system should be mostly USB. There are some external hardware capable of converting other protocols to USB, like RS232, CAN and I^2C.

Platform	Size (cm)	Weight(kg)	Payload (kg)	Max. Speed (m/sec)	Autonomy
Eratic	40x41x15	4.5(base) 12(+ batteries) 12.9(+computer, sonar) 13.9(+Hokuyo LRF, pan/tilt, STOC)	20	2.0	
Khepera	Diameter:13 Height:7	.69	2	0.5	8h
Rescuer	110x78x60	250	200	1.25	8h

Table 6.1: Comparison table of the mobile platforms

Table 6.2: Protocols for the GUARDIANS mobile robots

Platform	I^2C	SPI	USB	RS232	CAN	IEEE-1394b	Ethernet	Wi-Fi	Other
Khepera III	X	X	X	X	X			X	X
Erratic			X			X	X	X	
Rescuer			X		X		X	X	

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