Int. Conf. AUTOMATICS AND INFORMATICS 2003
October 6-8, 2003, pp. 95–98, Sofia, Bulgaria.

COMMUNICATION BETWEEN KHEPERA MINI ROBOTS FOR COOPERATIVE POSITIONING

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Abstract: For implementing efficient cooperative behaviour strategies of a group of robots an appropriate communication system is needed. Depending on the robot's task different communication techniques may be used. We have analyzed an ultrasonic detection and communication system, a communication technique that uses infrared transmitters and receivers and a radio based system using Bluetooth technology. In addition a passive vision system for cooperative robot recognition and positioning has been analyzed. For each system we have developed particular sensor and communication components, that can be used for experiments. As a platform for embedding and testing our hardware we use the mini robot Khepera.

Keywords: communication, infrared, ultrasonic, radio, cooperative positioning, Khepera

1. Introduction

When several robots work together in a cooperative way communication facilities are important. The exploration of space, land, or, especially, hazardous environments is a task for which robots are ideally suited. This implies that the machines must be capapable of a kind of intelligent behaviour. Based on their perceptions, they have to make decisions autonomously in every situation [1]. When a task is accomplished by one robot only it may take a long time for finalizing a certain job on the one hand. On the other hand the success of a task may be vulnerable if the one available robot fails. A solution is a team of cooperating robots working together whereas every robot may be relatively simple. But by acting in cooperation they can achieve altogether large efficiency.

The basis for coordinated behaviour of a group of robots is cooperative positioning, that enables the robots to navigate precisely through their environment and to build detailed maps that represents the robots surrounding. The positioning including distributed exploration and the map building is especially important for save detection of landmines [3]. In this paper we consider positioning systems for teams of autonomous mini robots Khepera. Typically, autonomous systems are supplied by batteries. Hence, we have to manage these resource economically. Furthermore, there are limitations in weight and space for the computing device. By considering these boundary conditions we have analyzed and implemented various sensing and communication techniques for distributed positioning. These are an ultrasound-based [6] technique, active and passive infrared based sensor systems [11], [2], [12] and cheap vision approaches [8] for the cooperative localisation. For high data rate and wide range communication in respect of robot's size a radio based system utilizing Bluetooth technology is developed for usage on the mini robot Khepera.

2. Robot platform and test environment

As a test platform for integration and testing developed algorithms the mini robot Khepera is used. The Khepera, in its basic configuration, consists of two printed circuit boards each measuring 55 mm in diameter [4]. The bottom PCB contains the rechargeable batteries and two DC motors with incremental encoders. Eight infrared sensors are implemented for obstacle recognition. The core component of the second printed circuit board is a Motorola MC68331 microcontroller, running at 16.7 MHz and possessing 256 Kbyte RAM as well as a maximum of 256 Kbyte ROM. The K-Extension bus opens up a wide variety of modular expansion options. Figure 1 depicts the Khepera with additional active infrared communication module.

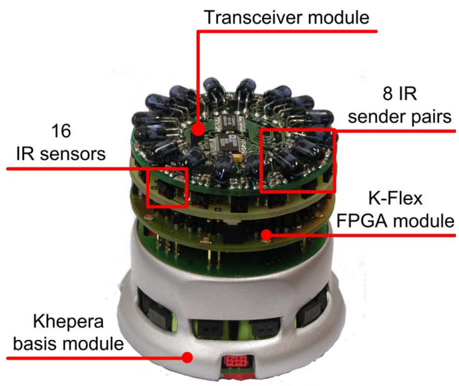

Fig. 1. Mini robot Khepera equipped with active infrared communication module.

3. Detection of landmarks

Global positioning information can be achieved by detecting outstanding landmarks that are available naturally in the environment or the landmarks are artificial like beacons as used in navy navigation. We have analyzed both approaches. First, a visual environment sensing for getting position information is used. In this case a team of robots estimate their positions in a cooperative way. Second, we present a infrared based beacon sensing and positioning system with artificial beacons or landmarks in the robot's environment.

3.1. Visual environment sensing

The linear vision sensor that is used on the mini robot has a flare angle of 36° with a resolution of 64 pixels (8 bit greyvalues) [8]. Each robot is covered with a black cylinder which results in a huge contrast in the image. In order to distinguish the distance and direction to the object, a preprocessing is carried out. Firstly, a gradient G_i of the original image B_i is calculated ($G_i = B_i - B_{i+1}$) and subjected to a noise

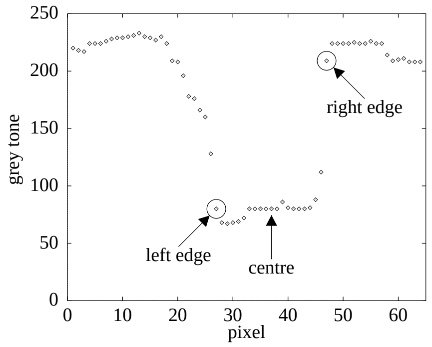

Fig. 2. Picture of a black cylinder in view of the robot as sub-symbolic vision data.

suppressing threshold ($|G_i| < 20 \rightarrow G_i = 0$), which allows the detection of the right and left edges of the object, thereby permitting the identification of the robot. The result of this operation on a typical image is shown in (fig. 2). Every image is the average of 10 recordings; if in at least 4 recordings the system fails to identify two edges, the process is stopped. With respect to the gradient, the width of the image of the cylinder is calculated. Subsequent the distance is distinguished. The angle to the cylinder is the outcome of centre (fig. 2). Note that due to the diameter of the utilised landmarks (about 4.8 cm) and the flare angle of the camera (36°), a minimal operating distance of 10 cm is necessary.

3.2. Position estimation

In the case that the robots can identify each other, they can synchronise their relative positions in a common used map. The other case is a bit more complicated because each robot has to identify itself within a lot of possible positions. Therefore each estimated position of a robot is broadcasted to all robots including the robot's ID and the change of the positions since the last message. Each robot compares the estimated path with the its own from the optometrical path integration [7]. If the travelled distance calculated from both systems is the same, the robot will adapt its position (fig. 3) and adjust it with the other robots. Therewith a positioning accuracy of 2.6 cm within a distance of up to 1.5 m is achieved. Utilising this positioning system only one robot needs the capability to detect other robots. Admittedly, the accuracy will increase with the number of robots with these capabilities.

3.3. Infrared environment sensing

The infrared environment scheme uses active infrared emitting beacons that are distributed in the robot's environment. In our case we use four beacons (fig. 4) emitting light pulses in a non overlapping timing scheme.

Main component for information processing to determine the position and the orientation of the robot is a self-organizing feature map [5]. We use a map size of 64 × 64 Neurons with a vector dimension of 6. Aim of the training process of the map is the learning of the relation of a detected sensor pattern and corresponding position and orientation of the robot. The global positioning is performed by analyzing the received beacon light by off-line trained self-organizing maps. The beacon light is received by a sensor array of 32 photo transistors on the top of the robot (fig. 5). The relation between the detected light pattern and the accompanying position and direction of the robot is trained off-line and the resulting self-organizing maps are stored in the robot for online use. The advantage of this positioning system is that the beacons may be distributed randomly in the environment and that the computational load for analyzing the sensor

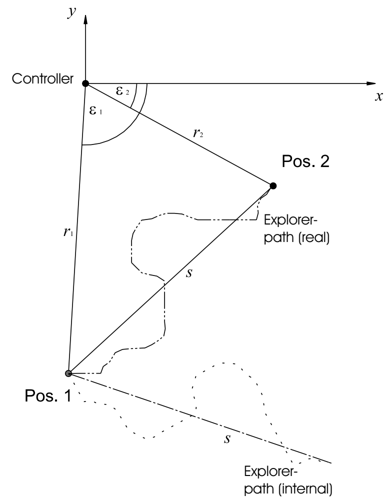

Fig. 3. Illustration of the adjustment of the position between two robots. The one with the sensor system is called "Controller", whereas the other is called "Explorer".

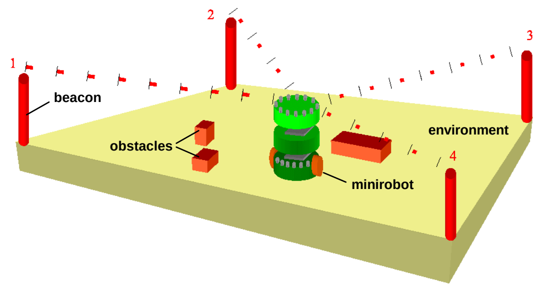

Fig. 4. Schematic environment with obstacles and four beacons sending characteristic light pattern.

data is growing linearly with number of beacons only.

4. Environment sensing and communication using an active infrared module

The infrared sensor system used here is a facet eye consisting of 16 sending and 16 receiving elements having a horizontal field of view of 360 degrees as depicted in fig. 1. The outputs of the eight infrared detectors form an eight dimensional signal vector, with each component having a resolution of 8 bit. The signal vectors depend on the distance and the orientation of the robot in relation to the object to detect. To extract the spatial information from the signal vectors an adaptive method is employed. Therefore, the robot is equipped with a two-dimensional feature map with square grid geometry ($N \cdot M$ neurones). The map organizes itself entirely on the basis of the information contained in the incoming signal vectors [2].

To receive information about objects in the environment the map is considered in recall phase, where each neuron receives the same input vector and compares it with its parameter (weight) vector. The neurone, which is most similar to the input vector is the winning neurone and represents the position of the object. So the position of robots which are equipped with the same sensor system can be estimated.

For communication via infrared the IR communication module in fig. 1 is used in a bidirectional mode. With this module the mini robot Khepera is capable of transmitting and receiving simultaneously in eight sectors (directions) with different transmission powers. Incoming signals are detected by searching for a known synchronization preamble. The

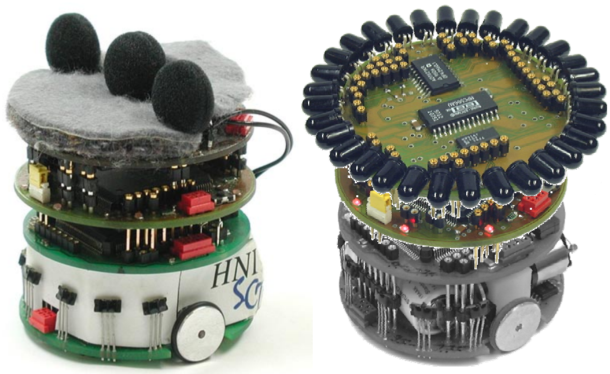

Fig. 5. Mini robot Khepera with ultrasonic module (left) and infrared module (right).

most undistorted infrared light pulse is selected by a simple minimum search and used to synchronize the receiver clock. The direction-of-arrival (DOA) of the signal is extracted by searching for the focal point of the sensor array response. Our experiments with a prototype implementation have shown that the error of the DOA estimation is below 10°. However, mathematical and simulative analysis reveal that parallel transmissions and receptions in adjacent sectors at the sender and receiver reduce the packet delivery ratio by about 30-40%. Therefore, our current research concentrates on medium access control (MAC) schemes that perform an appropriate channel scheduling in these situations [12].

5. Ultrasonic environment sensing

Ultrasonic sensors enable mobile autonomous systems to obtain information about obstacles in large environments. Regarding the limited resources of mini-robots piezo-ceramic ultrasonic transducers—two receivers with one transmitter in their middle—are evenly spread over a distance of 5 cm [6]. The two receivers enable two-dimensional impressions of the surroundings. Deviating from the pulse echo measurement techniques used so far the time-continuous transmitting and receiving from modulated pseudo-random sequences are regarded. Thus the narrow bandwidth of a piezo-ceramic transducer can be compensated by an increased measuring period.

Due to the limited bandwidth and the centre-frequency of the ultrasonic transducers, the pseudo-random sequence spectrum has to be shifted. The transmitted signal has approximately a centre-frequency of 40.2 kHz and a bandwidth of 25.6 kHz. The sequence is continuously transmitted and simultaneously received, which ensures an uninterrupted perception. Similar to the sense of vision of humans it is possible to evaluate an average impression of the environment with ≈ 28.6 cycles per second.

For the analysis the average time-of-flight (τ) of both received signals, the time difference between them ($\Delta\tau$) and their correlation with the transmitted signal has to be regarded. The position of the obstacle is given in cylindrical polar coordinates (ρ, φ) and results in:

$$\rho \approx \frac{c \cdot \tau}{2} \qquad \varphi \approx \arcsin\left(\frac{c \cdot \Delta\tau}{q}\right) \tag{1}$$

The resolution of the system is for the angle (φ) 1.5° and for the distance (ρ) 0.73 mm. Objects can be detected up to a distance of $\rho_{max} = 1.5$m within a sector of ±60°. It should be remarked, that it is additionally possible to evaluate the intensity, spectrum and frequency changes e.g. Doppler shift of the received signals in order to obtain more information about an object.

Further on the knowledge of codes from other robots will permit communication between each other and also the bearing of their position is possible. For a communication it is necessary to differ between to states (0 and 1) which are the normal and the inverted sequence. This will result in a positive or negative outcome of the correlation. With the here described implementation a transfer rate of 28.6 bit/s for each channel is possible. The bearing to another robot is gained from the time-of-flight-difference between received signals of the two receivers. The combination of these information with the detected objects gives the position of the located robot.

6. Communication using Bluetooth

Bluetooth is a well defined standard for short-range radio communication capable of transmitting voice and data, intended to replace cables that connect personal electronic devices, such as PDAs, laptops, wireless headsets and printers [13]. Key features are its robustness, low complexity, low power emission, low cost and universality. It operates in the globally available, license free ISM band at 2.4 GHz. Since this frequency band shared by other devices there are some restrictions for use of ISM band. Spectrum spreading must be employed to reduce risk of interference; Bluetooth has Frequency hop spread spectrum (FHSS), the transmission frequency changed periodically. This feature of FHSS gives robustness against interference and fading. Bluetooth standard defines 79 frequencies for communication. The nominal hop rate is 1600 hops per second. Channel bandwidth limited to 1 MHz ($2402 + k$ MHz, $k = 0, 1, ..., 78$); in Bluetooth the band extends from 2400 to 2483.5 MHz and is divided into 1 MHz-spaced channels. Bluetooth supports an asynchronous data channel or up to three simultaneous synchronous voice channels or a channel which simultaneously supports asynchronous data and synchronous voice. For data channel transmission rate is 721 kbit/s (asymmetric), and for voice channel 64 kbit/s.

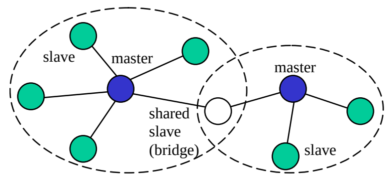

Fig. 6. Architecture of an example Scatternet.

In Bluetooth networks devices communicate using a master-slave structure. There are two basic form; piconet and scatternet. In form of piconet there is one master which is able to communicate up to 7 slaves. Slaves can not communicate directly, communication between slaves realized with the help of the master. Multiple piconets may cover the same area. Since each piconet has a different master, the piconets hop independently, each with their own channel hopping sequence and phase as determined by the respective master. In addition, the packets carried on the channels are preceded by different channel access codes as determined by the master device addresses. As more piconets are added, the probability of collisions increases; a graceful degradation of performance results as is common in frequency-hopping spread spectrum systems.

If multiple piconets cover the same area, a unit can participate in two or more overlaying piconets by applying time multiplexing. A Bluetooth unit can act as a slave in several piconets, but only as a master in a single piconet: since two piconets with the same master are synchronized and use the same hopping sequence, they are one and the same piconet. A group of piconets in which connections consists between different piconets is called a scatternet. A master or slave can become a slave in another piconet by being paged by the master of this other piconet, fig. 6. On the other hand, a unit participating in one piconet can page the master or slave of another piconet. Since the paging unit always starts out as master, a master-slave role exchange is required if a slave role is desired.

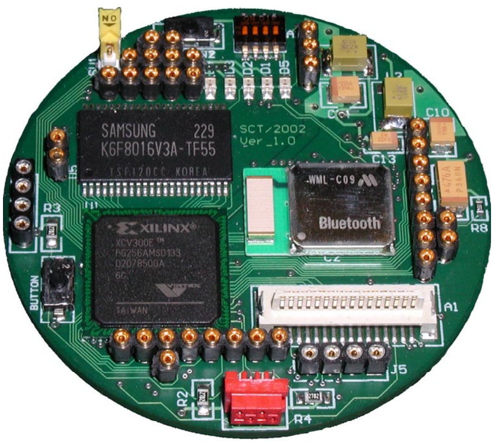

Fig. 7. Khepera FPGA module with bluetooth component.

For using Bluetooth communication technique in our robot environment with mini robot Khepera we have developed a multi purpose FPGA turret that can be equipped with a Bluetooth module with integrated baseband processing and integrated antenna. The FPGA module integrates the following components:

- Xilinx FPGA XCV300E-6
- SRAM 512 K × 16 bit
- FLASH memory 4 M × 8 bit
- Xilinx CPLD XCR3256XL-7

During start-up the FPGA is configured by the control logic via CPLD with data read from FLASH memory. Only a quarter of this memory is used for configuration data, the remaining memory is available for user applications. Like in our first FPGA module [9] the FPGA may run various algorithms, depending on the task [10]. The FPGA uses a clock frequency up to 60 MHz. Necessary communication between the mini robot's micro-controller and the Bluetooth module is handled by the FPGA, too. By equipping the Khepera with the Bluetooth module we can enable fast communication channels as depicted in fig. 6. The team of robots is able to communicate status data and position information. In addition, in our next software release we will be able to transmit camera data to a host computer that is helpful for debugging. The Bluetooth component that we use together with the FPGA module is a Mitsumi class 2 module with a CSR BlueCore chip and an integrated antenna. A communication range of up to 10 meters can be achived with a current consumption a typically 60 mA. By using a class 1 module with increased output level the range can be enhanced up to 100 m, but in this case the life time of the robot is significantly reduced due to the limited battery power.

7. Conclusion

To perform an efficient solution of a cooperative task, communication between the individual robots is essential. Therefore, we have introduced these different types of communication systems which are partly also able to locate other robots. The combination of the sensor and communication system should be chosen in consideration of the limited resources. The ultrasonic module provides an accurate positioning and identification capabilities, but with 28.6 bit/s it is restricted in terms of communication. The infrared sensor system provides a data rate of 23.4 kbit/s, but its position estimation is less accurate. The bluetooth module is the best module for communication (721 kbit/s), but it needs an additional module for the environment sensing. Therefore, the linear vision module could be used, because a passive sensor system requires less energy then an active one.
Eventually, we have shown a very flexible evaluation system for the design of a cooperative robot platform which should be able to explore an unknown environment under different situations. For example, the vision system could not be used in the dark where as the infrared system gets problems with glare sun light.

Acknowledgement

This work has been partly supported by the DFG-Sonderforschungsbereich 376 "Massive Parallelität" (M. Grünewald), and it is partly a result of common research under DFG-BAS Project "Robot Cooperation Behavior Control Based on KHEPERA micro-robots", 2003, during the visit of Dr. O. Manolov at the Department of System and Circuit Technology, Heinz Nixdorf Institute, University of Paderborn. O. Orhan is a PhD fellow in the International Graduate School "Dynamic Intelligent Systems" at University of Paderborn supported by the Ministry of Education, Science, and Research of the state NRW, Germany.

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