A MULTIROBOT SYSTEM FOR DISTRIBUTED SENSING

Janne Haverinen, Anssi Kemppainen, Janne Kivijakola and Juha Röning
Department of Electrical and Information Engineering, University of Oulu, Finland

Keywords: Multi-robot system, distributed sensing, laser, range sensing.

Abstract: This paper presents a modular multirobot system developed for distributed sensing experiments. The multirobot system is composed of modular small size robots, which have various sensor capabilities including a color stereo camera system and an infrared based sensor for infrastructure independent relative pose estimation of robots. The paper describes the current state of the multirobot system introducing the robots, their sensor capabilites, and some initial experiments conducted with the system. The experiments include a distributed structured light based 3-D scanning experiment involving two robots, and an experiment where a group of robots arrange into a spatial formation and measures distributions of light and magnetic field of an environment. The experiments demonstrate how the proposed multirobot system can be used to extract information from the environment, and how they can cooperatively perform non trivial tasks, like 3-D scanning, which is a difficult task for a single small size robot due to limitations of current sensing technologies. The distributed 3-D scanning method introduced in this paper demonstrates how multirobot system's inherent properties, i.e. spatial distribution and mobility, can be utilized in a novel way. The experiment demonstrates how distributed measurement devices can be created, in which each robot has an unique role as a part of the device, and in which the mobility of the robots provides flexibility to the structure of the measurement system.

1 INTRODUCTION

The miniaturization of mobile robots (Floreano and Mondada, 1998; Caprari et al., 2000; Sibley et al., 2002; Colot et al., 2004; Mondada et al., 2004) is rapidly progressing due to developments in electronics and material technology, for example. Multirobot systems composed of a group of miniaturized robots can have numerous applications in the future. They may be a regular sight on space expeditions or they may operate inside the human body for our well being. At present, multirobot systems are a rear sight in real world applications. However, they have already been used in surveillance applications, military demonstrations, and in distributed sensing applications. The distributed sensing is an interesting application domain as the multirobot system is inherently spatially distributed. As this paper shows, the spatial distribution of robots can be naturally utilized to overcome problems that the miniaturization of the robots introduces to the sensing technology in some problem domains. As an example, we will show how a multirobot system can be used as a distributed structured light based scanning device for extracting 3-D information from an environment. The distributed 3-D scanning concept is useful in applications where a group of robots needs to extract objects' geometrical information in remote locations without a requirement that a single robot must carry alone the necessary technology for performing the range measurements (Lee and Song, 2005).

An other experiment, which demonstrates the feasibility of the proposed multirobot system, shows how robots can be driven into a given spatial formation, and used to automatically perform measurements about illumination and magnetic field of the environment.

This paper briefly introduces the developed multirobot system and its sensor capabilities. Then, two experiments are briefly presented in order to demon-

Haverinen J., Kemppainen A., Kivijakola J. and Röning J. (2007).
A MULTIROBOT SYSTEM FOR DISTRIBUTED SENSING.
In *Proceedings of the Fourth International Conference on Informatics in Control, Automation and Robotics*, pages 137-142
DOI: 10.5220/0001649601370142

strate how the system can be used in interesting real world applications. The multirobot system is composed of miniature mobile robots first introduced in (Haverinen et al., 2005). Each robot can have various sensor capabilities including a color stereo camera system and an infrared based sensor for relative pose estimation (Kemppainen et al., 2006). The experiments are conducted by combining these sensor capabilities (modules) to form both heterogeneous, and homogeneous teams of robots.

2 THE MULTIROBOT SYSTEM

The presented multirobot system is composed of modular miniature mobile robots (Haverinen et al., 2005). One configuration of an individual robot is shown in Fig. 1. In addition to DC-motor (actuator) and power modules, the robot in Fig.1 has four other modules, which are (from top): the IR-location, the stereo camera, the radio, the environment, and the IR-proximity modules, respectively. Each of these modules provide an well defined serial interface for reading or writing data. All modules have an 8-bit low power 8MHz MCU (ATmega32), which implements the serial interface for accessing the module services, and controls the logic of the module.

Each module can have from one to three different serial interfaces (UART,I2C,SPI). While the UART interface is mandatory for each module, I2C and SPI interfaces are optional, and they are used for enhancing the bus performance. Each module with more than one interface can be commanded to switch between interfaces in order to adapt the bus performance.

The infrared based location module (Kemppainen et al., 2006) is used to estimate the relative poses of robots without external infrastructures such as beacons, WLAN base stations, GPS or landmarks. The operation principle of the location module is based on omni directional amplitude modulated infrared transmission and an infrared receiver that utilizes a rotating beam collector for finding the direction of the infrared transmission. The detected modulation frequency at the receiver identifies the transmitting system. Each location module has an unique transmission modulation frequency, which gives identity for each robot having the location unit.

By having the module, the robot can have estimated poses of the surrounding robots within five meters without any external infrastructure. The infrared location module is utilized in the experiments where robots must be driven into specific formations prior distributed sensing procedure. The module can also be utilized to maintain and adapt formations during a task execution. The infrared location module is used in all experiments described in this paper. In the 3-D scanning experiment the location module provides the necessary information to arrange the robots into given line formation prior the scanning procedure. In distributed sensing experiments, the module is used to setup the initial measurement formation (see Fig. 6), and to maintain the formation during the measurement procedure. Fig. 2 demonstrates how the location module can be used to estimate the poses of the surrounding robot. In Fig. 2 the robot at $(0,0)$ estimates the poses of the two other robots for a short period of time. Only the (x,y)-coordinates of the located robots are shown (heading is not plotted). See (Kemppainen et al., 2006) for more detailed description of the IR-location module.

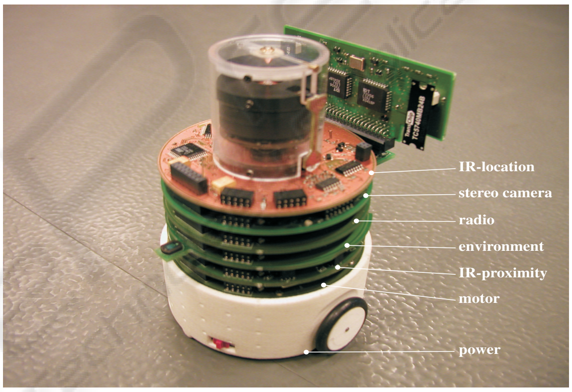

Figure 1: One configuration of the miniature robot. This robot has four modules in addition to motor and power modules. The modules include: the IR-location, the stereo camera, the radio, the environment, and the IR-proximity modules. The environment module is used to measure accelerations, temperature, ambient lighting, and the direction and magnitude of the magnetic field. The radio module implements the 868MHz 100kbits radio link for inter robot and PC communication. The purpose of the motor module is to control the two DC-motors of the robot. The power module is responsible of recharging the battery and providing the power for all modules through the module bus.

3 EXPERIMENTS

The purpose of the presented experiments is to demonstrate different strategies of using the multi-robot system for distributed sensing. The first experiment shows how a pair of heterogeneous robots can be used as unique parts of a distributed measurement device, and how system's inherent mobility can be utilized to provide a measurement device that has the necessary flexibility of adapting measurement geometry to the structure of the environment. The sec-

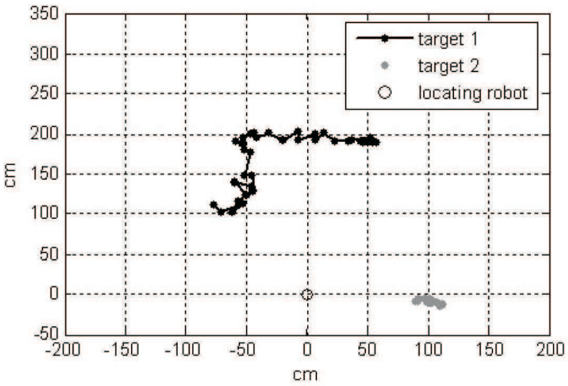

Figure 2: The infrared location system provides the pose estimates for two robots. The robot at $(0,0)$ is locating the two other robots for a short period of time.

ond experiment shows how a team of homogeneous robots can create a map of environment by moving in a given formation and by making point measurements about ambient lighting and magnetic field from locations found by dedicated infrared location modules.

3.1 Distributed 3-d Scanning

The setup of this experiment consist of two heterogeneous robots: one of the robots acts as a laser sheet projector, and the other as a laser stripe detector. The projector robot, shown in Fig. 3, has a special laser module which includes 1mW (class I) laser stripe projector. The projector provides a vertical sheet of light that is projected into the environment. The robot that is acting as a laser stripe detector uses one of the color CMOS cameras of the stereo camera module loaded with a program that extracts the projected laser patterns from the surfaces of objects in the camera's field of view.

The measurement geometry is depicted in Fig. 4. First, the projector and the detector robots are aligned into a given line formation in which the laser and the camera are pointing to the left in regard to the driving direction. Both robots have now the same heading. In order to have absolute range measurements the parameters of the measurement geometry has to be known (Haverinen and Röning, 2000). However, relative range measurements can be made without knowing the exact mutual poses of the two robots. In our experiments, we have used both machine vision technique (Heikkilä and Silven, 1997) and the location module (Kemppainen et al., 2006) to arrange the robots into the known initial measurement formation. The machine vision technique utilizes the know landmark pattern mounted on the laser robot (shown in Fig. 3) in order to estimate the mutual poses of the robots.

The measurement geometry described in Fig. 4 is not the only option. The robots can also be arranged onto a circumference with both optical axis and the laser sheet pointing to the center of the circle. By driving along the the circumference with equal velocities the robots can perform a full scan of an object that resides inside the circle. Yet another option is to keep the robots on fixed locations and rotating the projector robot: in this way the robots can scan a large area from fixed locations. However, the angular motion of the projector robot must be known in order to compute the range image.

In our experiments the scanning procedure starts after the robots are properly aligned. Both robots are moving with equal velocities. The camera robot performs the image processing in order to extract the projected laser patterns reflected from the surfaces of objects. The image coordinates of the laser stripe on the image plane are locally saved into the camera module's SDRAM. At the end of scanning, the image data is transferred through the radio link to the host computer (PC), which computes the final range image.

Fig. 5 shows examples of range images acquired by the cooperating robots. The images demonstrate how cooperating miniature robots can perform a demanding measurement task by acting as distributed parts of the physical measurement device. The cooperative scanning can have important applications: a pair of miniature mobile robots can perform a remote 3-D scanning procedure and acquire range data from selected objects in environments that might be unreachable by traditional 3-D measurement devices. The range data gives important information about an (possible hazardous) environment, objects, and their geometrical properties. The presented distributed sensing technique can provide dense range data for creating 3-D maps of unknown environments without computationally intensive stereo image processing (Rocha et al., 2005), for example. The technique can also be an alternative for creating data for vision based 3-D SLAM (Tomono, 2005).

3.2 Cooperative Measurement of Spatial Data

This experiment demonstrates how heterogeneous robots can be used to perform a simple distributed sensing task, and to create a spatial map of point measurements. The experiment also highlights the feasibility of the infrared location module in applications domains where locations of the robots must be known. The infrared location system is used to create and maintain the measurement formation, while the robots are making point measurements with the

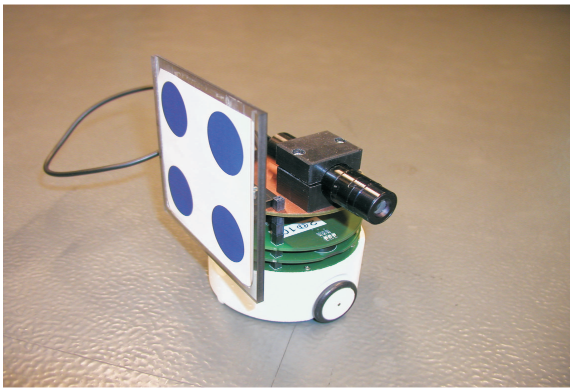

Figure 3: The laser robot. The robot consist of the 1mW laser line projector. This robot also has a landmark pattern which can be used to estimate the pose of the projector robot in the detector robot's coordinate system using the calibrate camera module and defining its extrinsic parameters in regard to the known landmark pattern (Heikkilä and Silven, 1997). Another technique to estimate the pose is to utilize the IR-location module.

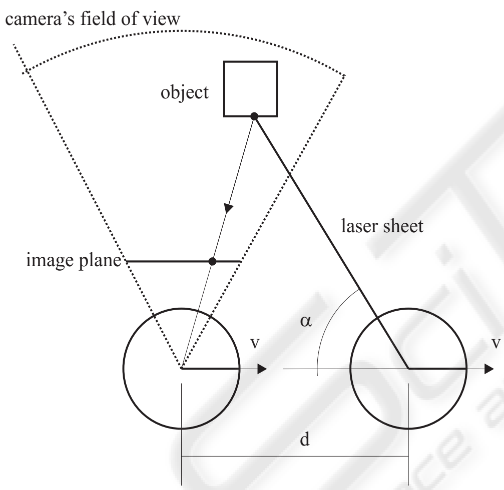

Figure 4: The measurement geometry used in the cooperative scanning experiment. The robots are first aligned into a line formation - both robots having the same heading. The distance d and the angle α control the measurement resolution and the measurement range. d and α can be adapted on the basis of the measurement task. During the scanning procedure, both robots maintain the same velocity v.

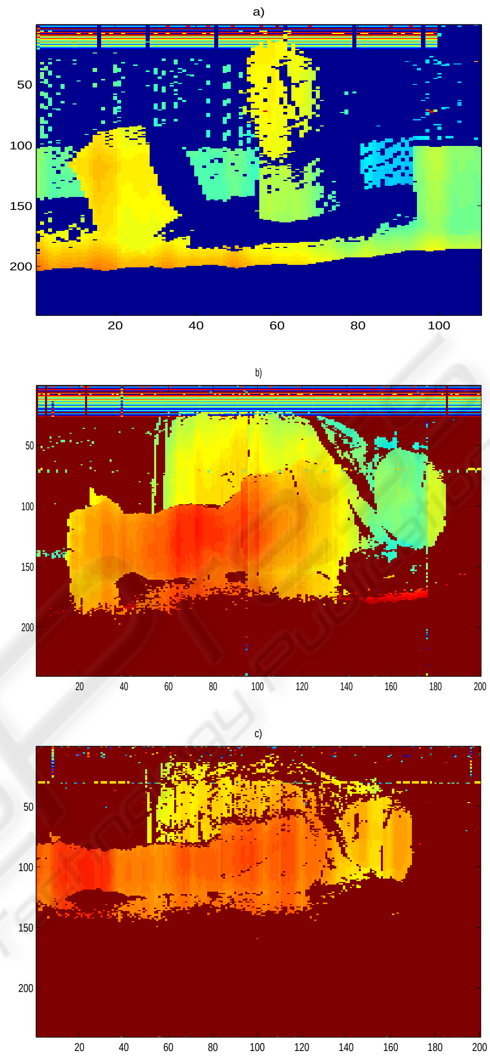

Figure 5: Range images from three cooperative 3-D scanning experiments. a) range image from arbitrary artificial objects (a head statue and some polyhedrons). b) and c) robots have scanned a person laying on the floor. These images demonstrate how, by simple cooperation, a pair of miniature mobile robots can obtain dense range data from objects of an environment.

scalar sensors of the environment module. The measurements are stored into a grid map with predefined cell size. The value of each cell is the mean value of the point measurements made in the corresponding cell.

Although the experiment is simple, it has important applications as it makes possible to automatically gather spatial scalar data from the area of interest. The data can then be used to analyze the lighting properties of the environment or to visualize how the magnetic field of the environment behaves due to metallic structures in the environment, and analyze its properties over time, for example.

Fig. 6 shows the initial arrangement of the robots prior the experiment (left): from these locations the robots are driven into the measurement formation using the infrared location module (right). While maintaining the measurement formation, the robots start moving and doing measurements. The lighting measurements are shown in Fig. 7, and the direction of the magnetic field in each cell in presented in Fig. 8. The Fig. 8 shows how the direction of the magnetic field varies in the environment due to metallic objects and structures. If this magnetic fingerprint of the environment is static it can be used to classify environments based on previous observations of the field on the same area, for example.

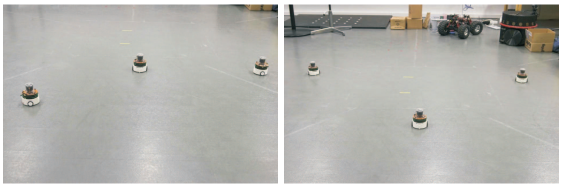

Figure 6: Left: the initial (arbitrary) positions of the robots. From initial poses the robots are driven into the measurement formation by using the IR location module. Right: The IR-location system has been utilized to drive the robots into the given measurement formation. The robot in the middle acts as a leader and the other two robots as followers.

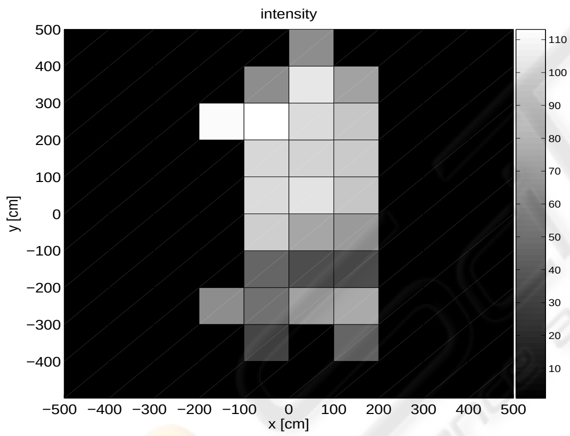

Figure 7: Measured ambient light intensities. The figure shows the value, given by the ambient light sensor, for each cell of the grid.

4 CONCLUSION

This paper presented a multirobot system developed for distributed sensing experiments and applications. Each robot has variety of sensors for measuring properties of an environment. The sensors include a temperature sensor, an ambient light detector, a compass module, accelerometers, and a color stereo camera system.

Distributed measurement tasks are naturally suited for multirobot system as they are inherently

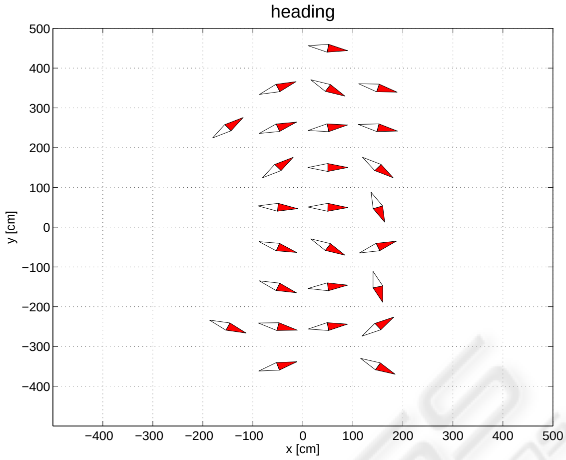

Figure 8: Measured directions of the magnetic field. The figure shows how magnetic field varies due to metallic structures of the environment. The variation (assuming it being static over time) can be used to classify environments based on previous observations from the same environment.

spatially distributed. The 3-D scanning experiment showed how a pair of heterogeneous robots can cooperate by acting as parts of a distributed 3-D scanning device. This observation is particularly important, as this kind of measurement instrument is otherwise very difficult to implement for a single miniature mobile robot. The scanning experiment also demonstrated how the multirobot system's spatial distribution and mobility can be utilized in a novel way to create distributed measurement devices in which each robot has an role as a part of the device, and in which the mobility of the robots provides flexibility to the structure of the measurement system.

The aim of this research is to develop multirobot systems which help humans to have meaningful information from (remote) environments and its objects. This information is then used to analyze the state of the environment or to execute multirobot tasks autonomously.

Based on the presented experiments, our purpose is to go toward more demanding implementations on which a person can instruct a multirobot system to measure selected objects of the environment after which the robots take their positions and cooperatively gather information, like range data, about the objects.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the Academy of Finland.

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