An Infrared Location System for Relative Pose Estimation of Robots

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Abstract. In this work we present an infrared location system for relative pose (position and orientation) estimation in a multi-robot system. Pose estimates are essential for tasks like cooperative simultaneous localization and mapping (C-SLAM), and formation control. In simultaneous localization and mapping (SLAM) relative pose estimates enable more accurate and less time-consuming map building. Respectively, formation control requires accurate pose estimates of other robots to enable robot cooperation in required formation. To address these challenging tasks for small-sized robots, we present a small-sized infrared location system with low current consumption. In the location system, robots use intensity and bearing measurements of received infrared signals to estimate the positions of other robots in polar coordinates. In addition, each robot has a unique modulation frequency from which they are recognized. The location system performs position estimation by rotating a beam collector at constant rotation speed and by measuring the bearing and intensity of the received signal. Infrared signals are received through a small aperture in the beam collector enabling accurate bearing measurements. In order to maximize the measurement range, infrared radiation is reflected sideways into a uniform zone using a conical mirror. Experiments were performed in a group of three robots with a measurement range of up to 3 m while the maximum number of robots was eight. The location system implemented enables relative position estimation among a group of small-sized robots without exchanging position estimates. This is advantageous since the robots are able to maintain formation also in the absence of a radio link.

1 Introduction

Surveillance, rescue and exploration tasks have motivated robot scientists in developing multi-robot systems capable of cooperating in unknown environments. Multi-robot systems compared to single mobile robots can carry out more complex tasks, through their potential to use a greater amount of sensors and actuators. In addition, performing time-critical tasks, for example, finding and rescuing people from a burning house is faster using multiple robots instead of one. Location is essential in multi-robot systems since cooperation, for example, carrying injured people in a group of robots requires each robot to be aware of other's locations.

Location in a multi-robot system consists of self-localization and relative location of other robots. A typical approach to self-localization is simultaneous localization and mapping (SLAM), where the robot's pose (position and orientation) in an unknown environment is defined by measuring position estimates of landmarks. A map is built by fusing landmark perceptions and the robot's pose estimate from dead reckoning. In addition, by measuring the relative locations between robots, formation control and optimal map building, often referred to as exploration (Burgard et al., 2005), can be realized. Cooperative simultaneous localization and mapping (C-SLAM) improves the maps by fusing the relative pose estimates of landmarks among a group of robots. These systems have recently been examined by several authors (Fox et al., 2000), (Howard, 2005),(Mourikis and Roumeliotis, 2005), (Hajjdiab and Laganiere, 2004), (Rodriguez-Losada et al., 2004). By fusing map estimates, the map becomes more accurate and mapping time decreases substantially.

A formation control is task where robots are required to maintain a movement formation as they travel from their starting point to the goal target avoiding collisions with obstacles. Maintenance of a particular formation is required in many applications. For example, in military applications, formation allows each robot to concentrate their sensors across one portion of the environment, while other robots cover the rest(Balch and Arkin, 1998). Secondly, tasks like demining, harvesting (agriculture) and security patrol may require specific formations depending on the surroundings. For example, in narrow corridors or on footpaths, column formations are recommended, whereas in huge hallways or wide areas, diamond or wedge formations are more suitable. Formation control does not require a global location system. Instead, robots need to have position estimates on where other members of the group are located. However, without an absolute positioning system, uncertainty about the absolute position will grow continuously without bound (Roumeliotis and Bekey, 2002).

In this paper, we present an infrared location system for relative pose estimation where each member of the robot group locates and recognizes other robots. The location system is designed to be suitable for both large and small robots. It was developed to be a part of a swarm robotic research programme to be performed with miniature robots (Haverinen et al., 2005). One advantage in the presented infrared location system is that the robots' positions are estimated and they are recognized without data transmission between robots. However, relative orientations can be estimated only by fusing location estimates among a group.

2 Design considerations

In our study, the purpose was to design a relative location system for a group of robots. As robots build and maintain different formations as well as perform exploration tasks in an unknown environment, the system accuracy must be sufficient and the measurement range large. In hallways, as robots carry out exploration tasks in a minimal group, distances between robots may grow to close to 10 metres. Respectively, when moving through narrow corridors or in small disorganized rooms among a large group of robots, the robots may be required to operate very close to each other. Because of these factors, there is the requirement that the accuracy must be sufficient, to be precise, smaller than the lowest distance between robots. Secondly, in order to operate in both small and large groups, as tasks and environments vary, the measurement range must be wide-ranging.

The primary goal of this work was to implement an exact and yet wide-ranging relative location system for small mobile robots. In the related systems, except for one (Grabowski et al., 2000), systems have functioned with larger robots. In order to be suitable for small robots, several restrictions must be introduced. Because our miniature robots (Haverinen et al., 2005) use 1000 mAh lithium batteries, in order to enable a few hours operation time, current consumption was expected to be only a couple hundred milliamperes. In addition, due to the small size of the robots, the sensors have to be light and small enough.

The design considerations focused tightly on selecting appropriate sensors from between laser, vision, ultrasound and IR (infrared) sensors to attain the required accuracy and measurement range, and to achieve small enough size with low current consumption. Related systems have been presented exploiting several techniques including laser range finders (Schneider and Wildermuth, 2004), (Montesano et al., 2004), (Howard et al., 2003),(Moors et al., 2003), ultrasonic TOF measurement (Shoval and Borenstein, 2001), (Grabowski et al., 2000) and vision (Montesano et al., 2005), (Spletzer et al., 2001) for location and recognition of other robots. Laser range finders are accurate and have wide-ranging sensors which measure relative distance and angle to a target. However, range finders cannot distinguish objects from each other, and in addition, sensors are in general large. Vision offers reliable robot recognition for a relative multi-robot location system, provided that differences between robots are visible. Relative locations can be estimated by extracting the robots' features from a captured image. Feature extraction requires, however, a great deal of performance from the location system. Ultrasound sensors are mostly used as sonar sensors in mapping tasks. TOF (time-of-flight) measurements (Grabowski et al., 2000) can be also used to estimate relative distances between robots. Systems of this kind require, however, at least three robots presence since relative positions among a group of robots are estimated by trilateration. In this work, we selected IR sensors since they are small and capable of relative angle measurements between an emitter and receiver. In addition, infrared radiation does not reflect from walls and object surfaces as much as ultrasound. In relative angle measurements, the effects of multipath reflection would be crucial because of ambiguous angle estimates.

3 The architecture

The implemented location system consists of mechanics and control electronics. The mechanics and control electronics were separated in order to minimize size, and to ease the manufacturing of the system (Fig. 2). Mechanics is used to emit infrared radiation and to receive radiation from other robots, whereas control electronics drive the beam collector at a constant angular velocity and estimate the positions of the detected robots. Figure 1 presents a block diagram of the system.

The mechanics consists of an IR emitter and receiver, a DC motor, Hall-effect-sensors, a rotating beam collector and a see-through cylindrical body (Fig. 2). In order to increase

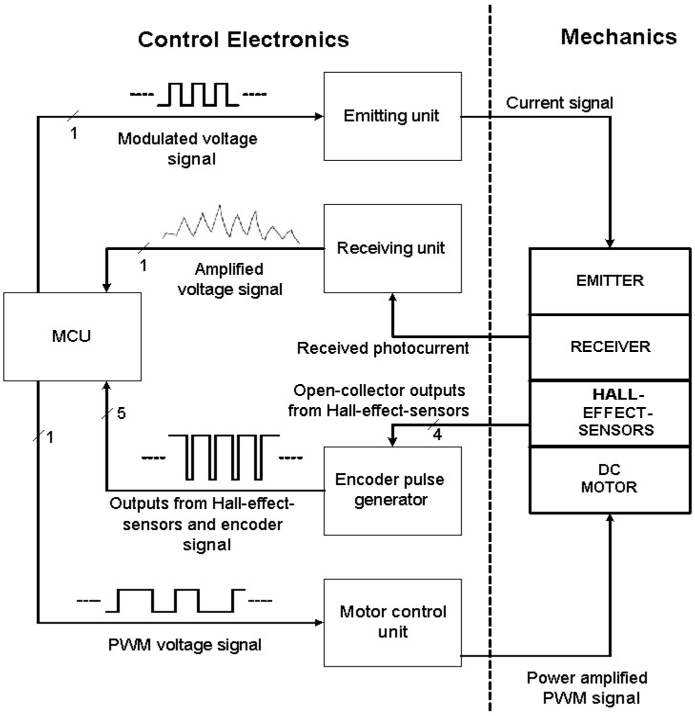

Figure 1. In the location system, the MCU drives beam collector at a constant angular velocity and estimates the positions of the detected robots.

the measurement range, conical mirrors were exploited to reflect the emitted signals sideways into a narrow zone. Signals were received through a small aperture in the beam collector and reflected to the receiver using a mirror. Scanning the surroundings at a constant rotation speed is realized using a DC motor, Hall-effect-sensors and discrete PID controller performed in an MCU.

The control electronics consists of an MCU, an emitting unit, a receiving unit, an encoder pulse generator and a motor control unit (Fig. 1). In order to recognize the emitting robot, the MCU generates in each robot unique modulation frequencies. The emitting unit drives a current-controlled IR emitter by transforming a frequency modulated voltage signal into the current signal. The receiving unit consists of a preamplifier in which the amplification can be changed to enable a wider measurement range. The encoder signal is generated from four Hall-effect-sensor outputs. Using four encoder pulses in a round, the lowest rotation speed in which rotation was sufficient smooth was five revolutions per second. The motor drive was implemented in a motor control unit by amplifying the PWM signal with a half-bridge circuit.

The MCU performed both the rotation speed control and the position estimation. The stable rotation speed of the beam collector was realized by a controlling DC motor

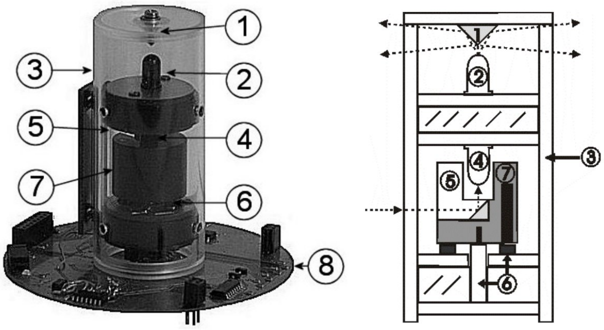

Figure 2. The actual system and the illustration of mechanics: 1) mirror, 2) emitter, 3) see-through body, 4) receiver, 5) aperture, 6) DC motor and Hall-effect-sensors, 7) beam collector, 8) control electronics.

with a discrete PID controller using encoder pulses as speed measurements. The position estimates were calculated by triggering the rising edge of the received signals. As each new signal was detected, the bearing of the beam collector was used to estimate the angular coordinate. Similarly, the radial coordinate was estimated using the intensity of the received signal. In addition, each emitting robot was recognized by the modulation frequency of the received signal.

4 Results

The performance of the implemented location system, presented in figure 2, was measured in a group of three robots. The position error and standard deviation were measured in three different position configurations where one of the robots was locating and the others were targets. In addition, the performance of the location system was measured as one of the targets was moving along a short route.

Figures 3a–c present three test cases where two targets were located in different places around the locating robot. Figure 3d presents a fourth test case where one of the targets was moving along a short path for around one minute. Depending on the distance to the targets, the location estimates were updated at intervals of 1–2 seconds.

The location system located robots in polar coordinates, and position estimates were transformed into cartesian coordinates to be able to define average position errors (see Table 1). The position errors were at their highest over 20 cm, the main reasons for this being faults in the distance measurements (see Table 2).

The standard deviation was calculated for the angular and radial coordinates (see Table 2). The angular coordinate was obtained by using the bearing of the beam collector. In all measurements the standard deviation for the angles was less than 1.5°. Standard deviation for distances suffered from both variations of intensities and different clusters of estimates caused by different amplifications in the preamplifier. Added to this, the standard deviation for the radial coordinate depends on the distance. Since the distance

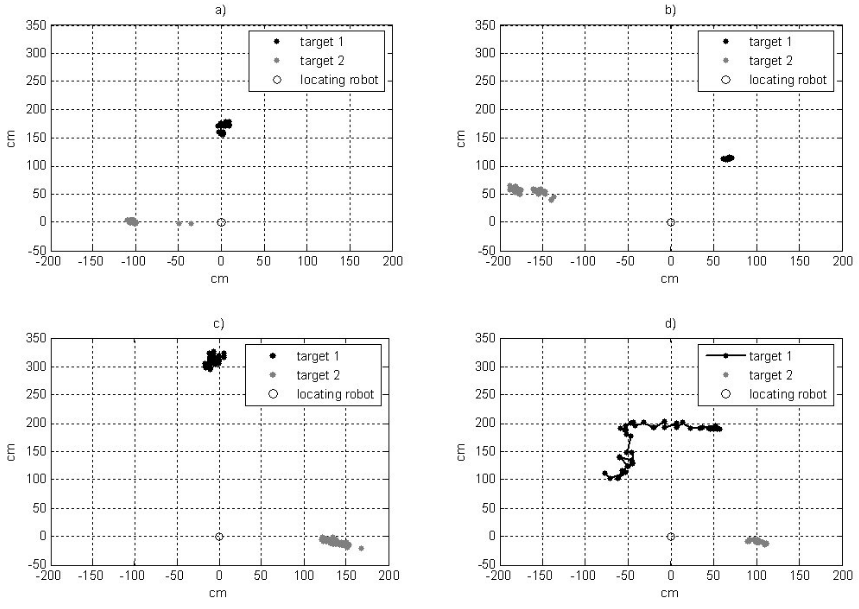

Figure 3. Four test cases: a) Target 1 at (0, 150) and target 2 at (-100, 0), b) Target 1 at (50, 100) and target 2 at (-150, 50), c) Target 1 at (0, 300) and target 2 at (150, 0), d) Target 1 moving from (-50, 100) through (-50, 200) to (50, 200) and target 2 at (-100, 0)

is an inversely exponential function of the intensity of the received signal, the further away the target is located, the sharper the curve is. For this reason, small variations in the received intensity and small noises will significantly increase the standard deviation as the located robot is far away.

In all four test cases target recognition using different identification frequencies for targets was faultless. Target 1 used 1 kHz and target 2 used 2 kHz modulation frequency while permitted frequencies were between 800 Hz and 2.2 kHz at intervals of 200 Hz:s. In addition, the functionality of the target recognition for a group of 8 robots was witnessed by changing the different modulation frequencies and by testing that the recognition was faultless.

5 Conclusions and future work

In this paper, we presented a relative infrared location system for a group of robots. Relative locations among a group of robots are essential for tasks where robots have to cooperate, for example, in carrying injured people. In addition, relative pose estimates can be exploited in simultaneous localization and map building, enabling faster and more

Table 1. Position errors.

Robot	Real positions		Mean value		Position error
	x(cm)	y(cm)	x(cm)	y(cm)	e(cm)
target 1	0	150	3.7	169.8	20.2
target 1	50	100	66.8	111.7	20.5
target 1	0	300	–7.1	310.0	12.2
target 2	–100	0	–101.5	0.8	1.7
target 2	–150	50	–170.1	55.0	20.7
target 2	150	0	139.4	–11.7	15.8

Table 2. Standard deviation.

Robot	Real coordinates		Mean value		Standard deviation	
	r(cm)	θ(deg)	r(cm)	θ(deg)	r(cm)	θ(deg)
target 1	150	90	169.9	88.7	6.3	1.0
target 1	111.8	63.4	130.2	59.1	1.9	0.7
target 1	300	90	310.1	91.3	6.8	1.3
target 2	100	180	101.5	179.6	11.2	1.4
target 2	158.1	161.6	178.8	162.0	13.7	1.2
target 2	150	0	139.9	355.3	8.8	1.3

reliable exploration in unknown environments. In the location system design, infrared sensors were selected since they are suitable for small robots, and since infrared enables reliable bearing measurements. The system uses the bearing and intensity measurements of a received signal to estimate the emitting robot. In addition, the frequency information of the received signal is used for robot recognition. The location system designed is advantageous since IR sensors are small, and since the relative positions of the other robots are estimated without data transmission between robots.

The location measurements testified that the location system was able to recognize targets faultlessly at a distance of 3 m. The bearing estimates were accurate, unlike the distance estimates which in several measurements increased the position error and produced a large standard deviation for the radial coordinate. A three metres measurement range may prove to be inadequate for certain tasks, and yet accurate position estimates must be obtained. For these reasons, among others, the location system has been redesigned and the first measurements have proved an improvement with an increase in the measurement range to close to 10 m.

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