A Simple and Low Cost Angle Measurement System for Mobile Robot Positioning

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***Abstract*—Positioning is a fundamental issue in mobile robot applications that can be achieved in multiple ways. Among these methods, triangulation with active beacons is widely used, robust, accurate, and flexible. Our paper presents a new active beacon-based angle measurement system for indoor navigation using infrared signals. We propose a complete system for global positioning on a 2D plane based on the following parts: (1) a mirror, a lens, and a light guide, (2) a mini stepper motor and its controller, (3) an infrared receiver (TSOP7000), (4) a PIC microcontroller, and (5) three infrared beacons. The acquisition rate is 10 [Hz] and the accuracy is about 0.1 [degree]. The entire sensor is contained in a $(8 \times 8 \times 8)$ [cm^3] volume. The key innovation is the use of a cheap and simple infrared receiver as the main sensor for the angle measurement principle. The beacons too are simple cheap infrared LEDs. Furthermore, the system requires only one infrared communication channel, and no synchronization between the beacons and the robot is required.**

***Index Terms*—Infrared detector, microcontroller, mobile robot, robot sensing system.**

I. INTRODUCTION

Positioning is a fundamental issue in mobile robot applications. Indeed a mobile robot that evolves in its environment can not execute its actions correctly without any form of positioning. Therefore, sensory feedback is compulsory to position the robot in its environment [3]. Positioning can be achieved in different ways [5]: odometry, inertial navigation, magnetic compasses, active beacons, landmark navigation, map-based positioning, and vision-based positioning. We can identify two main families in these methods: (1) relative positioning (or dead-reckoning) and (2) global positioning (or reference-based). The first group is mainly achieved by odometry which consists in counting the number of wheel revolutions (e.g. with optical encoders) and integrate them to compute the offset from a known position. Inertial navigation (based on gyroscopes or accelerometers) is less used because of its poor accuracy [5]. Relative positioning based on odometry is very accurate for small offsets but is not sufficient because of the unbounded accumulation of errors over time (due to the integration step, wheel slippage, etc). A global positioning system is thus generally required to recalibrate the position of the robot periodically. On the other hand, such systems will never reach the accuracy of odometry and this is why both methods are essential and complementary to each other [1], [3], [6]. Typically relative and global positioning are merged together by using a Kalman filtering strategy [10], [14].

To the contrary of GPS for outdoor applications, no universal indoor positioning system exists [5]. It explains the large variety of existing systems depending on the target application and constraints such as cost, accuracy, available volume, covered area, usable technologies, and safety (e.g. laser class). Many existing hardware systems may be found in [4], [5], [8], [12], [13], [15]. Although it doesn't focalize on mobile robots, a survey about indoor positioning technologies may be found in [11].

In many cases, positioning is reduced to beacon-based triangulation or trilateration problems. In this context a beacon is a discernable object of the environment, that may be natural or artificial, passive or active. Triangulation is used when the robot measures the angles from the robot reference to the beacons. Trilateration (like GPS) is used when the robot measures the distances from the sensor to the beacons. Anyway, any triangulation problems can be reduced to a trilateration problem, which means computing the intersection of at least three circles in the 2D plane. Triangulation with active beacons is widely used, robust, accurate, and flexible [9]. Another advantage of triangulation versus trilateration is that the robot can compute its orientation (heading) in addition to its position.

Overview

Our paper presents a new active beacon-based angle measurement system for indoor positioning using infrared signals. Our system was primarily developed for the EUROBOT contest but can be used in any other mobile robot application. The paper is organized as follow: hereunder we briefly describe the EUROBOT contest and associated constraints, Section II details the whole hardware platform. Then, we present, in Section III, the software architecture and the angle measurement principle. Experimental results and physical characteristics of our platform are given in Section IV. Section V concludes the paper.

The EUROBOT *contest*

This contest opposes two autonomous mobile robots in a completely symmetrical playing field of (2.1×3) [m^2] area (Fig. 1, right). Although the rules change every year, the background is always the same: each robot must pick up some objects and place them in some containers, the winner being the one who accumulates the most points in 90 [s].

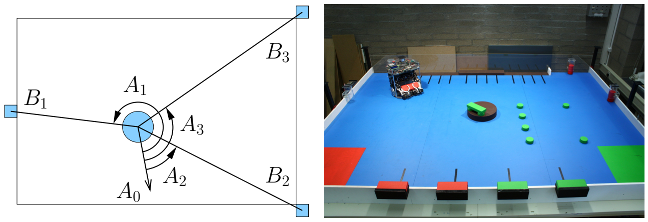

Figure 1. Left-hand side: sketch of the triangulation setup: the circle is the mobile robot and the small squares are the fixed beacon supports. Right-hand side: playing field of the EUROBOT contest 2009.

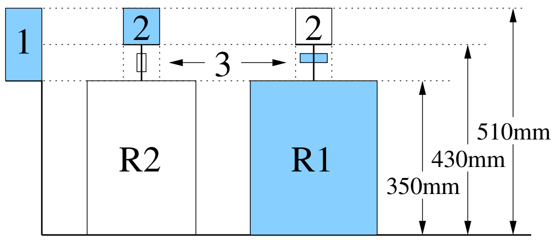

Figure 2. Side view of the playing field. R1 and R2 are the robots. The fixed (1) and opponent beacon (2) supports are $(8 \times 8)\,[\text{cm}^2]$ surfaces. The fixed support height is imposed. The robot height has a maximum. The beacon height has a maximum. The sensors (3) must remain within the vertical projection of the beacon supports.

In this kind of contest, positioning is a critical issue. As explained hereinbefore, the odometry is mandatory but not sufficient, and each robot should implement some kind of global recalibration. Although each robot must be equipped with an avoidance system, robots collisions may be another source of odometry error. To help the global positioning, three beacon supports per robot are available around the playing field, one in the middle of the small edge and two at the opposite corners (Fig. 1, left). Moreover a fourth beacon may be placed onto the opponent robot, helping for the avoidance system.

A side view of these supports and associated constraints is drawn in Fig. 2. One can see that fixed beacons must be included in a $(8 \times 8 \times 16)\,[\text{cm}^3]$ volume and opponent beacon and sensor in a $(8 \times 8 \times 8)\,[\text{cm}^3]$ volume. It is also shown that a line-of-sight between the beacons and sensor is available, allowing an optical system. Commercial laser systems are subject to many constraints in the EUROBOT rules and home-made laser systems are prohibited for safety reasons.

II. HARDWARE DESCRIPTION

The hardware part of the system is composed of the three fixed beacons (placed around the playing field) and the sensor (placed onto the robot top center, just below the opponent beacon support). The goal of the sensor is to measure the azimuthal angles A_1, A_2 and A_3 from the robot's reference A_0 to the beacons (Fig. 1, left). The use of these angles to compute position or navigate can be found in [1], [2], [3], [7], [9] and won't be addressed in this paper.

A. The beacons

The main part of a beacon is a single and cheap IR LED (SFH485P), parallel to the playing field and directed towards the table center. These LEDs have a large emission beam so that a single LED per beacon can cover the whole table area (a minimum power is guaranteed at the receiver). The source is thus as punctual as possible. Each beacon continuously emits its own IR signal so that the receiver can determine the beacon's identifier (ID). Fig. 3 shows a picture of a beacon.

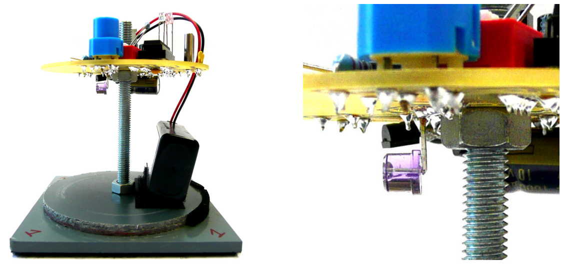

Figure 3. Left-hand side: picture a complete beacon. Right-hand side: detailed view of the IR LED. It is located under the PCB, parallel to the playing field and directed towards the table center.

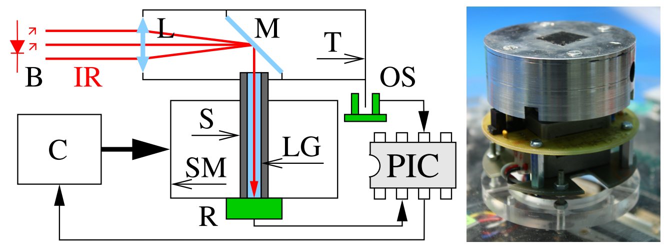

Figure 4. Left-hand side: scheme of the complete system. B is a beacon emitting IR light, L is the lens, M is the mirror, LG is the light guide, R is the receiver, SM is the stepper motor, S is the drilled shaft, T is the turret, C is the motor controller, PIC is the microcontroller, and OS is the optical switch. Right-hand side: picture of the sensor with the rotating turret.

B. The sensor

The sensor is composed of a mini hybrid stepper motor, a convergent lens, a small front surface mirror with a 45 [degree] tilt, a polycarbonate light guide placed in the center of the motor shaft (which has been drilled for this purpose), the IR receiver (TSOP7000) and an optical switch used to calibrate the zero angle reference (see Fig. 4 for a scheme of the sensor). The lens and mirror are placed in a "turret" which is fixed to the motor shaft. The receiver is fixed to the bottom of the motor, just below the light guide. This configuration allows IR signals to reach the fixed receiver through the entirely passive "rotating turret" and light guide. Finally a PIC microcontroller is used to decode the output of the receiver and to drive the motor through its controller.

III. SOFTWARE DESCRIPTION

The building blocks of the software are detailed in Fig. 5. The main tasks are based on a common timer. The key idea is to use this common timer to drive the stepper motor at a constant speed and capture the receiver output edges. The captured values are used to compute the beacons angular positions and to identify the beacons.

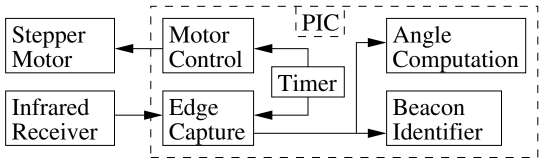

Figure 5. Software organization. A common timer is used to drive the stepper motor at a constant speed and to capture the edges of the receiver output. These captured values are used to compute the angular positions of the beacons and also to identify the beacons.

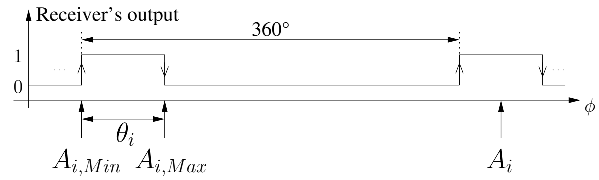

Figure 6. While the turret is turning, a beacon B_i is seen with an angle of view θ_i ranging from an angle $A_{i,Min}$ to an angle $A_{i,Max}$. This angle of view depends on the received IR power. The angular position A_i of that beacon B_i is estimated by the algebraic mean of $A_{i,Min}$ and $A_{i,Max}$.

A. Stepper motor control

The stepper motor is driven in open loop and step by step via its controller which requires a simple input square signal to advance the motor from one step to the next. The frequency of this step signal directly controls the rotation speed of the motor and is derived from the common timer (since the timer is running faster than the step signal, we have a substep resolution and the number of "virtual" steps is actually 62400). The motor is turning at a constant speed and the angular position of the turret $\phi(t)$ is thus directly proportional to the value of this timer and thus to time. Whereas the motor is controlled step by step, the rotation is assumed to be continuous thanks to the high inertia of the turret.

B. Edge capture

The receiver output is connected to a capture module of the PIC. Depending on this module configuration, a falling or a rising edge of the receiver output latches (captures) the actual timer value to a register that may be read later by the software. This allows to associate a time and thus an angular position to an event (falling or rising edge). On each new capture, the configuration is alternately swapped between falling and rising edge, the initial condition being "capture rising edge".

C. Principle of angle measurement

First let's assume that the beacons send a continuous IR signal (i.e. each IR LED is simply turned on) and that the receiver output is equal to "1" when it receives IR light, and "0" otherwise. Then, assume that the transitions "0 → 1" and "1 → 0" occur for the same IR power threshold.

The angle measurement works as follows: while the turret is turning, the receiver begins to "see" IR light from a beacon B_i, which causes a rising edge and a captured value corresponding to an angle called $A_{i,Min}$. The receiver continues to receive that beacon IR light until the IR power threshold is reached, which causes a falling edge and a captured value corresponding to an angle called $A_{i,Max}$. The angle of view $\theta_i = A_{i,Max} - A_{i,Min}$ while the receiver "sees" the beacon depends on the received IR power; it decreases if the emitted power decreases or if the distance increases. As the source emissions are punctual and the optical part is symmetric, the angular position A_i of a beacon B_i is estimated by:

$$A_i = \frac{A_{i,Min} + A_{i,Max}}{2} \quad (1)$$

Fig. 6 shows the receiver output for a single beacon in static condition, that is the beacon is seen every 360 [degree].

D. Beacon identifier and infrared codes

The continuous IR signals used in previous section are not realistic because (1) we can't distinguish the different beacons and (2) we can't be sure of the beacon ownership (especially in the EUROBOT contest where other IR sources may exist). These comments lead us to code the beacon IR signals and to use a commercial IR receiver.

The TSOP7000 is a miniaturized IR receiver working with an On-Off keying modulation of a 455 [kHz] carrier frequency. The modulated signal is simply the carrier wave multiplied by "0" or "1" (the binary message). The receiver's output is equal to "0" when it detects the carrier and "1" otherwise.

Each beacon continuously emits a 455 [kHz] square wave modulated by a periodic signal which is composed of an infinite repetition of a particular code (the beacon's ID). These codes are subject to many constraints due to (1) the receiver, (2) the loop emission, (3) the desired precision, (4) the immunity against noise, and (5) the number of beacons:

1. Receiver. The TSOP7000 requires that the burstlength (presence of carrier) should be chosen between 22 and 500 [µs], the maximum sensitivity being reached with 14 carrier periods ($\frac{14}{455000} = 30.8$ [µs]). The gap time between two consecutive bursts (lack of carrier) should be at least 26 [µs].

2. Loop emission. There must be no ambiguities between codes because of the loop emission and the lack of synchronization between beacons and receiver (it can be seen as an asynchronous transmission). For example [0101] is equivalent to [1010] when sent in a loop. Thus any rotation of any code on itself must be different.

3. Precision. Because there is no synchronization between beacons and the receiver, the first received IR pulse may be preceded by a maximum of a gap time, resulting in an imprecision on $A_{i,Min}$. We have the same phenomenon for $A_{i,Max}$. The gap time must be reduced as much as possible.

4. Immunity. The codes should contain enough redundancy to be robust against noise or irrelevant IR signals.

5. Number of beacons. The codes should be long enough to code a few beacons (actually 5, 3 fixed, 1 opponent beacon and 1 optional) but as short as possible to be seen many times by the rotating sensor, thus improving the decoding robustness.

These constraints lead us to the following family of codes:

$$C_i = [0^1 1^i 0^1 1^{10-i}] \qquad i = 1, \ldots, 5 \quad (2)$$

where the duration of a bit is $T_b = 30.8$ [µs] and the duration of a code is $T_c = 12\,T_b$. The last part of the codes can be seen as a checksum since the number of ones is always equal to 10. Fig. 7 shows some of the codes.

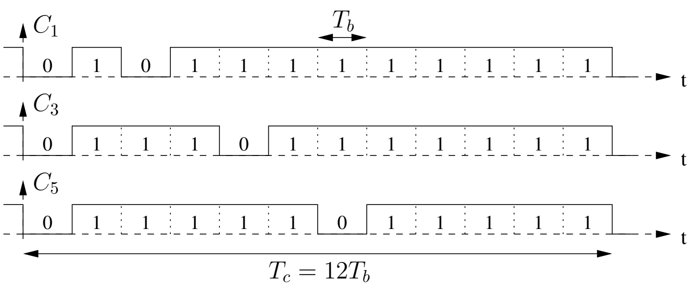

Figure 7. Temporal representation of C_1, C_3 and C_5. These codes are repeated continuously and multiply the 455 [kHz] carrier wave to constitute the complete IR signal.

The angle measurement would operate exactly as in Section III-C if the IR carrier was not modulated (except for the output inversion). Since there are gap times in the IR signal, there are more than one rising and one falling edge per beacon in the demodulated signal. The first and last edges corresponding to $A_{i,Min}$ and $A_{i,Max}$ are isolated thanks to a timeout strategy since the separation time (or angle) between two different beacons is much larger than the separation time between consecutive edges of a code. The intermediate edges are used to compute the durations of burstlengths and gap times and to determine the beacons ID.

IV. Experimental results and characteristics

The Table I summarizes the main characteristics of our system. The rotation speed and thus the acquisition rate is 10 [Hz]. The angular resolution is equal to $\frac{360}{62400} = 0.00577$ [degree] since there are 62400 virtual steps. The sensor consumption includes the motor, microcontroller, receiver, etc. The given working distance is linked to the given beacon consumption since more IR power allows a greater working distance. The working distance could be increased for a given IR power by increasing the lens size (currently 12 [mm] diameter) and thus collecting more IR light. The number of allowed beacons is currently 5 but could be increased by modifying the codes. The standard deviations (precision) were computed over 1000 measures and for different distances. The values in Table I are maximum values. The accuracy is not given because the measurements of such small angle values are not easy to realize (because of the uncertainties of the setup itself). The only information we have about the accuracy is the positioning (via triangulation calculus) error on our playing field which is about 1 [cm]. This leads to an angle accuracy of about 0.1 [degree]. The embedded software of the PIC microcontroller was written in simple assembly language (about 1500 instructions). No operating system or C language is needed. The cost is given for information only and must be handled with care since our system is a prototype. It is an estimation of the sum of the main components of the system.

V. Conclusion

We present a new low cost system for the measurement of angles that are combined to position a robot in real time. The platform has been used and improved during the EUROBOT contest for two years. The acquisition rate is 10 [Hz] which is sufficient to position a robot moving at a moderate speed. The entire sensor is contained in a $(8 \times 8 \times 8)$ [cm^3] volume, which is small compared to other systems. Furthermore, the system requires only one infrared communication channel and no synchronization between the beacons and the robot is needed. The beacons are univocally identified so that the robot can compute its position without maintaining an estimation of its position. The system is composed of cheap, classical and easy-to-find components (PIC microcontroller, IR LEDs, IR receiver, stepper motor, etc). The mechanical part is nothing else but a single motor (no gears, etc) thanks to the drilled shaft.

Table I
CHARACTERISTICS OF THE COMPLETE SYSTEM.

acquisition rate (speed): 10 [Hz]	precision (A_{min}): 0.144 [degree]
angular resolution: 0.00577 [degree]	precision (A_{max}): 0.094 [degree]
sensor consumption: 100 [mA]	precision (A_{mean}): 0.085 [degree]
beacon consumption: 100 [mA]	working distance: 0.5 → 8 [m]
number of beacons: 5	carrier frequency: 455 [kHz]
sensor diameter: 70 [mm]	wavelength: 870 [nm]
sensor height: 65 [mm]	targeted applications: indoor
cost: 100 €→200 €	embedded software: 1500 [ASM instr.]

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