Hardware realization of autonomous robot localization system

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Abstract - One of the most important problems in autonomous robot guidance is their localization, i.e. determining their physical location within their operating area. In this paper we describe hardwre realization of triangulation method for localization of wheeled autonomous robot that operates on flat rectangular surface. Triangulation is a method of calculating location of robot relative to 3 landmarks (beacons) located on fixed predetermined positions. This method usually needs measurement of distances between robot and beacons, to be able to calculate robot position. Different approach based on angle measurement is described in this paper, advantages of this method are discussed and details of hardware realization are explained. System is realized and tested, measurement results are given.

I. INTRODUCTION

For autonomous robots which must operate without human interfering it is of vital importance that robot has information about its position on the playing field available during the whole duration of the match. There area many systems used for robot positioning, depending of the type of the robot and location where it will be used indoors or outdoors, flat or uneven terrain, small or large moving space…

System in this paper is designed to be used in EUROBOT [1] competition, with mostly flat playing field of relative small dimensions (2x3m). Simple localization systems for this type of terrain uses infrared beacon which allows them to know their orientation on the field, but not exact location. More complex systems use ultrasonic measurements [2], but these systems are not useful in location with significant environmental noise. Camera systems with image processing [3] are most sophisticated, and can be used in robot navigation, since these systems can be developed to detect object on terrain. These type of systems suffer from problem of variations in environmental illumination, complex algorithms and quality hardware must be used to operate in these conditions.

There are numerous papers [4], [5] with robot localization system based on infrared beacons, but they are usually with emphasis on theoretical explanation of this type of systems and algorithms for their calculation, they don't present hardware realization of the system. In this paper, we first describe some of the existing and frequently used localization methods in EUROBOT competition, and then we describe our localization method based on angle measurement, with detailed hardware description. Similar system for robot localization is reported in [6]. This system uses additional lens and mirror for directing optical signal to the sensor. High quality mirrors reflected above 80% of the incident light but they are quite expensive. Same goes for good lens. Additionally, in order to achieve maximum efficiency of the beam directing, lenses and mirrors must be accurately adjusted. In this paper we propose another solution without the use of additional optics which allows greater range of the sensor. Our solution is based on rotary transformer which allows contactless transfer of supply voltage to the sensor, as well as transfer of signal from sensor.

The position is calculated by sensor measurements. Since the robot moves on the bounded flat surface, its position is fully defined by three coordinates (x, y). Coordinates x and y actually signify the position of robots central point in fixed coordinate system anchored to the playing field, and is the orientation, i.e. the angle between central axis of robot and x axis (Fig. 1).

II. LOCALIZATION METHODS

A. Odometry

Odometry [7] is a robot localization method based on usage of rotary encoders. The robot has two wheels which are constantly in the contact with the surface. These wheels are mechanically coupled with encoders. The number of the pulses produced by encoders depends on the number of turns, in other words the distance traversed by wheels. This is an incremental method, which takes into account the assumption that the robot trajectory consists of sequence of segments that are approximately straight. The data coming from encoders is processed periodically, with a period short enough that the assumption about the straightness of trajectory segments still holds (10 ms). If we assign the number of encoder increments read from respective encoders during nth period by LEFT and RIGHT, it is possible to calculate the growth for all three coordinates during given period.

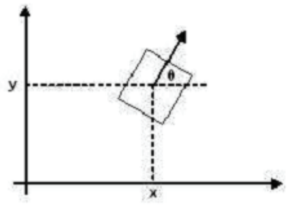

Figure 1. Position of robot in coordinate system

Basic flaw of this method is existence of systematic error which accumulates through time. The error appears due to slipping of wheels, the assumption of straightness of trajectory between two consecutive readings, numerical error of calculation, etc. It is possible to acquire information about robot position with acceptably small deviation with this method, but if robot slides laterally (in contact with opponent robot or some object) , system based on this method will not be able to correct error that will be produced on this situation, or even to be aware that error has happened.

B. Triangulation Based On Distance Measurement

Triangulation is well known and frequently used localization method. The position of robot is determined by measuring distances between the robot and three fixed points on known positions. For this purpose, we use three beacon positions on the edge of the field, as defined in competition rules. In Fig. 2, these positions are designated by B_1, B_2 and B_3. One of the ways to measure distances L_1, L_2 and L_3 between robot and beacons is to put an ultrasonic transmitter in each beacon and ultrasonic receiver in robot. By measuring time between the moment of issuing the command and reception of ultrasonic signal, it is possible to calculate distances, knowing the speed of sound.

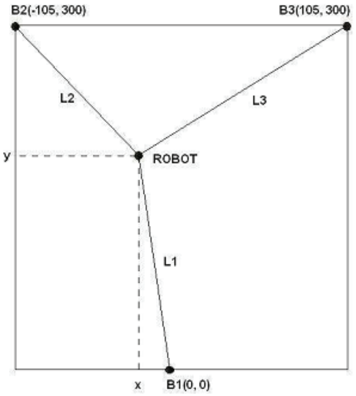

Figure 2. Triangulation based on distance measurement

Now that we have measured distances L_1, L_2 and L_3, it is possible to calculate position of robot. The coordinate system is perpendicular to the playing field, with origin in B1. The unit of measure is centimeter, so the positions of the beacons are B2 (-105, 300) and B3(105, 300). By applying basic trigonometric laws, we get the following equations for robot position:

$$x = \frac{L_2^2 - L_3^2}{420}$$

$$y = \sqrt{L_1^2 - x^2}$$

The advantage of this method is that it doesn't accumulate error. When it comes to realization, the biggest problem is inadequacy of measuring methods.

The ultrasonic receivers are too sensitive to environment sounds, which leads to false distance measurement in environment that is not quiet. More sophisticated methods of distance measurement such as laser measuring sensor can be used, but this type of equipment is very expensive. It is also important to mention that this method cannot provide the information about robot orientation, so it would be necessary to use some other system do measure it (i.e. electronic compass).

C. Triangulation Based On Angle Measurement

Our approach to localization problem is based on angle measurement. Like in previous section, we use three beacons again, but this time we use coded infrared beacons. All of the beacons continuously and simultaneously transmit modulated infrared light signals with different codes, by which a receiver unit on the robot can distinguish them. The receiver sensor is in the end of the narrow cylinder which is mounted on the rotating platform. The cylinder has a narrow aperture in order to enhance directivity; the receiver is able to receive and decode the signal only when it is watching directly towards the transmitter. The mechanism that turns the receiver around contains a sensor that provides the information about its orientation (i.e. rotary encoder). This way, by turning the receiver for a full circle the robot is able to register in which positions it sees all of the 3 beacons, in other words to measure angles between these positions. The situation is shown in Fig. 3.

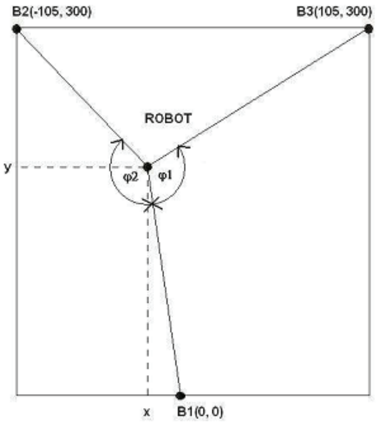

Figure 3. Triangulation based on angle measurement

If we designate the central point of robot by R, by measurement we acquire angles $\varphi 1 = \angle B1RB3$ and $\varphi 2 = \angle B1RB2$, which are the input parameters for the equations that are used for determining the position

We get the equations for calculating the position by using the following idea. Geometrical place of points R such that angle $\angle B1RB3 = \varphi 1$ is a circle with center in C1 (x1, y1), constructed above the chord B1B3, with inscribed angle $\varphi 1$. That property comes from the theorem that all of the inscribed angles over the same chord (in this case B1B3) are equal. The same way, we can construct a circumscribed circle with center in C2(x2, y2), constructed above the chord B1B2, with inscribed angle $\varphi 2$. These two circles intersect in two points, one of which is B1, and the other is R. So, the first step is to determine positions of C1 and C2 by applying laws of trigonometry and analytical geometry. It can be shown that:

$$r_1 = \frac{\sqrt{\frac{L_1^2}{4} + L_2^2}}{2\sin\varphi_1}$$

$$x_1 = \frac{L_1}{4} - \frac{L_2}{2} ctg\varphi_2$$

$$y_1 = \frac{L_2}{2} - \frac{L_1}{4} ctg\varphi_1$$

Lengths of sides of playing field are L1 and L2, r1 and r2 are radiuses of circumscribed circles. In equations for r2,x2 and y2 φ2 is used instead of φ1.

After we have calculated coordinates of centers of both circles, we determine robot coordinates by solving the system of circle equations:

$$(x - x_1)^2 + (y - y_1)^2 = r_1^2$$

$$(x - x_2)^2 + (y - y_2)^2 = r_2^2$$

By solving the system, we get final equations for robot coordinates:

$$x = 2\frac{(x_1 y_2 - x_2 y_1)(y_2 - y_1)}{(y_2 - y_1)^2 + (x_1 - x_2)^2}$$

$$y = 2\frac{(x_1 y_2 - x_2 y_1)(x_1 - x_2)}{(y_2 - y_1)^2 + (x_1 - x_2)^2}$$

III. SYSTEM REALISATION

Since maximum speed of the robot can be up to 1m/sec or even more in short period of time, to achieve constant monitoring of position of robot system localization system has to calculate its position adequately fast. For margin of error of 10 cm, which is usually acceptable, system must be able to give 10 measurements in one second. To achieve this speed, we used brushless DC motor from VCR as rotating platform. This motor is integrated with rotary transformer which allows contactless transfer of supply voltage to the sensor, as well as transfer of signal from sensor to the microcontroller that is used for its decoding, and later for calculating the position.

Since motor needs 100 ms to rotate full circle, receiver is “seeing” the transmitters for the time that motor need to turn around 1 ° ,or 100ms/360=270us. Each transmitter are sending unique code continuously, and to distinguish them code should be at least 10bit-s long, which leads to 27us for one bit. Duration of each bit is 10 periods of carrier (Fig. 4), so one period should be minimum 2.7us. To receive this signals we use TSOP7000 infrared (IR) receiver [8], which receives the signal modulated on 455 kHz (signal period of 2.2 us).

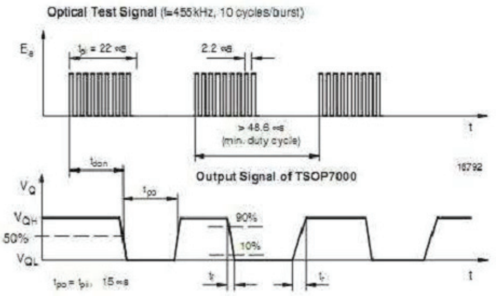

Figure 4. Coded beacon signal and output signal from TSOP7000

Transmitters are realizes with low-cost microcontrollers which generates adequate signal for IR diodes. Since IR diodes which we use have radiation angle of 20°, an array of this diodes is used, to send IR signal on whole playfield.

Communication between transmitters (beacons) and the receiver is done via standard UART (Universal asynchronous receiver/transmitter) protocol which greatly simplifies the decoding of the corresponding beacons. Each beacon continuously transmits a unique code via UART protocol.

Functional diagram of receiver system is given on Fig. 5.

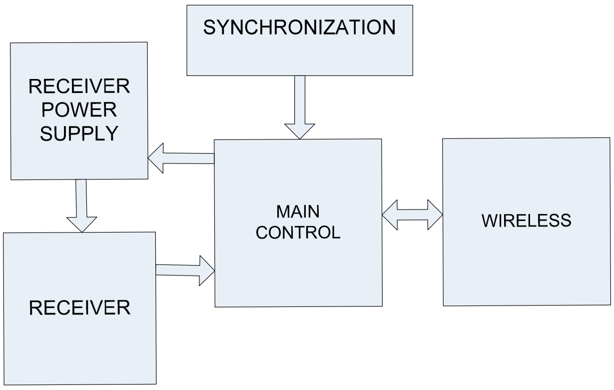

Figure 5. Functional diagram of receiver system

A. *Power supply for receiver circuit*

Since IR receiver is on rotating part of the motor, and rest of the electronic are fixes, no wire connection is possible, so rotary transformer is used to supply power. To achieve that main controller sends square signals of around 250 kHz to integrated H-bridge, which drives primary of transformer. On secondary of transformer simple diode circuit is used to obtain DC voltage.

B. *IR receiver circuit*

Acceptance angle of the infrared receiver TSOP7000 is around 90^O. To increase the accuracy of the robot localization, acceptance angle must be reduced. Otherwise the error in determining the angle between the beacons can be very large, and therefore the position of robots would be misleading. In order to reduce acceptance angle, sensor (TSOP7000) is packaged in a casing with two parallel slits (Fig. 6). In this way light can reach sensor only through the slits and acceptance angle of the receiver is reduce from 90^{O} (Fig. 6 b) to about 1^{O} (Fig. 6 c).

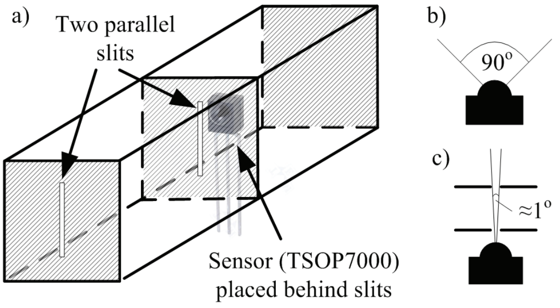

Figure 6. Sensor packaged in a casing with two parallel slits

Output of IR receiver TSOP7000 is in form of TTL logic signals. Output is connected to buffer realized with operational amplifier which also drives second pair of transformer coils. On secondary coil this signal is attenuated and mixed with signals from supply coils, but since frequency of useful signals is around 30 kHz, it is possible to extract them with active four-pole low pass filter. Next stages are amplifier and comparator which regenerates signal to TTL levels. Signals are then send to microcontroller.

C. *Synchronization circuit*

Although brushless motor have constant speed during one rotation, it changes with time due to decrease of battery supply of whole system. To know the time motor needs to make one rotation, we use hall sensors in combination with small permanent magnet connected to rotary part of the motor. Once per rotation hall sensor gives rising signal, but duration and amplitude of this signal varies with speed of the motor, and since there is low frequency hum from surrounding electronics, additional processing is required before it can be send to microcontroller. High pass filter eliminates noise, and voltage comparator sets level of the signal to TTL logic.

D. *Wireless communication*

This localization system is suitable for detecting the position of opponent robot, because it is allowed to put a beacon system on top of it. Then, the system uses wireless link to inform our robot about opponent position, which is very important for collision avoidance (as it is strictly forbidden by rules).

XBee module is used for wireless communication. This module has range of around 10 meters, and is able to send data on 115200 bauds, which is more than needed for our application. It is connected to serial port of microcontroller. Besides data transfer, Xbee module enables wireless control of power on and off localization system, which can significantly expand battery life.

E. *Main control circuit*

Control circuits consist of microcontroller and its peripherals. Microcontroller receives data from receiver, computes triangulation algorithms and sends position data over wireless module. It also controls peripheral circuits and motor speed.

IV. EXPERIMENTAL RESULTS

In Fig. 7 photograph of receiver of the implemented system for robot localization is presented.

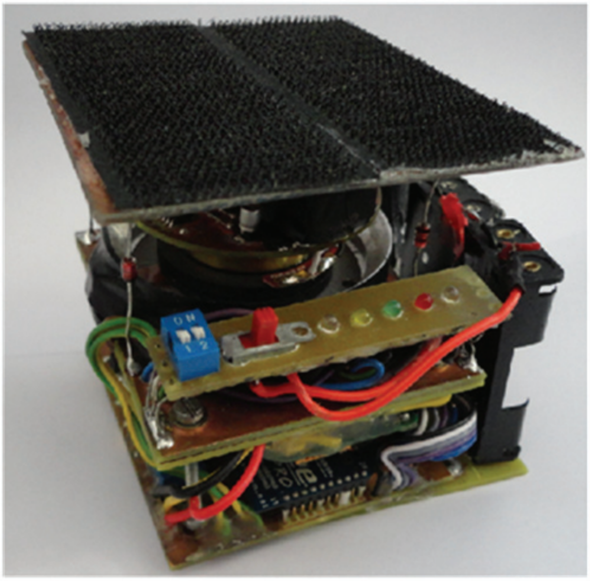

Figure 7. Photograph of the receiver for robot localization

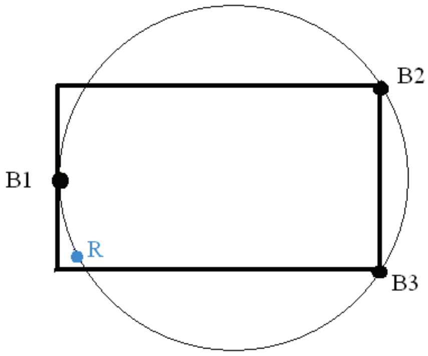

Figure 8. Robot and all beacons lies on the came circle

This system was realized and tested on the playing field for EUROBOT competition. Most precise measurements were on the center of the field, and highest errors were measured when robot was close to the parts of the fields where circle on (Fig 8.) intersect with the field. This is the extreme case when the robot and all beacons lie on the came circle, and the intersection point is not unique so position of the robot is not attainable, as it was explained in paper [4]. In this situations system detects that measured position is wrong, and that measurement is omitted. This is the reason that last measurement on Fig. 9 is omitted, and why is measurement on bottom right position so incorrect, with error above 30cm.

On Fig.9 measurement results (for the speed of 10 revolutions per second) on whole table are presented, usual error for both x and y coordinate was up to 5 cm, except on one position where this error was 10 cm. Measurement results from positions close to circle from Fig. 8 were useless. When rotation was slower, more precise results were achieved, typical error was up to 2cm for speed of 2 revolution per second.

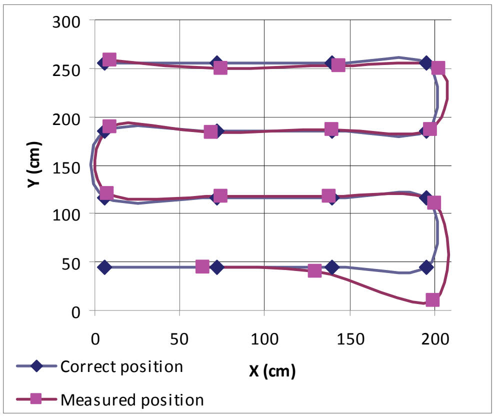

Figure 9. Measurement results for speed of 10 revolutions per second

In addition, measurement up to 5 meters between receiver and transmitter were made, system was able to detect transmitted code on every measurement.

V. CONCLUSION

In this paper we described details of realization of a sensor system for determining position of an autonomous robot. The system has been developed and successfully used in EUROBOT competition in 2011. This system is relatively cheap, especially compared to a laser triangulation system. Besides, it is much more reliable than an ultrasonic system. Still, it is prone to error of angle measurement, mostly because of different periods of time needed to detect transmitted code. Still, such system is suitable for detecting the position of opponent robot, because achieved precision is adequate, and it is allowed to put a beacon system on top of it.

This system can be easily adapted to be used in other applications, by readjusting beacons and location constants. It can be also used on larger areas, distances up to 5 meters were successfully tested, and even larger distances can be obtained with increase of number of transmitter IR diodes.

ACKNOWLEDGMENTS

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