An Encoded Infrared Sheet of Light Navigational Beacon System for Precise Localization of Indoor Mobile Robot Vehicles

Received 12th August 2008; accepted 8th December 2008.

James Kurian, P. R. Saseendran Pillai

Abstract:

A new localization approach to increase the navigational capabilities and object manipulation of autonomous mobile robots, based on an encoded infrared sheet of light beacon system, which provides position errors smaller than 0.02m is presented in this paper. To achieve this minimal position error, a resolution enhancement technique has been developed by utilising an inbuilt odometric/optical flow sensor information. This system respects strong low cost constraints by using an innovative assembly for the digitally encoded infrared transmitter. For better guidance of mobile robot vehicles, an online traffic signalling capability is also incorporated. Other added features are its less computational complexity and online localization capability all these without any estimation uncertainty. The constructional details, experimental results and computational methodologies of the system are also described.

Keywords: *infrared beacons, position estimation; robot localization; sheet of light beacons.*

1. Introduction

Accurate sensing of vehicle position and attitude is a vital requirement in many mobile robot applications. In this modern age the autonomous or semi autonomous robot vehicles find applications in automated inspection systems [1], floor sweepers [2], hazardous environments [3], autonomous truck loading systems [4], agriculture tasks, delivery in establishments like manufacturing plants, office buildings, hospitals [5], etc. and providing services for the elderly [6]. In addition to this, autonomous vehicles are widely utilized in undersea exploration and military surveillance systems [7,8]. Mobile robots are also finding their way into a growing number of homes, providing security, automation [9,10], and even entertainment. In order to navigate to their destination, the robots must have some means of estimating *where they are* and in *which direction they are heading*. Information about the location of an inanimate object, for example a cargo pallet, can streamline inventory and enable warehouse automation. A variety of technologies have been developed and used successfully to provide position and attitude information. However, many of these existing positioning systems have inherent limitations in their workspace. These limitations generally fall into two main categories: line-of-sight restrictions and insufficient resolution/precision as they require multiple clear lines-of-sight and absolute drift-free measurements.

In mobile robot applications, two basic position estimation methods are employed concurrently, viz., the *absolute* and *relative* positioning [11]. *Absolute* positioning methods usually rely on the use of appropriate exteroceptive (external) sensing techniques, like navigation beacons [12,13], active or passive landmarks [14], map matching [15], or satellite-based navigation [16] signals. Navigation beacons and landmarks normally require costly installations and maintenance, while map-matching methods are usually slower and demand more memory and computational overheads. The satellite-based navigation techniques are used only in outdoor implementations and have poor accuracy, of the order of a few metres. Relative position estimation or dead reckoning is based on proprioceptive (internal) sensing systems like odometry [17], inertial navigation system (INS) [18] or optical flow techniques [19], where the error growth rate of these systems are usually unacceptable. The vehicle performs self-localization by using relative positioning technique, called dead reckoning. For implementing a navigational system many indoor mobile robots use active beacons [13] together with traditional inertial navigation systems employing gyros and accelerometers or position odometric system or both. The latter provides accurate and precise intermediate estimation of position during the path execution.

Inertial Navigation System (INS) is complex and expensive and requires more information processing for extracting the required position and attitude information. The localization based on INS uses accelerometers or gyros, where the accelerometer data must be integrated twice to yield the position information, thereby making these sensors extremely sensitive to drift. Though the odometric system is simple, inexpensive and accurate over short distances, it is prone to several sources of errors due to wheel slippage, variations in wheel radius, body deflections, surface roughness and undulations. For better traction most of the mobile robots use rubber tires, which have unevenness in their diameter and these tires compress differently under asymmetric load distribution or load imbalances, causing further position and attitude errors.

For the successful navigation and path planning of mobile robots, a well-defined and structured workspace is required. This can provide high-rate of precise positioning and attitude information for reliable estimation of the vehicles' localization and navigation map. For outdoor applications Differential Global Positioning System (DGPS) based localization techniques provide adequate resolution, whereas for indoor use, this resolution is insufficient and moreover the satellite signals may be obstructed, which further aggravate the situation. Substantial research works are going on in the area of simultaneous localization and map building (SLAM) [20] using various sensing systems, which require more memory and computational overhead for feature extraction. The errors in kinematic and environmental parameters will lead to poor estimation of positions during the path execution and this necessitates the need for frequent absolute localizations. For indoor applications like localization of personnel, products and vehicles in warehouses as well as production environments, where a stable and accurate localization system is necessary, the ultrasonic, infrared, [27] radio frequency [21] and laser techniques [22] are commonly used. The use of ultrasonic sensors [23, 24] is limited to the proximetry because of poor system characteristics like moderate axial resolution, low lateral resolution, and high rate of inaccuracies in measurements resulting from multiple reflections, environmental complexity and the aperture cone. Radio frequency systems are very expensive and are susceptible to reflections from metallic objects. These localization systems, which utilize triangulation or trilateration techniques [25], have high uncertainty in position estimations, incurring extra computational overheads, resulting possibly in slowing down the path execution process of the vehicle.

Most of the high-resolution systems are complex and expensive. A cost effective commercially available infrared Beacon System used for indoor robot localization application is the *Northstar* from Evolution Robotics Inc. [28]. This system requires a reflecting roof for its functioning which is not always feasible in an industrial/ warehouse environment. The reflective characteristics as well as the indoor lighting system may affect its performance. This system suffers from the computational overheads due to the triangulation technique.

The limitations of the above diverse ways of positioning systems that are already in use open the scope for further research opportunities for improvement and innovations. Many applications that depend on position measurements could benefit from the development of a new positioning system technology that alleviates these restrictions. The development of a cost effective, accurate and reliable system, utilising an infrared sheet of light, which minimizes position errors during the path execution is presented in this paper. This provides a cost effective position and attitude sensing system designed specifically to face the challenges in a realistic, cluttered indoor environment, such as that of an office building or warehouse. In the proposed approach, a number of beacon transmitters are installed in the well defined and structured workspace as required and all the transmitters provide the estimates in a common reference frame or even universal frame. Two sensor units on the mobile robot read the beacon and process the measurements to determine its position, attitude and traffic signalling information. The real-time identification and correction methods mitigate the impact of localization errors caused by the robot vehicles and the environment. A novel resolution enhancement algorithm suggested in this paper satisfies the requirements for a high-resolution localization system. A prototype system has been built to demonstrate the suggested approach.

2. Sheet of light beacon

2.1. Principle of operation

The localization systems based on computer vision, range finders or other sensors that do not require a special arrangement of the environment are computationally expensive and not too robust. Most of the infrared, ultrasonic or radio frequency beacons have inherent emission characteristics that may affect the resolution of the measuring system. Hence it is essential to consider a robust, low-cost system for the absolute positioning of mobile robots or other moving objects. This work describes an assembly utilizing an infrared LED source that restricts the spreading of the light intensity distribution confined to a sheet of light.

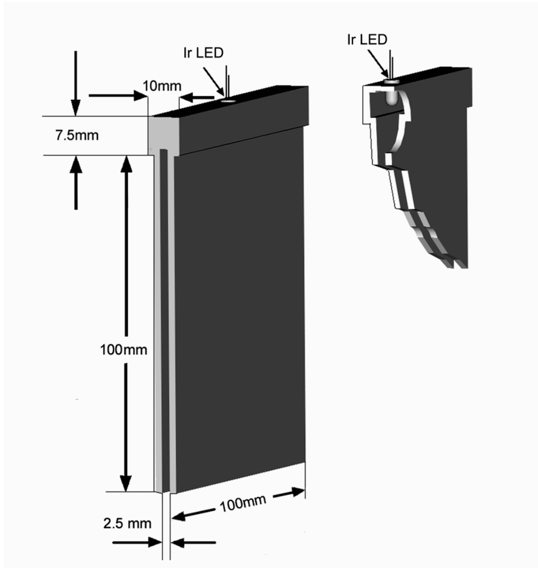


Fig. 1. The infrared LED of the beacon transmitter mounted on the structural assembly.

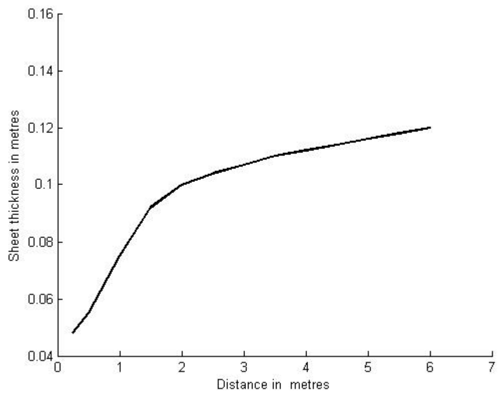


Fig. 2. Variation of effective light sheet thickness against the mounting height of the beacon.

Sheet of light techniques are utilized in robotics and industrial applications for sensing objects, its shape and size [26]. Here a new approach to produce the sheet of light and an encoding scheme for localization application is described. In order to produce a sheet of light for high-resolution localization applications, an innovative assembly as shown in Fig. 1 has developed. The infrared beam is guided through the space between two identical sand blasted parallel metal plates of dimensions 100 mm x 100 mm, kept 2.5 mm apart. These metal plates will be acting as Lambertian scattering surfaces (diffuse reflectors) and their dimensions have effects on the sheet thickness as well as infrared light intensity. A single infrared LED mounted at the centre of the LED housing, as shown, is seen to have a beam angle of around 45 degrees, which can be increased by mounting multiple LEDs. ***The width of the region of the infrared light sheet where the receiving system can properly read the encoded position is the Effective Light Sheet Thickness (ELST).*** The variation of effective infrared light sheet thickness against the height (h) of the mounting structure has been studied and the results are shown in Fig. 2, which illustrates a linear increase in light sheet thickness for mounting heights above two metres.

2.2. The beacon transmitter

The Digital Infrared Sheet of Light Beacons (**DISLiB**) constructed using the above assembly are location encoded and are designed around a 16F675 PIC microcontroller as shown in Fig. 3. The system transmits a carrier frequency of 40 kHz, which is pulse width modulated with 12 bit Beacon Identification Number (**BIN**), one parity bit and appropriate start pulse. The BIN is assigned to each beacon installed in the workspace. The system employs a scaled version of Sony Infrared Remote Control (**SIRC**) protocol to transmit the data and the protocol structure is shown in Fig. 4. The time taken to transmit a location information is around 6 ms, which may vary slightly as the protocol uses different burst lengths for '1's and '0's. Besides continuously transmitting the encoded position information the microcontroller in the beacon transmitter drives the infrared LED(s) by switching a transistor in series with a current limiting resistor.

By interfacing micro-switch inputs to the microcontroller for the configuration of a particular Beacon Identification Number (**BIN**), one can easily encode different location information to the beacons without modifying the firmware in each unit. Traffic signalling information like speed limits, sharp turnings etc., can be communicated by adding a few more bits and properly encoding the beacon. A number of beacon transmitters are mounted at various locations to define the environmental structure. Each beacon will send fixed BIN plus traffic signalling bits to the receiver. By establishing an RS 485 network among the beacons and a host computer, the position information in case of restructuring, as well as traffic signalling commands can be modified online. The RS 485 interface is designed using DS75176 transceiver chip and the RS 485_USB bridge is designed around an 18F2550 PIC microcontroller with inbuilt USB support. Thus the system can be made user friendly by incorporating the RS 485 network with the host computer.

3. Vehicle localization

3.1. Method of Installation and Working

Most of the absolute localization methods using ultrasonic, infrared, radio frequency or laser require multiple known beacons or encoded strips in the vicinity of the robot vehicle as well as rotating/scanning, control and computational units to estimate the position of the system. If multiple localization systems are installed, a sensor fusion algorithm must be used to obtain a better estimate [27]. A prerequisite for a successful map matching or landmark based technique of localization, is an acceptable accuracy in the relative position estimation. By eliminating all the inherent problems and complexities of these existing systems a high-resolution absolute localization is possible with the use of Digital Infrared Sheet of Light Beacons (**DISLiB**). By properly installing the Digital Infrared Sheet of Light Beacons (**DISLiB**) at known locations (**B**) vertically above the track as shown in Fig. 5, an accurate and robust representation of the workspace

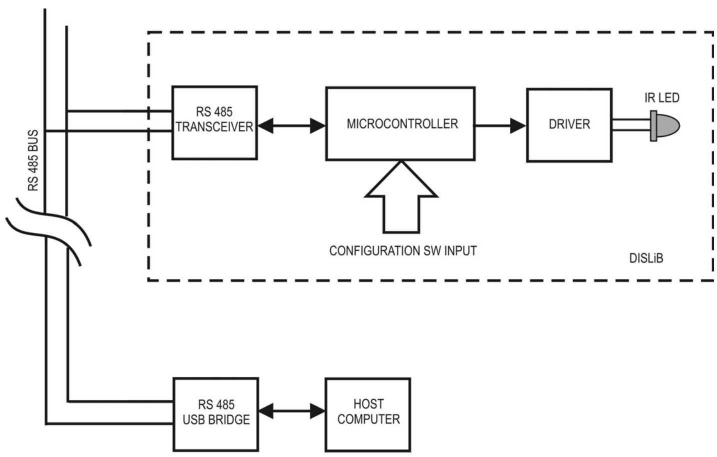


Fig. 3. Functional block diagram of the beacon transmitter.

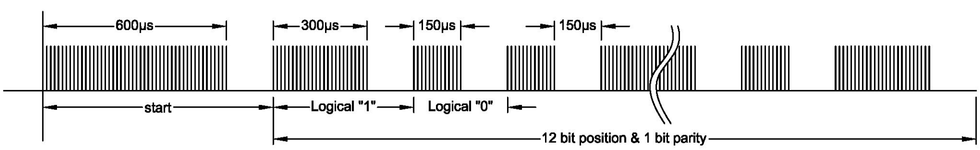


Fig. 4. The scheme of the scaled version of SIRC communication protocol.

can be achieved for path planning and object identification of the mobile robot. In a typical indoor structure, the beacons should be mounted at a height (h) of about three metres for covering the entire width of the track and for greater track widths either multiple infrared LEDs or increased mounting heights within the reading threshold of the beacons are preferred. For a systematic implementation of the system, the entire workspace can be divided into various zones and tracks, where each track in the zones is properly labelled for effective functioning. The beacon distributions can be identified based on the systematic errors resulting from the kinematic imperfections of the vehicle and non-systematic errors due to the environment and depending on the resolution requirements.

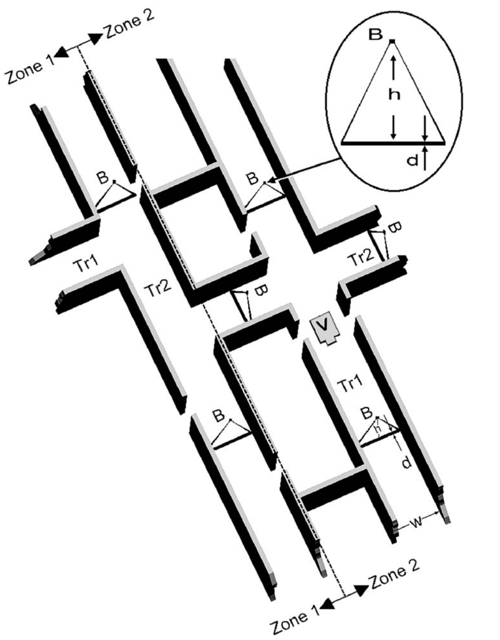


Fig. 5. A typical workspace showing the beacon positions (B) and mounting of the same vertically above the tracks $Tr1, Tr2$ etc. at a height of h metres.

3.2. The Beacon Receiver and Controller

During path execution, the position information gathered by the infrared remote control receiver module from the beacon is processed by the microcontroller system of the vehicle that manages its navigation and guidance. As the vehicle crosses the infrared light sheet of thickness d, the microcontroller based navigation system directly captures the location-encoded information (**BIN**) and the position is updated after retrieving the corresponding absolute position from the database. The receiver takes 6 ms for position decoding and hence at least 12 ms is required for a guaranteed position update while crossing a DISLiB. For a mounting height of about three metres the effective light sheet thickness (d) is around 0.12 m (Fig. 2), and hence the maximum speed of the vehicle has to be limited to a value less than 10 m/s. As the speed of practical indoor vehicles is less than this, it does not cause any problem in field applications. Up to this speed, the resolution of the system remains as the effective light sheet thickness.

The functional block diagram of a typical beacon receiver is shown in Fig. 6. The odometric sensors provide the position information to the microcontroller, which manages the drive and control systems. A wireless link is established to monitor and assist the navigational guidance system of the robot vehicle, which utilizes an RF Programmable System on Chip (PSoC) module [29] from Cypress Semiconductor Corporation - CYWM6935 PAEC. The module can have a range of about 200 metres and operates at 2.4 GHz ISM band. It has inbuilt Direct Sequence Spread Spectrum (DSSS) communication [30] facility with a 64 bit PN code for spreading and dispreading of data. The on chip serial peripheral interface (SPI) can be utilized for configuration and establishing communication with the module. This RF transceiver module is ideal for short-range indoor applications. For the receiver/controller design microchip PIC 18F4550 40-pin microcontroller with inbuilt SPI support is used. The system performance can further be improved by using multiple microcontroller-based designs.

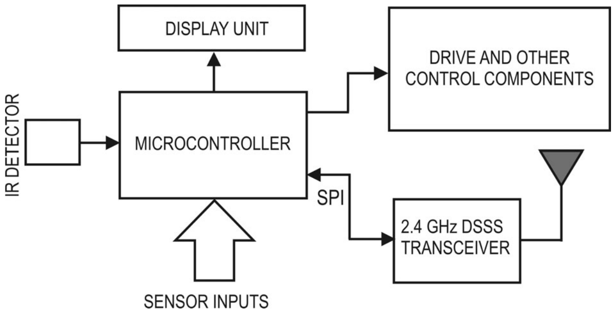
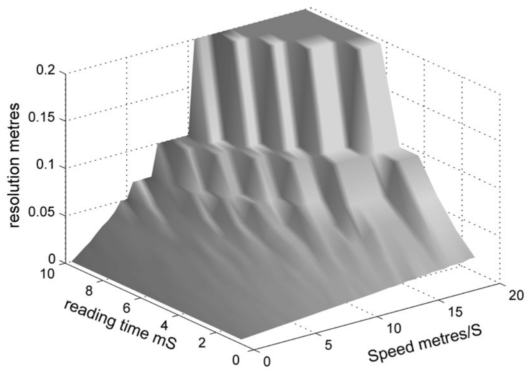


Fig. 6. Block diagram of the beacon receiver and controller.

3.3. The Beacon performance and evaluation

a)



b)

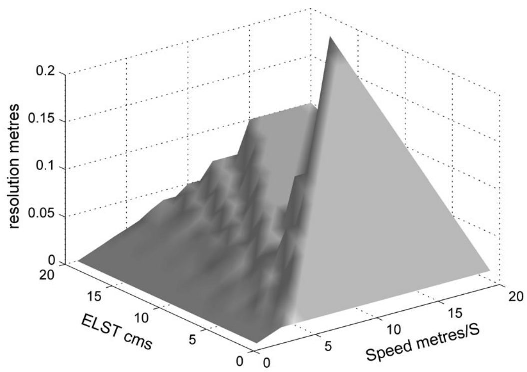


Fig. 7. 3-D surface plots (a) indicates the variation of resolution with respect to speed and reading time (b) the variation of resolution with respect to speed and ***ELST****.*

This is an absolute localization system for correcting the errors caused by the inbuilt sensory system of the mobile robot vehicle. In situations where frequent correction is required, more numbers of beacons are to be installed. The beacon (**DISLiB**) performance is associated with various parameters like the speed of the vehicle (during beacon crossing), effective light sheet thickness (**ELST**) of the system and the reading time, which depends upon the coding scheme of the beacon transmitter. As the vehicle crosses the **DISLiB**, the system takes a certain number of readings depending on reading time, **ELST** and the speed of the vehicle. The role of these parameters, which affect the performance, has been studied and a resolution enhancement algorithm has been developed which is explained in section 4. The characteristics are plotted in Fig. 7. These 3-D surface plots show the role of vehicle speed, beacon's reading time and Effective Light Sheet Thickness on the resolution of the system. Fig. 7a indicates the plot of speed and reading time against the resolution with an effective sheet width of 0.12 metres. The discrete variation of the resolution depends on the number of beacon readings, which is a function of speed and reading time. Fig. 7b shows the effect of ELST on the resolution and vehicle speed.

4. Resolution Enhancement

During path execution, as the vehicle crosses the **DISLiB**, the system takes n number of readings depending on the ELST and the speed of the vehicle. For vehicles moving at a speed less than the maximum speed allowed by the system, the resolution could be increased by making use of a resolution enhancement algorithm. Fast moving vehicles have to be slowed down during the localization process for achieving acceptable resolution enhancement. The system generates a lookup table with the count (n), beacon reading (**BIN**) and the odomertic position information (P_n), as shown in Table 1.

Table 1. Lookup table formulated for the execution of the resolution enhancement algorithm.

Count	DISLiB Reading	Odometric Reading	
1	BIN	P_1	
2	BIN	P_2	
3	BIN	P_3	
.	BIN	.	
n/2	BIN	$P_{n/2}$	t_r t_b
.	BIN	.	
.	BIN	.	
n	BIN	P_n	

Under a particular **DISLiB** the beacon identification number is the same for all the observations. The beacon identification number points to a memory location in the database from where the position information can be retrieved. The position information furnished by the proprioceptive sensors corresponding to $n/2^{th}$ or $(n+1)/2^{th}$ position respectively for even or odd values of n *can be updated*. For an even value of n, $P_{n/2}$ can be replaced with an absolute position value from the database pointed by **BIN** and hence the resolution of the system is enhanced from effective width of light sheet d to d/n. In fact the algo-rithm replaces the $P_{n+1}{}^{th}$ position value with [**BIN**] + (P_{n+1} - $P_{n/2}$). The vehicles fitted with two sensors create separate tables and finally updates with the average value.

The resolution is effectively improved in the present set up, as it is the product of the speed of the vehicle and reading time, as illustrated below. The enhanced resolution r, which is the ratio of the effective light sheet thickness to the number of readings, can be deduced to:

$$\boldsymbol{r} = \frac{d}{n} = \frac{s_v t_b}{INT(t_b / t_r)} \approx (s_v\, t_r) \qquad (1)$$

Where

s_v - *speed of the vehicle*
t_b - *time taken by the vehicle to cross the light sheet (ELST)*
t_r - *time required for one beacon reading*
$INT(t_b/t_r)$ - *integer value of the ratio* (t_b/t_r).

Equation (1) gives the inference that a reduced vehicle speed improves the resolution. When $t_r = t_b$, the resolution enhancement algorithm will fail since $n=1$, and the resolution remains at d. For a vehicle crossing the DISLiB at a speed of around 3 m/sec. with a reading time of 6ms equation (1) computes the resolution to be approximately 0.02 m. A further improvement in resolution can be obtained by reducing the beacon reading time, which in turn is achieved by decreasing the infrared burst lengths. Usually the reading time is constant for a set up so that the resolution of the system varies with the speed of the vehicle.

5. Position and attitude update

The kinematics and navigation equations for a three-wheeled mobile vehicle with one driving-steering wheel and two fixed rear wheels in-axis is considered for this study. The odometric navigational systems are implemented using three optical incremental encoders. The driving steering wheel (front) is attached with a permanent magnet DC motor with inbuilt encoder, which measures the angular increments and a multi-turn potentiometer for the measurement of the steering angle ϕ. The rear wheels are also attached with encoders to estimate the position and attitude of the vehicle. The **DISLiB** beacon receivers are utilized to update the position and heading of the vehicle by utilizing the update equations for this vehicle geometry.

The symbols used in the equations are defined below:

α - *the angle between the light sheet footprint and the line joining between the beacon receiver sensors* S_1 *and* S_2.
β_i - *the angle between the light sheet footprint of the* i^{th} ***DISLiB*** *and y axis of the fixed reference frame.*
θ - *the estimated attitude of the vehicle with respect to the fixed referenceþ*
θ_i - *the estimated attitude of the vehicle using the* i^{th} ***DISLiB*** *with respect to the fixed referenceþ*
ϕ - *the steering angle with respect to axis of symmetryþ*
R - *the wheel radius of the vehicleþ*
n_L - n_R - n_F - *the encoder incremental pulse counts from the*

left, right and front wheel encoders respectively.
N *- the number of pulses per revolution of the encoder.*
L *- the distance between the rotation axis of the front (driver) wheel and the axis of the back wheel.*
D *- the distance between rear wheels.*
t_b *- the time required to cross the beacon light sheet.*
t_d *- the time delay between two sensor outputs.*
a *- half the distance between two beacon sensors.*

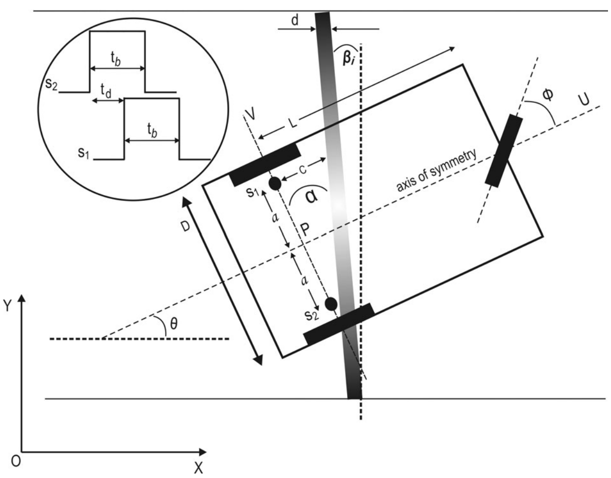


Fig. 8. Kinematic scheme of the three-wheeled mobile robot vehicle and the footprint of the effective light sheet width d*. The attitude* θ *is the angle between the absolute reference frame OXY and the mobile reference frame PUV. The origin* P *is attached to the mid point of the axes joining the rear wheels and the sensors* S_1 *and* S_2*.*

Fig. 8 shows a typical posture of the mobile vehicle with an orientation "θ" and steering angle "ϕ". Two identical DISLiB sensors S_1 and S_2 are mounted at the top of the rear wheel axis of the vehicle at a distance of $2a$. If the vehicle's axis of symmetry is normal to the sheet of light both the sensors receive the signal simultaneously. From the **BIN** received, the mounting angle of the corresponding beacon transmitter, β_i can be retrieved from the database. If the vehicle crosses the beacon with a heading angle "θ" (not equal to β_i) there will be a lag or lead between the received signals, which is a measure of the attitude of the vehicle. The signal waveforms derived from the start pulse is shown in Fig. 8 (inside the circle), in which the time duration t_b is the time required to cross the beacon and the lag or lead time t_d is the time required to cover the distance "c" by the vehicle. The lead or lag time t_d is a measure of the attitude of the vehicle. The attitude θ_i computed by the receiver unit in the vehicle is given by the following expression:

$$\theta_i = tan^{-1}\left(\frac{c}{2a}\right) + \beta_i = tan^{-1}\left(\frac{t_d s_v}{2a}\right) + \beta_i \qquad (2)$$

The computed value of θ, which is $\theta(k)$ in equations (5) and (8) is updated with this θ_i. For the computation of the position and attitude let us consider the pulse counts from the two independent optical encoders attached to the rear non-driven idler wheels of the vehicle which have less coupling with the steering and driving system and very less slippage between point of contact and the floor. The update equations for this model are as follows [31]:

$$x(k+1) = x(k) + \frac{\pi R}{N}(n_R(k) + n_L(k))cos\ \theta(k) \qquad (3)$$

$$y(k+1) = y(k) + \frac{\pi R}{N}(n_R(k) + n_L(k))sin\ \theta(k) \qquad (4)$$

$$\theta(k+1) = \theta(k) + \frac{2\pi R}{N}\frac{(n_R(k) - n_L(k))}{D} \qquad (5)$$

The distance moved by the wheel's point of contact could be derived by considering the vehicle's front driving steering wheel's incremental pulse count data. The steering rotation is limited to ±40° about the axis of symmetry of the vehicle. The potentiometer sensor attached to the steering system generates a voltage in the range of 0.5 V to 4.5 V for representing the steering angle. This is fed to the analog to digital converter, the output of which can be read by the microcontroller and the corresponding steering ϕ can be computed. The update equations for this model are described as follows:

$$x(k+1) = x(k) + \left(\frac{2\pi R}{N}\right) n_F(k)\ cos\ \theta(k)\ cos\,\phi(k) \qquad (6)$$

$$y(k+1) = y(k) + \left(\frac{2\pi R}{N}\right) n_F(k)\ cos\ \theta(k)\ sin\,\phi(k) \qquad (7)$$

$$\theta(k+1) = \theta(k) + \left(\frac{2\pi R}{N}\right) n_F(k)\ \frac{\sin\phi(k)}{L} \qquad (8)$$

In a practical environment the pulse count received from certain encoders may indicate an over count due to workspace and operating conditions. So the least value of $x(k+1)$, $y(k+1)$ and $\theta(k+1)$ estimated from the equations *(3) to (8)* can be used for computing the pose of the vehicle.

6. Conclusions

The **DISLiB** described in this paper, developed for mobile robot localization is a high resolution system which is simple, fast and accurate without much of computational burden or significant processing. Most of the localization research works are experimented in laboratory or room like environment. But most of the service mobile robot vehicles are employed in industries, warehouses etc. where a particular path is defined for their movement. Most of the available beacon's performance in corridors and narrow passages are not satisfactory but the performance of **DISLiB** is very encouraging in these situations. The installation is not limited to corridors, provided the vehicle crosses the light sheet for position update and error correction. Even in indoor applications the inclined paths cause localization errors which are very difficult to eliminate. But by installing **DISLiB**s at appropriate locations one can easily reduce the same. Normally the **DISLiB**s are fixed in such a way that the vehicle crosses the beacon with an angle α equals to zero *(i.e.* $\theta = \beta_i$*).*

The bit length used for position encoding can be easily increased for mapping large workspaces. Separate firmware for encoding different beacons can be eliminated by incorporating either configuration switch inputs to the system or a RS 485 type of network and a host computer. The wireless closed loop monitoring increases the overall efficiency of the system. While crossing the very short distances of around 0.12 m (ELST), the system assumes uniform vehicle speed and accurate odometry. In order to guarantee this, the beacon installation points can be selected accordingly. For exterior mobile robot localization, the beacon systems can be organised on pillars in a side looking arrangement. The effective light sheet thickness depends on light intensity, mounting height and receiver sensitivity. The non-uniform distribution of the beacon light intensity results in slight variations of light sheet thickness on the sides of the passage. This can be reduced by the use of multiple infrared LEDs. This system will obviate the inherent odometric and INS position errors.

AUTHORS

James Kurian* and P. R. Saseendran Pillai - Department of Electronics, Cochin University of Science and Technology, Cochin-682022, INDIA. Phone: +91-484-2576418; Fax: +91-484-2575800.
E-mails: james@cusat.ac.in, prspillai@cusat.ac.in.
* Corresponding author

References

[1] Siegel M., Gunatilake P., "Remote Inspection Technologies for Aircraft Skin Inspection", *IEEE Workshop on Emergent Technologies and Virtual Systems for Instrumentation and Measurement,* Ontario, Canada, May 1997.

[2] Prassler E., Ritter A., Schaeffer C., Fiorini P., "A Short History of Cleaning Robots", *Autonomous Robots*, *Special Issue on Cleaning and Housekeeping Robots,* vol. 9, issue 3, December 2000.

[3] Iborra A., Pastor J., Alvarez B., Fernandez C., Merono J., "Robots in Radioactive Environments", *IEEE Robotics and Automation Magazine*, December 2003.

[4] Stentz A., Bares J., Singh S., Rowe P., "A Robotic Excavator for Autonomous Truck Loading", *Autonomous Robots,* vol.7, 1999, pp. 175-186.

[5] Rossetti M. D., Kumar A. and Felder R., "Mobile Robot Simulation of Clinical Laboratory Deliveries". In: *The Proceedings of the Winter Simulation Conference. 1998*.

[6] Montemerlo M., Pineau J., Roy N., Thrun S., Verma V., "Experiences with a Mobile Robotic Guide for the Elderly". In: *Proceedings of the AAAI National Conference on Artificial Intelligence*, Edmonton, Canada, 2002.

[7] Bahl. R., "Object Classification using Compact Sector Scanning Sonars in Turbid Waters". In: *Proc. 2nd IARP Mobile Robots for Subsea Environments, Monterey, CA*, vol. 23, 1990, pp. 303-327.

[8] Anthony J. Healey, "Application of Formation Control for Multi-Vehicle Robotic Minesweeping". In: *Proceedings of the IEEE* CDC *Conference,* 2001.

[9] Everett H.R., Gage D.W., "From Laboratory to Warehouse: Security Robots Meet the Real World", *International Journal of Robotics Research*, *Special Issue on Field and Service Robotics,* vol. 18, no. 7, July 1999.

[10] Pastore T.H., Everett H. R., and Bonner K., "Mobile Robots for Outdoor Security Applications". In: *American Nuclear Society 8th International Topical Meeting on Robotics and Remote Systems* (ANS'99), Pittsburgh, PA, April 1999.

[11] Borenstein J., Everett H., Feng L., Wehe D., "Mobile Robot Positioning - Sensors and Techniques", *Journal of Robotic Systems*, *Special Issue on Mobile Robots,* vol. 14, no. 4, 1997.

[12] Kleeman L., "Optimal Estimation of position and Heading for Mobile Robots Using Ultrasonic Beacons and Dead-reckoning". In: *Proceedings of the IEEE International Conference on Robotics and Automation*, Nice, France, 1992.

[13] Leonard J. J. and Durrant-Whyte H. F., "Mobile Robot Localization by Tracking Geometric Beacons", *IEEE Transactions on Robotics and Automation*, vol. 7, no. 3, 1991, pp. 376-382.

[14] Wijk O., Christensen H.I., "Localization and navigation of a mobile robot using natural point landmarks extracted from sonar data", *Robotics and Autonomous Systems,* vol. 31, 2000, pp. 31-42.

[15] López-Sánchez M., Esteva F., de Màntaras R.L., Sierra C., Amat J., "Map Generation by Cooperative Low-Cost Robots in Structured Unknown Environments", *Autonomous Robots,* vol. 5, no. 1, 1998, pp. 53-61.

[16] Sukkarieh S., Nebot E.M., Durrant-Whyte H.F., "A High Integrity IMU/GPS Navigation Loop for Autonomous Land Vehicle Applications", *IEEE Transactions on Robotics and Automation,* vol. 15, no. 3, 1999, pp. 572-578.

[17] Borenstein J., Feng L., "Measurement and Correction of Systematic Odometry Errors in Mobile Robots", *IEEE Transactions on Robotics and Automation*, vol. 12, no. 6, 1996, pp. 869-880.

[18] Barshan B., Durrant-Whyte H.F., "Inertial Navigation Systems for Mobile Robots", *IEEE Transactions on Robotics and Automation*, vol. 11(3), 1995, pp. 328-342.

[19] Lee S., Song J.-B., "Robust Mobile Robot Localization using Optical Flow Sensors and Encoders". In: *Proc. of the IEEE Int. Conf. on Robotics & Automation*, April 2004, pp. 1039-1044.

[20] Leonard J.J., Durrant-Whyte H.F., Cox I.J., "Dynamic map building for an autonomous mobile robot", *Int. J. Robotic Research*, vol. 11, no. 4, 1992, pp. 286-298.

[21] Winton, P. and E. Hammerle , "High resolution position estimation using partial pulses", *IEE Electronics Letters*, vol. 36, no. 10, 2000, pp. 897-898.

[22] Lingemann K., Nuchter A., Hertzberg J., Surmann H., "High-speed laser localization for mobile robots", *Robotics and Autonomous Systems, vol.* 51, 2005, pp. 275-296.

[23] Hoppenot P., Colle E, Barat C., "Off line localization of a mobile robot using ultrasonic measures", *Robotica, vol.* 18, 2000, pp. 315-323.

[24] Han Y., Hahn H., "Localization and classification of target surfaces using two pairs of ultrasonic sensors", *Robotics and Autonomous Systems, vol.* 33, 2000, pp. 31-41.

[25] F. Thomas and L. Ros, "Revisiting trilateration for Robot Localization", *IEEE Transactions on Robotics*, vol. 21, no. 1, 2005, pp. 93-101.

[26] Fu K.S., Gonzalez R.C., Lee C.S.G, *Robotics - Control, Sensing, Vision and Intelligence,* McGraw-Hill, 1987.

[27] Cox I.J., "Balache-An Experiment in Guidance and Navigation of an Autonomous Robot vehicle", *IEEE Transactions on Robotics and Automation*, vol. 7, no. 2, 1991. pp. 193-204.

[28] http://www.evolution.com/products/

[29] Data sheet, "CYWUSB6935 Wireless USB LR 2.4-GHz DSSS Radio SoC", *Cypress Semiconductor Corporation*, 2005, *www.cypress.com*.

[30] Peterson R., Ziemer R., Borth D., *Introduction to Spread Spectrum Communication*, Prentice Hall, 1995.

[31] De Cecco M., "Sensor fusion of inertial-odometric navigation as a function of the actual manoeuvres of autonomous guided vehicles", *IOP Measurement Science and Technology,* vol. 14, 2003, pp. 643-653.