Mobile node localization using infrared angle of arrival sensor

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Abstract - This paper presents mobile node localization algorithm for environments in which GPS or other positioning systems are not applicable or available. Existing localization systems are using propagation characteristics such as attenuation or speed of radio or ultrasound signals or timings of controlled laser radiation to estimate node azimuth and/or distance to nodes with known position (anchor nodes). Presented algorithm is using azimuth estimation based on measured angle of incidence of controlled infrared radiation from anchor nodes. Angle of arrival estimation and localization algorithms are implemented on low cost, small footprint and low power wireless nodes based on 8-bit microcontroller. Experimental evaluation results are promising and with further sensor optimization can guarantee high precision of estimated locations.

I. Introduction

Solution to mobile node localization problem in environments where general purpose localization methods are unavailable is presented in this paper. Method is implemented on low cost and low power wireless sensor network nodes [1]. Each node consists of microcontroller, radio module, and angle of arrival sensor prototype (Figure 1).

Node with unknown location receives true coordinates of limited set of nodes with known position (anchor nodes). Subsequently, using angle of arrival sensor it measures angle of incidence of infrared radiation emitted by anchor nodes and estimates their azimuths. With the data obtained from at least 3 anchor nodes, mobile node is able to calculate its position.

Existing solutions are based on radio interference measurements and require more expensive hardware with three [2] or two [3] antennas. There are also solutions that use rotating lasers [4] but they come with significant setup overhead.

A. Platform

Wireless sensor node platform used is commercially available under name JeeNode. This low cost platform consists of an 8-bit AVR RISC Atmel ATmega328P microcontroller, RFM12B radio module and 4 input/output ports. Communication with PC is possible through serial UART port. Each of 4 available ports provides digital and analog input/output, power lines, interrupt line and ground. The whole platform has small footprint and low power usage.

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II. Hardware

A. Angle of arrival sensor

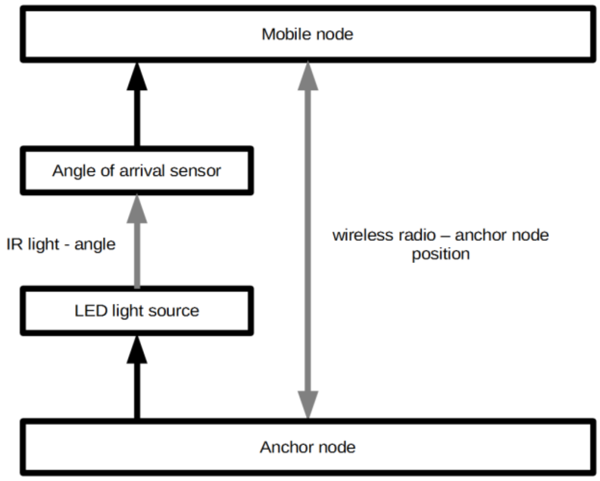

Figure 1. Conceptual scheme

Angle of arrival (AoA) sensor consists of 12 infrared phototransistors (Figure 4) [5] evenly distributed along the circular rim of the sensor. Infrared radiation is chosen to minimize expected interferences with visible light.

Each phototransistor emitter is connected to multiplexer input and with resistor in series to ground. Voltage is fed to phototransistor collector. Multiplexer channel selection is controlled by dedicated slave microcontroller and this way each voltage drop can be measured using 10 bit A/D converter on microcontroller's analog input (Figure 2).

B. IR radiation source

IR radiation source consists of 15 evenly circularly distributed infrared LE diodes [6] that can be switched on and off by microcontroller. LEDs are triggered (for short duration) by microcontroller digital output pin (DOP) that is connected to MOSFET because digital output pin can only provide 40 mA of current which is not enough for powering all LEDs. LEDs are connected directly to battery power source that provides 5 V (Figure 3).

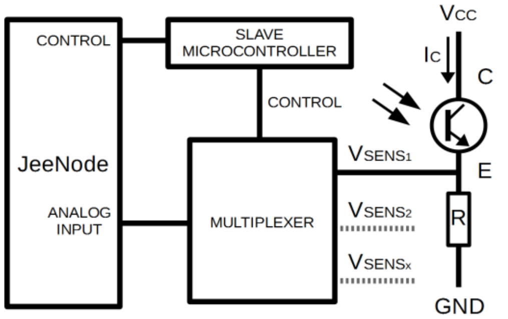

Figure 2. Phototransistor circuit collector current I_C (max 0.31 mA) is dependent on IR radiation intensity, V_{SENS} (max. 3.1 V) is voltage detected by microcontroller, pin is connected to multiplexer input.

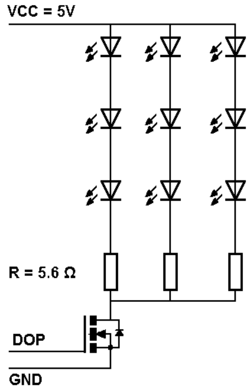

Figure 3. Radiation source scheme, total current drawn from voltage source by LEDs is 565 mA.

III. Node Localization

A. Localization method

In the current setup, mobile node is the node with unknown position, likewise nodes with known coordinates or anchor nodes are stationary [7]. Anchor nodes are equipped with omnidirectional IR radiation source and mobile node is equipped with IR AoA sensor. If the mobile node is in the communication and AoA sensor range of at least 3 anchor nodes, then it is able to localize itself. In this paper only 2D localization is considered.

B. Localization procedure

Based on the stated assumptions, procedure for node localization is as follows:

1. Mobile node broadcasts request for nearby node IDs. All nearby anchor nodes in range send their ID with different delay (ID based) to mobile node.
2. Mobile node measures ambient IR radiation, that is, IR radiation in the environment with all anchor nodes having their IR diodes turned off.
3. Mobile node sends request to the first (by ID) nearby anchor node in range for position and IR radiation.
4. Anchor node switches its IR LEDs on, transmits location and lights on confirmation.
5. Mobile node using AoA sensor measures IR radiation intensity from different directions. To be able to calculate intensity that originates from anchor node IR LED, ambient IR radiation that was measured in step 1 is subtracted from values obtained in this step.
6. Mobile node estimates azimuth of the anchor node using measured intensity values (from each phototransistor, thus in each direction) of its IR radiation and sends confirmation that the location is received and angle of light arrival is measured. Estimated azimuth and anchor location are stored in memory.
7. Localized node turns off LED light and transmits light off confirmation
8. After light off confirmation is received the steps 2. through 7. are repeated for each anchor node in the range.
9. After all anchors in the range have sent their locations and all azimuths are estimated mobile node selects three anchors with minimum geometric dilution of precision (GDOP). Localization precision depends on the relative locations of anchor nodes and this selection is mandatory to select most appropriate anchors triplet.
10. Location is estimated using selected anchors.

C. Azimuth estimation

Azimuth of the anchor node is estimated using measured voltage on each photodetector. Photodetectors on sensor are distributed evenly in order to cover fields which cover equal azimuth of circle. (Figure 4)

Radiation intensity is represented by voltage drop on a resistor in series with photodetector (phototransistor) and equals a numerical value.

Two phototransistors with maximum measured intensity are selected and their values V_1 and V_2 are used in estimation using the following expression

$$\beta = \frac{V_1 \times \alpha_1 + V_2 \times \alpha_2}{V_1 + V_2} \tag{1}$$

In which β is the angle of arrival, α_1 orientation of the phototransistor with highest voltage and α_2 orientation of the phototransistor with second highest voltage value.

D. Location estimation

Location estimation method is based on assumption that there are three anchor nodes in range (q_1, q_2, q_3) with known position (x_j, y_j) and unlocalized node p with unknown position and orientation (x, y, θ) (Figure 5) [8].

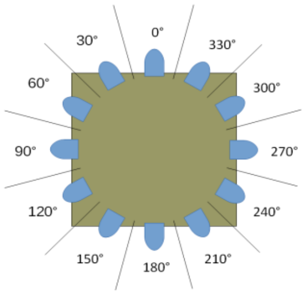

Figure 4. AOA sensor distribution of fields for sensor with 12 photodetectors

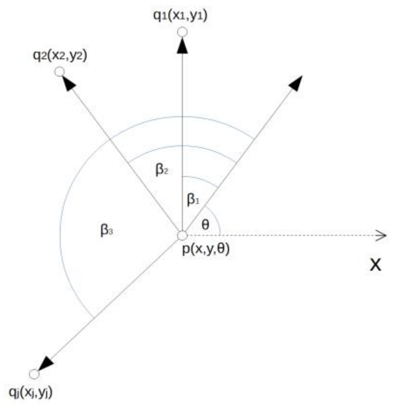

Figure 5. Nodes in 2D environment, q_1 q_2 and q_3 are selected anchors with known position and p is node with unknown position and orientation.

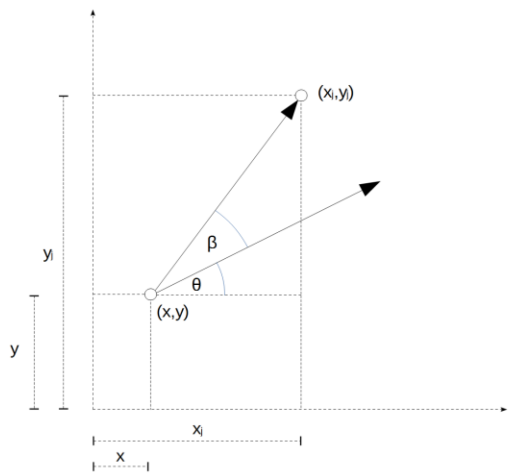

Figure 6. Nodes relation

$$q_j = [x_j + y_j],\ j = 1,2,3 \tag{2}$$

$$p = [x, y, \theta] \tag{3}$$

Anchor j azimuth β_j can be expressed using:

$$\tan(\theta + \beta_j) = \frac{y_j - y}{x_j - x},\ j = 1,2,3 \tag{4}$$

where (x_j, y_j) represent j-th anchor node location, (x, y) mobile node location, θ mobile node orientation, and β is the angle between mobile node and anchor node as shown on Figure 6.

Equation (4) can be written as:

$$(x_j - x)\tan(\theta + \beta_j) = y_j - y,\ j = 1,2,3 \tag{5}$$

and by using trigonometric addition equations (5) it can be transformed to:

$$\frac{\tan\theta + \tan\beta_j}{1 - \tan\theta\tan\beta_j}(x_j - x) = y_j - y,\ j = 1,2,3 \tag{6}$$

$$(\tan\theta + \tan\beta_j)(x_j - x) = (y_j - y)(1 - \tan\theta\tan\beta_j) \tag{7}$$

After (7) multiplication and grouping:

$$\begin{aligned} &\tan\beta_j(x + y\tan\theta) - (y - x\tan\theta) - \\ &-(x_j + y_j\tan\beta_j)\tan\theta = x_j\tan\beta_j - y_j \end{aligned} \tag{8}$$

To simplify (8) can be multiplied with $\cos\beta_j$:

$$\begin{aligned} &\sin\beta_j(x + y\tan\theta) - \cos\beta_j(y - x\tan\theta) - \\ &-(x_j\cos\beta_j + y_j\sin\beta_j)\tan\theta = \\ &= x_j\sin\beta_j - y_j\cos\beta_j \end{aligned} \tag{9}$$

One can introduce following auxiliary variables:

$$\begin{aligned} u_1 &= x + y\tan\theta \\ u_2 &= y - x\tan\theta \\ u_3 &= \tan\theta \end{aligned} \tag{10}$$

So we can write (10) as:

$$\begin{aligned} &(\sin\beta_j)u_1 - (\cos\beta_j)u_2 - (x_j\cos\beta_j + y_j\sin\beta_j)u_3 = \\ &= x_j\sin\beta_j - y_j\cos\beta_j \end{aligned} \tag{11}$$

Equation (11) can be used for three nodes with known location to get three linear equations with three unknown variables in matrices:

$$A = \begin{bmatrix} \sin\beta_1 & -\cos\beta_1 & -x_1\cos\beta_1 & -y_1\sin\beta_1 \\ \sin\beta_2 & -\cos\beta_2 & -x_2\cos\beta_2 & -y_2\sin\beta_2 \\ \sin\beta_3 & -\cos\beta_3 & -x_3\cos\beta_3 & -y_3\sin\beta_3 \end{bmatrix} \tag{12}$$

$$b = \begin{bmatrix} -x_1\cos\beta_1 & -y_1\sin\beta_1 \\ -x_2\cos\beta_2 & -y_2\sin\beta_2 \\ -x_3\cos\beta_3 & -y_3\sin\beta_3 \end{bmatrix} \tag{13}$$

$$U = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} \tag{14}$$

Then we can write:

$$AU = b \tag{15}$$

$$U = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = \left(A^T - A\right)^{-1} A^T b \tag{16}$$

From (10) one can substitute:

$$\begin{bmatrix} x \\ y \\ \theta \end{bmatrix} = \begin{bmatrix} \dfrac{u_1 - u_3 u_2}{1+u_3^2} \\ \dfrac{u_2 - u_1 u_3}{1+u_3^2} \\ \tan^{-1} u_3 \end{bmatrix} \tag{17}$$

IV. Experiments

Experiments were carried out to evaluate performance and precision of the angle of arrival sensor and mobile node location estimation.

A. Azimuth estimation accuracy

Accuracy was measured in three different luminance conditions with different light sources:

- Complete darkness (0 lux)
- Incandescent light bulb (90 lux)
- Sunlight (1280 lux)

TABLE I. Measurments in darkness

Luminance:	0 lux
Distance between LED light source - sensor	**Angle measurement root mean squared error**
180 cm (edge of detection range):	30°
90 cm (half range distance)	3.58°
2.5 cm (source and sensor touching)	7.15°

The data in Table I. represents angle measurement root mean squared error at different distances between the source and the sensor. Distances that were used are:

- Edge of IR detection range – when angular movement of light source can be barely detected by sensor
- Half range distance
- Source and sensor touching – source IR LED and sensor photodetector are touching

Figure 7 shows measured angle deviations from real angle values in range from 76° to 105° in complete darkness for 90 cm distance (half range) from light source to sensor.

Figure 7. Estimated azimuth deviation from real values in darkness

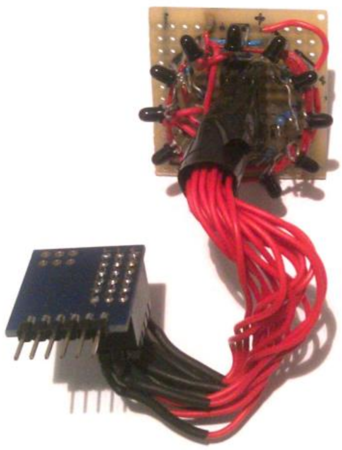

Figure 8. AoA sensor prototype

The best results were observed in complete darkness because there are no infrared components in light to interfere with the sensor operation and best accuracy is observed at half range distance. It is important to notice that observed results can be greatly improved by developing AoA sensor with smaller tolerances than prototype version (Figure 8) and by employing better filtering of surrounding noise (IR remote controllers, pulsating lights…)

B. Location estimation

Location estimation was carried using 3 anchor nodes at fixed coordinates (100,120; 10,100; 50, 20) and mobile node at different locations in range. True and estimated locations of the mobile node are presented in Table II.

TABLE II. LOCATION ESTIMATION RESULTS

True position x, y[cm]	**Estimated position x, y [cm]**	**Deviation x, y [±cm]**	**Error distance [cm]**
0,0	3,6	+3,+6	6,71
50,50	44,56	-6,+6	8,49
80,80	74,82	+4,+2	6,32
100,0	95,-8	-5,-8	9,43
0,120	-6,131	-6,+11	12,53
50,100	42,98	-8,-2	8,25
100,50	86,47	-14,-3	14,32
Error distance root mean square:			9,83

Position estimation is quite satisfactory if we take into account sensor price and still prototype development phase.

V. CONCLUSION

Although current platform and methods for azimuth and location estimation are still under development these initial results are very encouraging. Location estimation precision is high enough to be used for example in indoor mobile robot localization or assets tracking.

Future work includes integrated circuit development with both AoA sensor and IR LEDs using surface mount technology. Benefits would be twofold: precisely positioned phototransistors would allow better azimuth estimation accuracy and it would make platform more compact. As further optimizations each photodetector could be calibrated in order to compensate for systematic errors caused by imprecise phototransistors placements.

Another improvement could be more sophisticated algorithm for azimuth estimation that takes in account more than two phototransistors. Also, AoA range can be increased by driving IR LEDs with higher current for shorter period of time.

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