Low-Cost Optical Indoor Localization System for Mobile Objects without Image Processing

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Abstract

While being very successful in everyday life, GPS-based localization systems exhibit limited performance under trees, behind walls, and in closed rooms, and sometimes induce costs that are way too high to be acceptable for some applications. This paper addresses these problems by exploring an alternative localization system, which is based on image processing and does most of the processing in analog. *Because of its low-cost and low-energy properties, this system might also be interesting for other application areas, such as sensor networks.*

1. Introduction

Research and markets today offer localization systems of various sorts. GPS (global positioning system) [2] and Galileo are two examples that are known to virtually everyone and available everywhere on *earth*. As is well known these localization systems employ several satellites, which are emitting particular radio signals. These signals, actually their time stamps of arrival, are then used by the receivers to derive their actual positions.

Unfortunately, GPS and similar systems are of limited value under trees, behind walls, and in closed rooms. Recent industrial efforts in preventive grain care [6, 4], for example, have developed a grainbutler that requires a localization precision of about 40 cm in *closed* rooms of 50×50 m in size at a cost of less than 1000 USD.

Sensor networks [1, 3] are an application area with similar requirements. A sensor network consists of a huge number of tiny sensor nodes, which are usually randomly distributed over an area of interest. Due to the vast number, automatic localization procedures are of particular interest. Despite their notable successes in sensor networks, however, they are not suitable here due to cost and installation reasons.

Motivated by the specific requirements of the grainbutler application, this paper presents a low-cost alternative localization system. In its core, this system processes the location of a light source by means of an analog device, which is described in detail in Section 2. By employing a small lens system, the analog sensor determines the angle φ under which the light appears with respect to the sensor's surface. With four sensors attached to the four corners of a room, the system can easily estimate the light source's position as Section 3 illustrates. Then, Section 4 provides a detailed description of the entire localization system, which includes a microcontroller and some digital communication components.

The experimental validation, as presented in Section 5, indicates that the employed analog sensor works well in a large range of operation and that it seems suitable for indoor navigation tasks. The low total power consumption of about 60 mW makes this system an interesting option for the field of sensor networks. Finally, Section 6 concludes with a brief discussion.

2. Position Sensitive Device

Localization by image processing would be typically done by the use of a *digital* CCD camera. Despite its accuracy, processing speed, and very good signal-to-noise ratio, a CCD would require further digital processing stages. These processing stages would either employ an image recognition algorithm to recognize the object(s) of interest, or would compare two (full) images taken at two subsequent time steps. Both approaches would require a notable amount of memory. All these processing and data storage elements contain a huge number of capacitors. The charging and discharging of all these capacitors, however, would require a significant amount of energy. With respect to sensor networks and their desired long times-of-operations, it might be worth to investigate the utility of low-energy consuming analog devices.

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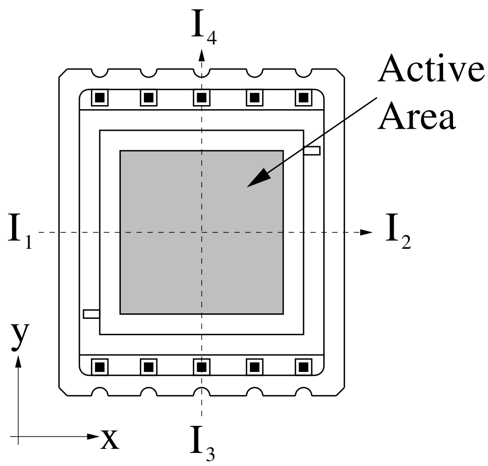

Figure 1. The analog sensor chip [5] has an active area of 9 × 9 mm. It yields four electrical currents I_1, I_2, I_3, and I_4 that code for the x and y coordinates of a light spot.

Figure 1 presents such a device. It is basically a two-dimensional photo diode [5] with an active area of approximately 9 × 9 mm in size. As with all photo diodes, such a device reacts sensitive to any illumination, which makes it a position-sensitive device (PSD). Depending on the relative position of a small light point that projects onto the active area, certain areas of the substrate change their relative resistance. To detect those changes, the position-sensitive device has four electrical connectors, each on every side, as well as a common ground (substrate) connector. The four currents I_1, I_2, I_3, and I_4 can be used to derive the relative x and y coordinates of light point, i.e., it's center of gravity, in the following way (with $I_{i=1..4}$ in the order of 50 nA..500μA):

$$x = \frac{L}{2}\frac{(I_2+I_3)-(I_1+I_4)}{I_1+I_2+I_3+I_4}$$

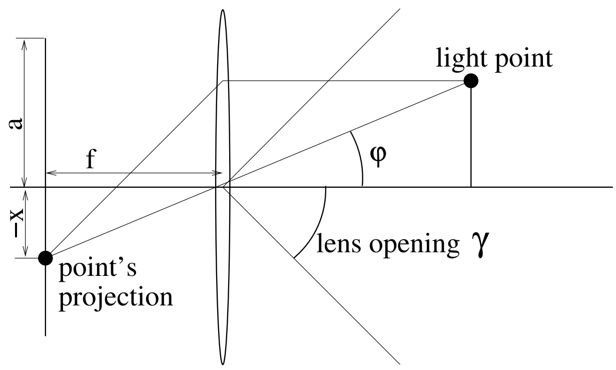

Figure 2. The angle $\varphi=\gamma a/x$ of a light point depends on its projection x, the length a of the sensitive area, and the lens opening γ.

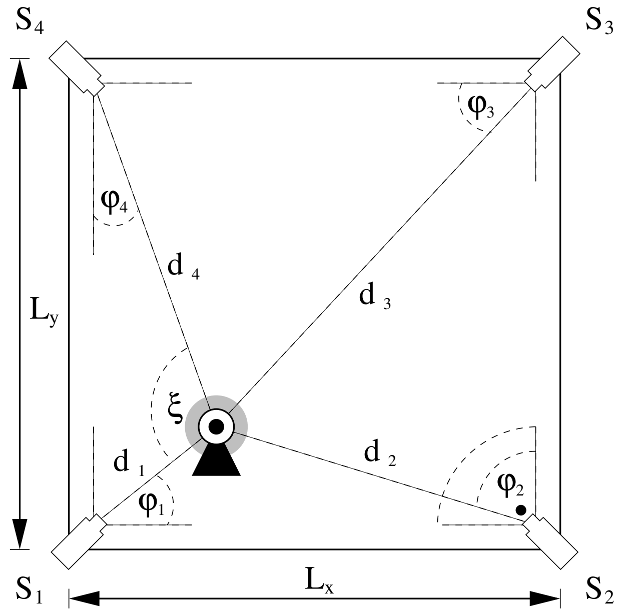

Figure 3. With four independently operating sensors S_1, S_2, S_3, and S_4, the system can determine the x/y-position of a robot by deriving the distances d_1, d_2, d_3, and d_4 from the angles φ_1, φ_2, φ_3, and φ_4.

$$y = \frac{L}{2}\frac{(I_2+I_4)-(I_1+I_3)}{I_1+I_2+I_3+I_4}\,, \qquad (1)$$

3. The PSD Approach

In combination with a lens (-system), the position-sensitive device can be used to estimate the angle φ under which a light source appears. According to Figure 2, such a light point projects onto the active area at position x. With a denoting the size of the sensor's active area, f denoting the focal distance between lens and sensor, and γ denoting the opening of the lens, the angle φ can be derived as $\varphi = \gamma\frac{x}{a}$.

Figure 3 shows the basic setup of the localization system. It consists of an autonomous robot with a "bright" light source mounted on top of it, and four localization sensors S_1, S_2, S_3, and S_4, with each one mounted in one of the corners. Each sensor node derives the angle φ_i under which the robot appears. Due to the law of sines, the following holds (see, also, Figure 2):

$$\frac{\sin\varphi_4}{d_1} = \frac{\sin\xi}{L_y}\,. \qquad (2)$$

Since the sum of the triangle's angles $\varphi_4 + (\pi - \varphi_1) + \xi = \pi$ equals π, eq. (2) can be rewritten as:

$$\frac{\sin\varphi_4}{d_1} = \frac{\sin(0.5\pi - \varphi_4 + \varphi_1)}{L_y} = \frac{\cos(\varphi_1 - \varphi_4)}{L_y}\,. \qquad (3)$$

Solving eq. (3) for d_1 and generalizing to the four distances $d_{i=1..4}$ leads to:

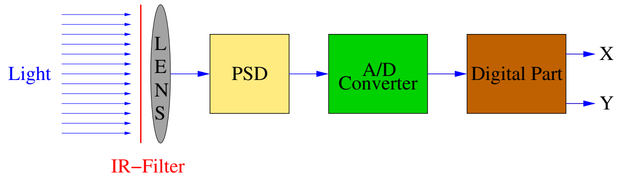

Figure 4. The sensor's processing stages.

$$d_1 = L_y \frac{\sin(\varphi_4)}{\cos(\varphi_1 - \varphi_4)} \qquad d_2 = L_x \frac{\sin(\varphi_1)}{\cos(\varphi_2 - \varphi_1)}$$
$$d_3 = L_y \frac{\sin(\varphi_2)}{\cos(\varphi_3 - \varphi_2)} \qquad d_4 = L_x \frac{\sin(\varphi_3)}{\cos(\varphi_4 - \varphi_3)} \;, \quad (4)$$

with L_x and L_y denoting the room's length in the x and y direction, respectively. In summary: based on the four angular measurements $\varphi_{i=1..4}$, the sensor system can determine the four distances $d_{i=1..4}$. On the other hand, the robots x/y-position is bounded by the following four constraints:

$$d_1^2 = x^2 + y^2 \qquad d_3^2 = (L_x - x)^2 + (L_y - y)^2$$
$$d_2^2 = (L_x - x)^2 + y^2 \qquad d_4^2 = x^2 + (L_y - y)^2 \;. \qquad (5)$$

Since two equations would be sufficient, eq. (5) allows for the derivation of *six* robot x/y-positions, which would be identical in the ideal, error-free case. In practice, noise and other causes result in *small* deviations, and thus the PSD approach derives the robot's position $\bar{x}/\bar{y}$ as the average of all six ones: $\bar{x} = \frac{1}{n}\sum_1^n x_n$ and $\bar{y} = \frac{1}{n}\sum_1^n y_n$.

4. The Sensor's Architecture

Figure 4 illustrates the basic architecture of the developed sensor node. As can be seen, it consists of five different processing stages, which are presented in more detail in the remainder of this section.

First of all, an infrared filter is used in order to increase the sensor's robustness with respect to ambient light and other noise sources. The filter eliminates all frequencies below 830 nm. This matches the sensor's sensitivity, which has its maximal sensitivity at 830 nm. Then, the filtered light passes a lens system with a focal length of about 8 mm.

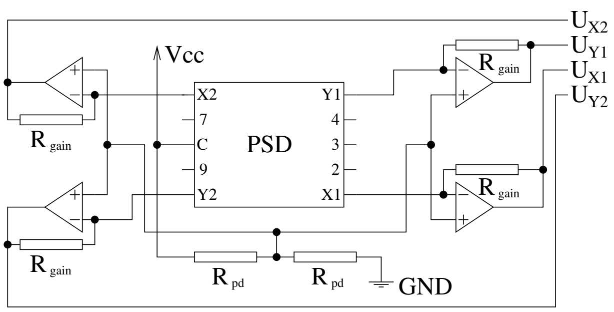

Figure 5. This analog component amplifies the four, low currents as provided by the PSD.

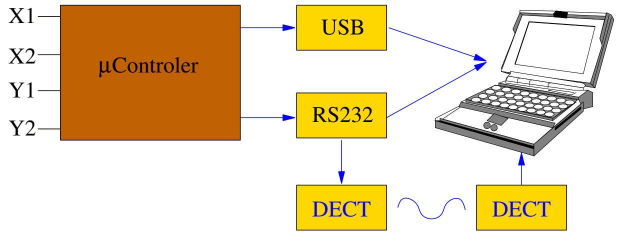

Figure 6. The sensor node can communicate via USB, RS232, and DECT.

As has already been presented above, the position-sensitive device estimates the position, actually its center of mass, of a projected light point by providing four different currents $I_{i=1..4}$. These currents are with about 50 nA..500μA relatively low. Thus, the four currents $I_{i=1..4}$ are amplified by four operational amplifiers, which are described in full detail in Figure 5. With a PSD's impedance of about $R_i \approx 1$ k and $R_{gain} = 900$ k, the gain is around $V \approx 900$, and the two resistors $R_{pd} = 10$ K clamp the non-negated inputs to 50 % of the supply voltage. In addition, these four operational amplifiers also do a current-to-voltage conversion.

Then, the four voltages are forwarded to four analog-digital (A/D) converters, which provide the signals in a digital format. The A/D converters are integrated into the microcontroller and store the results in dedicated registers. With 10-bits and an output range between 0..3.3 V, the A/D converters provide a resolution of about 3.2 mV for the least significant bit. And with a clock of about 5 MHz, the converters provide about 500,000 samples per second. After the conversion, an Amtel AT91SAM7S128 microcontroller derives the robots (actually the light's) position in an average of $t \approx 10\mu S$.

Figure 6 shows that the sensor module features three communication interfaces. With respect to an autonomous operation, the wireless DECT interface is of particular interest. With the current setup, the DECT module achieves a distance of about 50 m indoors and up to 50-300 m under free sight. With a power supply of 5 V, it consumes about $I = 12$ mA leading to a power consumption of $P \approx 60$ mW. The other two communications interfaces consume less than 30 mA.

The prototype is of 80 × 80 × 70 mm (W × H × L) (excluding the lens system), has a weight of about 100 g, and operates about 14 days with four standard Mignon 1.2 V batteries, if no messages are transmitted.

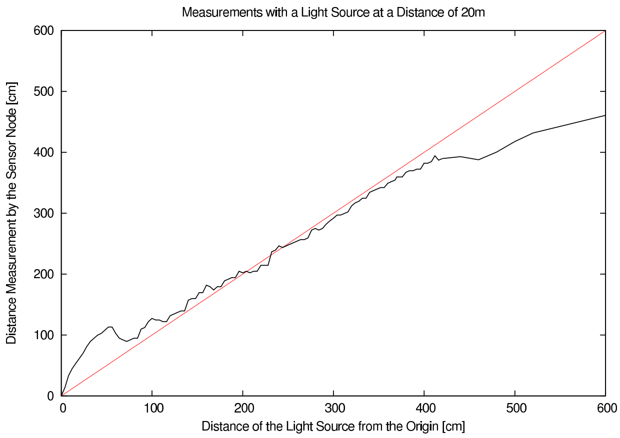

Figure 7. Practical validation experiments done with the prototype sensor module. As can be seen, the results are almost linear within a range of about 500 cm to the right and to the left (the latter is not shown here).

5. Results

The sensor prototype was used in some practical validation tests with only *marginal* ambient light disturbance. In these experiments, a bright light source was placed at a distance of 20 m. It was then moved to the right, and the new position as measured/calculated by the localization sensor was noted. These results are presented in Figure 7. The x-axis denotes the deviation of the light source with respect to the center, and the y-axis shows the localization sensor's results. It can be seen that in a large range, the measurements are linearly correlated. However, at the very beginning $\Delta x < 70$ cm as well as large distances $\Delta x > 440$ cm, however, the disturbances are becoming significant.

By now, the reasons for the observable non-linearities are unknown. It seems quite plausible that either the lens system, the operational amplifiers, and/or the position-sensitive device are significant causes. For example, it might be that at the point of operation of about 3.2 V of the sensor device, the two-dimensional diodes exhibit some non-linearities in their currents $I_{i=1..4}$ (eq. (1)) for $\Delta x > 440$ cm. Nevertheless, further digital processing stages might be able to compensate for these observable non-linearities. However, this requires a calibration process prior to the autonomous operation.

6. Conclusions

This paper has discussed a localization sensor that is based on a position-sensitive optical device. In contrast to widely-used CCD cameras, this sensor device does the processing of the information of interest entirely in *analog*. Due to this processing approach, the sensor device operates very fast at a quite low power consumption. Particularly the latter makes this device interesting for unmanned and/or autonomous operations.

In addition to the analog sensor device, the prototype also features analog/digital converters as well as several communication capabilities. In the first experimental validation tests, the localization sensor was operating in a linear regime within a large range of operation. However, the sensor unit also exhibited some non-linearities, particularly for large distances $\Delta x > 440$ cm.

Future research will be dedicated to finding and possibly eliminating these non-linearities, provided that they do not require too much hardware efforts. Furthermore, future research will be developing further compensation software, which can also be hosted on the onboard microcontroller, such that it is transparent for any further application software.

Furthermore, the localization system will be completed by an application software to allow its usage in the aforementioned grainbutler application. To this end, the system requires four sensor modules as well as an additional software component to calculate the robot's x/y-position. Moreover, the localization system will also be employed in the laboratory's robocup project.

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[6] `http://www.grainbutler.com`

[7] `http://www.navtechgps.com/supply/-rerad.asp`