Low-Cost Sonic-Based Indoor Localization for Mobile Robots

Daniel Wehden[a], Ralf Salomon[b], and Matthias Schneider[c]

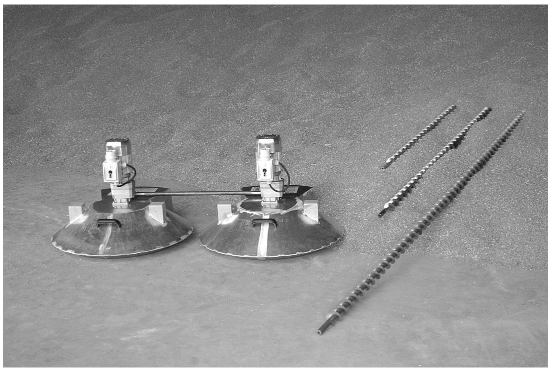
[a]University of Rostock, Germany, e-mail: daniel.wehden@uni-rostock.de
[b]University of Rostock, Germany, e-mail: ralf.salomon@uni-rostock.de
[c]University of Rostock, Germany, e-mail: matthias.schneider@uni-rostock.de

Abstract - Every year, several environmental causes let significant amounts of grain spoil even though it is properly stored in dedicated silos. To reduces the resulting financial losses, engineers have developed a special robot called grainbutler. The robot is supposed to cover the entire area in a systematic way. To this end, a PC-based control software derives the robot's current position and submitts appropriate control commands. This paper is about the necessary localization system. It is based on (ultra-) sonic acoustics, and yields a precision of about 2-4 cm in closed rooms of up to 50 m × 50 m in size at a cost of significantly less than 1000 € (approximately 1200 USD).

1 Introduction

Moisture and too high a temperature are two main causes that let huge amounts of grain spoil every year, which causes significant financial losses to many farmers. Regular grain care, such as systematic circulation, is a suitable preventive action, which however causes additional (labor) costs. For this purpose, engineers have developed a mobile robot [6], which utilizes two screw conveyors mounted underneath a platform in order to systematically circulate the grain. Figure 1 shows the robot and its basic components.

When operating in a grain silo, an additional pice of software constantly determines the robot's current position and consequently transmits appropriate control commands back to the robot. Because of the robot's dimensions of about 30 cm × 60 cm, the system requires a localization precision of about 30 cm. Since silos are *indoor* environments by their very nature, commonly used technologies, such as GPS (global positioning system) [2], sensor networks [1] or laser distance measurements, either do not work, require too high installation costs, or fail



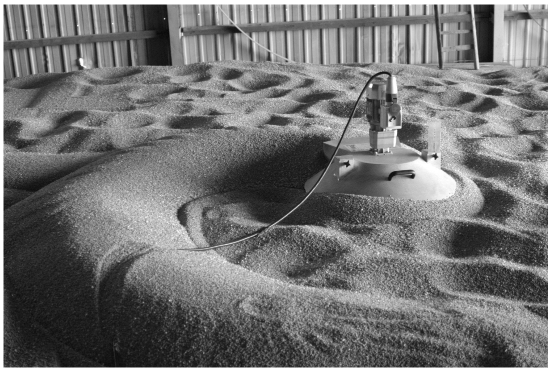


Figure 1: Left: a "twin-robot" and all its components. Right: a "single" robot in action [6].

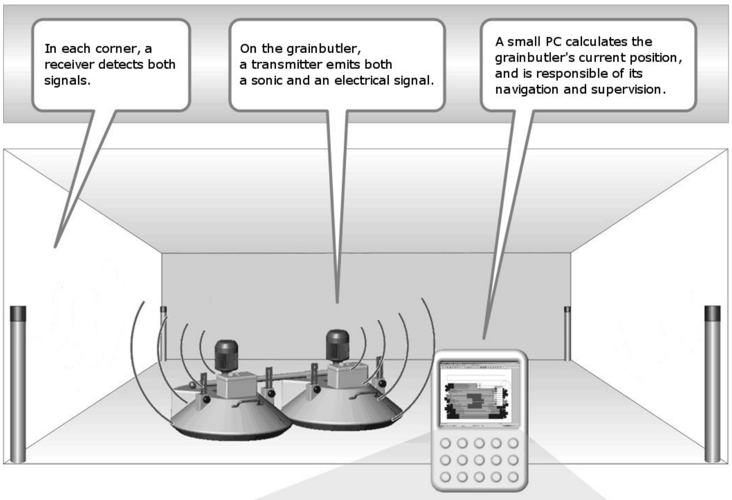


Figure 2: The basic system setup consists of a transmitter and four receivers $R_{1..4}$.

because of their mechanical requirements, which are not affordable in the present application. Therefore, these techniques are not further considered in this paper.

As an alternative to high-budget advanced localization techniques, Section 2 describes a low-budget system that is based on (ultra-) sonic. The choice of the actual frequency depends on the given constraints: ultrasonic cannot be heart by humans, however the signal strength degrades much more rapidly than normal sonic signals. This problem is further discussed in Section 3.

Section 4 nevertheless shows that the proposed (ultra-) sonic system yields a precision of just a few centimeters (approximately an inch) at a cost lower than 1000 €. With ultrasonic, the system is able to cover a distance of up to about 7.5 m; beyond that, the noise level increases too much. To alleviate this problem, Section 5 applies an auto-correlation algorithm to the received signal. This (computationally) simple extension at least doubles the range-of-operation. Finally 6 concludes with a brief discussion.

2 The Localization System

Figure 2 illustrates an overview of the architecture of the localization system. It consists of a transmitter that is mounted on the robot's surface and four independent receivers that are mounted at the silo's four corners. At certain time intervals, e.g., every 10 seconds, the robot simultaneously emits two signals, an electrical start-of-transmission signal and an (ultra-) sonic burst. Since these two signals travel at significantly different speeds, each receiver can utilize the time difference of their arrival in order to determin its distance to the sender. Since the electrical signal travels with the speed of light $v_l \approx 300.000$ km/s, which is orders of magnitude faster than the speed $v_s \approx 340$ m/s of the sonic burst, the traveling time of the former can be neglected and be used as an indication of the start of transmission. Since the grainbutler travels with an approximate speed of one meter per minute, about one measurement every 10 seconds satisfies to attain a resolution of just a few centimeters.

Figure 3 shows the sonic burst at the sender's side (top row) as well as at the receiver's side (bottom row). Such a burst consisting of five periods. With a sonic travel speed of $v_s \approx 340$ m/s, a 10 KHz sampling rate is sufficient to obtain a precision of about 4 cm, which can be easily realized by low-cost components.

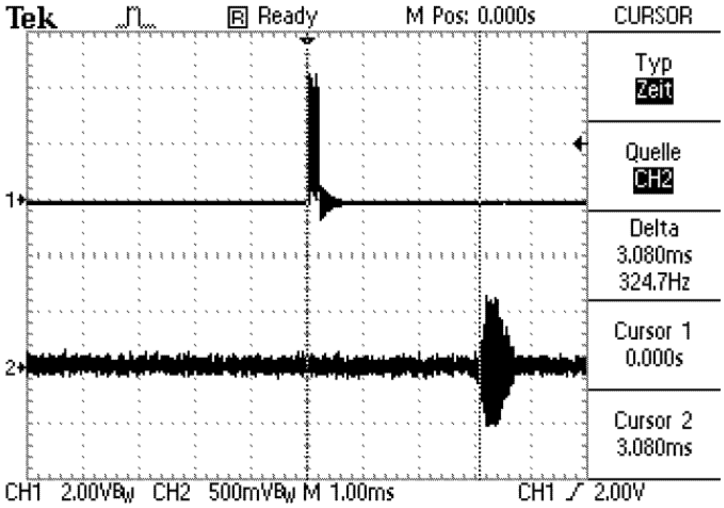


Figure 3: Run-time measurement by means of an oscilloscope.

3 The Problem: Absorption and Divergence

Unfortunately, two physical effects known as divergence and absorption reduce the signal's strength during its way to the receiver [4]. For perfect circular (sonic) signal waves, the divergence level is given as $L_{\text{div}} = 20\ dB\ \lg(r_1/r_2)$, with r_1 and r_2 denoting the distances to the sender and receiver, respectively. The absorption level can be calculated by $L_{\text{abs}} = -D(r_2 - r_1)$, with D denoting a damping constant that depends on the sonic frequency as well as the air temperature and humidity [5].

Figure 4 illustrates the influence of divergence and absorption $\Delta L = L_{\text{div}} + L_{\text{abs}}$ on both a 5 KHz and a 40 KHz sonic signal. The figure shows that absorption reduces the signal strength of a 40 KHz signal very strongly such that off-the-shelf low-budget devices cannot detect such a signal beyond 20 m. By way contrast, the damping factor D becomes very small for frequencies below 5 KHz such that off-the-shelf low-budget devices can be used for distances of up to 100 m.

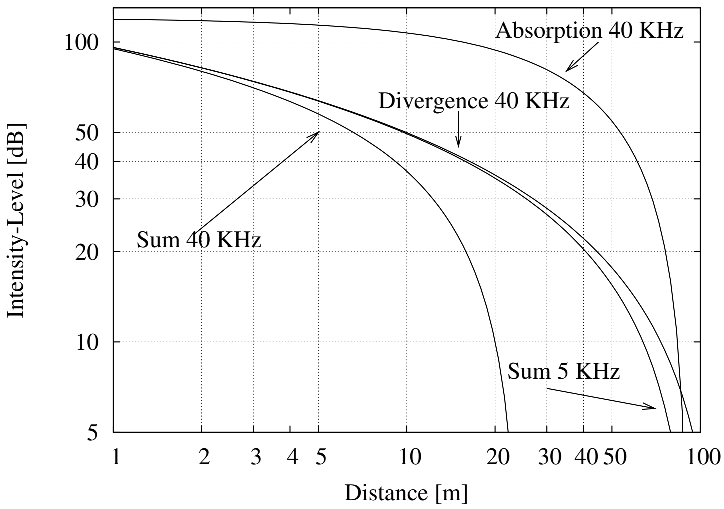


Figure 4: Influence of divergence and absorption on the signal strength.

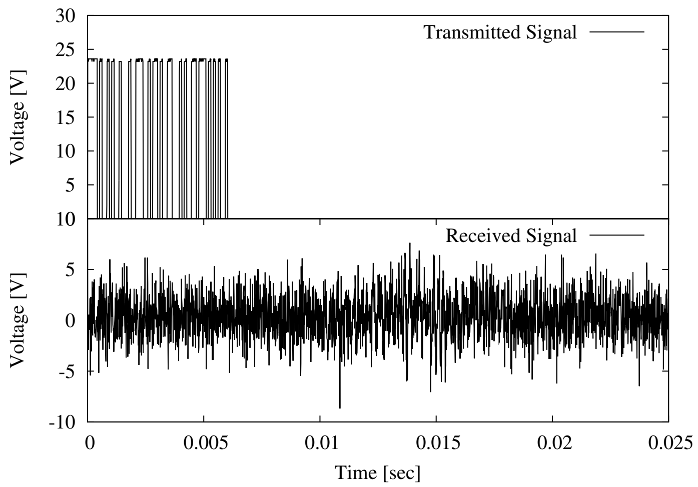


Figure 5: The electrical and sonic signals at the receiver's site with 60 % noise.

Since humans can hear signals of about 5 KHz, the burst's actual form is of particular importance. Experiments have indicated that short bursts of five to 15 periods in duration (see, also, Figure 3) are perceived as simple "clicks".

4 Results

The system described above was realized and tested in both a laboratory setup as well as the actual grain silo. In all experiments, the bursts were of five periods in duration. Then, both the emitted and received signals were displayed in the same oscillograph, and the time difference between the two onsets were used to determine the time of flight.

Frequency	Distance	Imprecision
40 KHz	7.5 m	21.30 mm
5 KHz	50.0 m	40.17 mm

Table 1: Precision and maximal distance for 5 KHz as well as 40 KHz (ultra) sonic signals.

The results, as summarized in Table 1, show that a 40 KHz ultra-sonic signal yields a precision of about 25 mm at a maximal distance of 7.5 m. In comparison, they also show that a 5 KHz sonic signal can yield precisions below 50 mm at a distance of up to 50 m. Unfortunately, a maximal distance, detected by low-cost components, of 10 m is too short for the application at hand, which require distances of up to 50 m. Furthermore, the results indicate that making one or two measurements per second, in which all echos entirely vanish, is sufficient, since the robot is moving at a maximal speed of about 1 m/min.

5 Improved Noise Robustness by Auto Correlation

Sonic transmission is very sensitive to any form of background noise. With standard off-the-shelf products, the signal already vanishes beyond a distance of about 7.5 m as the bottom row of Figure 5 illustrates. In such scenarios, auto-correlation may be able to significantly improve the system's noise robustness [3]. Sine due to the design the receiver already knows the shape of the transmitted signal, it then auto correlates it with the signal actually received. Auto-correlation is done as follows: $k(\tau) = \sum_{i=0}^{N-1}[e(i) - \overline{e}][r(i+\tau) - \overline{r}]$, with $r()$ denoting the received signal, $e()$ denoting the sent signal, N denoting the number of measured signal values, and τ denoting a time shift. The maximum value $k(\tau)$ reconstructs the actual time of flight τ.

As mentioned above, the top row of Figure 5 illustrates the transmitted sonic burst, whereas the bottom row shows the signal at the receiving side. When applying auto-correlation, the received signal is pice wise compared with sent signal. Depending on the particular time shift, this correlation yields different values. Figure 6 displays that at the point where the time shift equals the traveling time, the auto-correlation exhibits a significant peak. This peak represents the precise receive time of the sonic burst. A subsequent (digital) processing stage can detect this peak very easily.

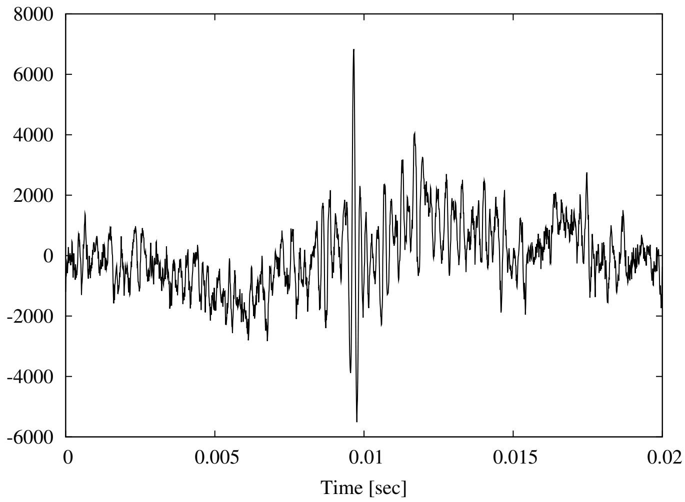


Figure 6: Result with auto-correlation.

With auto-correlation, the ultrasonic localization system can cover distances of up to 20 - 25 m. Unfortunately, this improved distance is still not sufficient for the application at hand. It might be interesting to note that auto-correlation can also be applied at the 5 KHz sonic signal. The positive effect is that the signal can be sent at a significantly lower energy level, which might vanish the signal for the human ear. Furthermore, auto-correlation might also improve the system's robustness in cases of obstacles between sender and receiver.

6 Summary

This paper has presented a localization system with audible sonic signals that has two advantages. First, the costs are significantly below 1000 €, and second, the precision is below 50 mm, which allows for the precise positioning of the mobile robot in a room of up to $50\,\text{m} \times 50\,\text{m}$. The auto-correlation method has improved the noise robustness and has decreased the required transmission energy.

References

[1] Ian F Akyildiz, Weilian Su, Yogesh Snkarasubramaniam and Erdal Cayirci, "A Survey on Sensor Networks" *IEEE Communication Magazine*, August, pp. 102-114, 2002

[2] Elliot D. Kaplan, *Understanding GPS: Principles and Applications.* Artech House Publishers, 1996

[3] John G. Proakis and Dimitris G. Manolakis, *Digital Signal Processing - Principles, Algorithms and Applications.* Macmillan Publishing Company, 1992.

[4] Jürgen A. Stein, *Physik für Ingenieure - Schall.* AVH - Verlag Hamburg, 1997.

[5] ISO 9613-1: Acoustics - Attenuation of sound during propagation outdoors - Part 1. *International Organization for Standardization*, 1993.

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