Experimental Validation for Opto-Acoustic Distance Measurement based on Code Division Multiple Access Amplitude Modulation and Differential Carrier Phase Estimation

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Abstract—In this contribution, an opto-acoustic system for distance measurement between a transmitter and a receiver is presented. This distance measurement is part of an indoor localization system which uses multilateration to obtain the position and orientation of rigid bodies. The novelty of the presented distance measurement is the efficiency in the sense that high accuracy is obtained with the use of standard components, making the overall localization system affordable and facilitating its prevalence. This efficiency is achieved by the simultaneous use of spread spectrum time-of-flight (TOF) on the one hand, and carrier phase measurements on the other hand. Specifically, we use a two-channel link which is made up of an ultrasound and an infrared channel, the latter using the same carrier frequency as the ultrasound channel. In order to render the system extendible for multiple transmitters and receivers, which is necessary for its use in the multilateration setup, code-division-multiple-access amplitude modulation using Gold codes is employed, as all ultrasound and infrared signals share the same carrier frequency. This is also advantageous for multipath scattering suppression. The phase difference between the ultrasound and infrared carrier signals offers a highly accurate but ambiguous distance signal. On the other hand, correlation of the received code-modulated signals establishes a TOF measurement yielding a coarse but largely unique distance signal in the form of a probability density function. The combination of those signals results in a highly accurate and unique position estimation. Experimental results obtained on our test rig are presented to show the performance of the unilateral distance measurement.

I. INTRODUCTION

A. Motivation

Opposed to outdoor localization, where GNSS (Global Navigation Satellite Systems) technologies like Navstar GPS are standard nowadays and widely available to consumers, no such ubiquitous technology exists so far for indoor localization [1]. Instead, a plethora of individually tailored localization and navigation solutions is commercially available or subject to academic research. The habilitation thesis of R. Mautz [2] gives a great overview.

In fact, there exist numerous possible and interesting applications for indoor localization and navigation. Those include for instance guiding people through public or private buildings such as airports, hospitals, museums, offices, and so on. Moreover, tracking parts in a manufacturing setup for increased efficiency and better quality control and documentation is another highly interesting and emerging field for the use of indoor localization technologies.

B. Our research and the scope of this contribution

The authors’ interest in indoor localization technologies stems from their previous research which has been conducted in the field of surgical navigation [3], [4], [5]. The localization task there is to retrieve the pose (i.e., position and orientation) of surgical instruments during an operation. The main challenge is the frequently occurring loss of the line-of-sight when using optical systems such as [6] or [7], which is due to the operation room staff like doctors and nurses that obstruct the cameras’ view on the surgical instruments. The optical systems provide a highly accurate pose, but are not efficiently scalable. By this we mean that in order to circumvent the problem of the loss-of-line of sight, a large number of cameras has to be installed. This renders the surgical navigation system extraordinarily expensive, which lowers the chance that it ever leaves a prototype stage. The goal of our research is therefore concerned with a system that yields a highly accurate pose estimate, and at the same time is scalable in both a technological and economic way. To this end, we consider an opto-acoustic system, which also requires a line-of-sight between transmitters and receivers, but allows for the distribution of a large number of receivers due to the use of standard components.

The system consists of several infrared and ultrasound receivers which are distributed at known locations in an indoor setup. Infrared and ultrasound transmitters are attached to moving rigid bodies (in our case surgical instruments) whose poses are to be retrieved. By using the infrared channel for synchronization, the distance between the ultrasound transmitters and receivers can be obtained by the method for unilateral distance measurement presented in the contribution at hand. Using multilateration (which is not the main contribution of this paper and will be shortly presented in Section II), the pose can be calculated. The novelty of the unilateral distance measurement is that we employ spread spectrum technologies and carrier phase measurements at the same time. Furthermore,
we provide the data of the former in terms of probability density functions.

Compared to our own previous work [8], where we already introduced the concept of the unilateral distance measurement and provided preliminary experimental results, the contribution at hand has the following novelties: We are now able to run several ultrasound transmitters at the same time and calculate their distances to a receiver. So, technically, this paper does not only cover unilateral distance measurement, but distance measurement from a transmitter (which has three transmitting piezos) to a receiver. This allows us to experimentally test the superposition of multiple ultrasound signals. Furthermore, we miniaturized the hardware by using surface-mount technology whenever possible, which makes it possible to attach it to an object that has to be tracked. Moreover, we migrated our code from Matlab to C, so that we are able to run the distance measurement in real-time. Furthermore, we provide a probability density function (pdf) for the results of the code-modulated time-of-flight measurements (instead of a single value).

C. Related work

A seminal PhD thesis concerning opto-acoustic indoor localization is the MIT cricket system [9]. Compared to the paper at hand, pings or bursts are used in that work, which makes the system susceptible with respect to multipath propagation. Moreover, it is not possible to distinguish individual transmitters. Spread spectrum modulation of ultrasonic waves is described in Aly et al. [10]. Their experimentally obtained accuracy is similar to our observations when using our spread spectrum operation mode. They do however not evaluate the carrier phase, which offers increased accuracy, as shall be presented in Section V. Other related work include Kayani [11], Gonzalez et al. [12], and Suzuki et al. [13]. Commercially available systems are for instance the Sarissa LPS [14], which is used in manufacturing environments, or Nexonar [15], which is a system for golf training. Neither of those systems uses spread spectrum technologies though.

D. Outline

The remainder of this paper is organized as follows. Section II gives an overview of the overall indoor localization system. Section III describes the setup that is used for unilateral distance measurement. The distance measurement technique using two different technologies, i.e., spread spectrum time-of-flight and carrier phase measurements, is described in Section IV. In Section V, we provide experimental validation that show the distance measurement performance. Finally, in Section VI, the main conclusions of the paper are presented and some hints on further work are given.

II. OVERALL SYSTEM OVERVIEW

The indoor localization system which is subject to our research efforts consists of one or more mobile units which are considered to be rigid bodies with six degrees of freedom (translational and rotational) that can move freely. Those are to be tracked. Furthermore, the system contains at least three measurement units which are distributed throughout the room. Their positions are assumed to be known and constant.

We employ remote positioning [16], i.e., the mobile unit (rigid body) transmits signals which are received by several fixed measurement units. The advantage of this approach is that the mobile device can be designed to be small and cheap, as the signal processing is done at the receivers. Specifically, our transmitters consist of three ultrasound piezos (US-TX), and one infrared LED bank (IR-TX). Each receiver consists of one ultrasound piezo (US-RX) and one infrared photodiode (IR-RX).

The concept of our system is inspired by the Global Positioning System (GPS), with the main conceptual difference being that we do not transmit an encoded time signal, but instead make use of the two kinds of channels (infrared and ultrasound) with complementary properties:

The infrared channels are used for synchronization, as light can be considered to propagate instantaneously within an indoor setting. The ultrasound channels are used for the actual distance measurement by virtue of the – compared with light – slow speed of sound $c_{\text{sound}}$. Employing multilateration, the three-dimensional position of every transmitter piezo can be determined. As there are three piezos per transmitter, the orientation of the transmitter can be calculated as well.

Fig. 1 shows a schematic overview of the localization system. Please note that – for the sake of clarity – there is only one link (with an infrared- and ultrasound channel) depicted.

![Figure 1. Schematic localization system overview: Mobile unit with three rigidly attached ultrasound transmitters and one infrared emitter, establishing links to room-fixed receiver units mounted on a frame. Note: only two links (one infrared link and ultrasound link) are shown.](image)

The kinematical model of the motion unit is described in our previous contributions [3], [5], where we considered the special case of the motion unit being a surgical instrument used in minimally-invasive surgical interventions. Those differential equations of motion remain valid for any rigid body though. We use them in a particle filter which takes the results of the distance measurement presented in the paper at hand as an input, and uses the plant equations to estimate the pose of the rigid bodies. This is however not the scope of this paper.

III. EXPERIMENTAL SETUP

Our current setup for unilateral distance measurement consists of a printed circuit board (PCB), which is in fact used as...
the rigid body being tracked in our localization system, and another PCB which is one of our receiver units. The transmitter and receiver boards are depicted in Figs. 2 and 3, respectively. They have both been designed at our institute as custom hardware for our localization system and are completely made from standard and affordable electronic components.

Fig. 2. Transmitter board: One can see the three piezos in three out of the four corners and the IR LED bank in the center close to the top edge. Compared with [8], this version has three piezos and has been heavily miniaturized so that it can be attached to a rigid body subject to position and orientation tracking. The board has dimension 125 mm × 80 mm. It makes no sense to miniaturize it further, as the piezos need to keep a certain distance with respect to each other for the orientation estimation.

Fig. 3. Receiver board: One can see the piezo and the IR photodiode in the top right corner. The remaining parts are used for analog signal processing, phase detection using comparators, and displaying the ID of the respective receiver.

The TX PCB consists of three piezos, six infrared LEDs (which are treated as one “big” IR LED), a Cortex-M4 MCU from Texas Instruments (which computes Gold codes [17] used for the code modulation, see Section IV), and some D/A converters (DACs), multipliers, and amplifiers for driving the piezos and LEDs. The RX PCB consists of one piezo and one IR photodiode, some circuitry for analog signal processing, and the same Cortex-M4 MCU for signal acquisition. We decided in favor of analog signal processing in order to meet real-time constraints under all circumstances.

IV. UNILATERAL DISTANCE MEASUREMENT

As already stated in our previous work [8], we employ two modes of operation for the unilateral distance measurement. Those are called ETF (Envelope Time-of-Flight) and CPH (Carrier Phase measurement) and are presented subsequently.

A. Envelope Time-of-Flight (ETF) Mode

The ETF mode consists of the amplitude modulation of the ultrasound and infrared carrier signals with a code. In our case, we use Gold codes [17], which are also employed in the Navstar GPS. Technically, the modulation scheme is ASK-CDMA (amplitude-shift-keying code-division-multiple-access). This means that the carrier signal \( c(t) \) is multiplied with the code signal \( b(t) \). The advantage over time-division-multiple-access is that all transmitters can send simultaneously [18]. The advantage over frequency-division-multiple-access is that one frequency is sufficient. This is an important feature as we want to use standard components, and piezos are not available in all frequencies.

On the receiver side, the signal is demodulated using an envelope detector based on an active rectifier and a low-pass filter. The envelope is then correlated with local replicas of the Gold codes. This correlation can be treated like a probability density function (pdf) for the respective transmitter. Figure 4 shows an example of those pdfs. Note that we employ an algorithm for interference mitigation. It takes the pdf that has the mode with the highest probability, and uses this mode’s position within that pdf to reconstruct the contribution of the associated transmitter’s code. This contribution is then subtracted from the overall envelope, which in turn increases the “sharpness” of the modes of the subsequent pdfs.

A challenge when using spread spectrum techniques on ultrasound piezos is their small bandwidth. This implies that it takes several cycles until they reach their full oscillation
amplitude, and it also takes several cycles until this oscillation vanishes. It turns out that by increasing the Gold code order, the method is still quite robust.

Another issue is carrier superposition. Depending on their phase, several transmitters might interfere with each other. This issue will be addressed as well in the future by migrating from ASK to BPSK (binary-phase-shift-keying), just like Navstar GPS does. Currently, our results are quite robust if – again – the Gold code order is sufficiently high.

B. Carrier Phase (CPH) Estimation

The carrier phase is actually the difference between the zero-crossings of the infrared carrier, and the ultrasound carrier. The latter is the superposition of the carrier signals of all active transmitting piezos. This phase difference yields a distance signal with a very high resolution, but it is ambiguous with respect to multiples of the carrier wavelength.

Currently, we stop sending a Gold code when we switch from ETF to CPH mode. Instead, a code consisting of only one chip with value “1” or “high” is sent. This corresponds to sending the bare carrier signal. The reason for this is that the carrier phase can only be evaluated when the chip is nonzero.

For $M$ active transmitting piezos, where the $i$th piezo has signal strength $s_i(t)$, the total phase difference between the ultrasound and the infrared signal is given by

$$
\varphi(t) = \frac{\lambda}{2\pi} \arg \left( \sum_{i=1}^{M} s_i(t) \exp \left(\frac{2\pi i}{\lambda} (d_i(t) \mod \lambda)\right) \right)
$$

with the ultrasound wavelength $\lambda$ and the distance $d_i(t)$ between the $i$th transmitting piezo and the considered receiver.

When combining the ETF and CPH mode in the future, Equation (1) can be used to design an observer which estimates the carrier phase of the individual piezos given the total phase $\varphi(t)$ and the individual signal strengths $s_i(t)$.

Another way of dealing with this issue is the use of BPSK-CDMA, as mentioned previously. This results in a permanently available phase, as a local oscillation is necessary for demodulation anyway.

V. EXPERIMENTAL VALIDATION

We provide our latest experimental results from our test rig in this section. We already provided a first performance estimation in [8]. Note that compared to [8], we are now able to use three piezos simultaneously. Furthermore, although not directly visible in this presentation, the evaluation of both the ETF and the CPH measurement can be done in real-time, which is crucial for the overall system.

As we have not yet implemented the real-time version of our multilateration algorithm, we cannot compare the distances with ground truth (which will be obtained using the optical tracking system OptiTrack [6]). Therefore, we cannot evaluate our distance measurement’s accuracy, but rather classify the resolution and noise properties. The actual accuracy depends on the knowledge of the exact speed of sound. The speed of sound in turn depends on quantities such as temperature and humidity.

For this reason, we consider nominal distances. Those are the approximate distances measured between transmitter and receiver. By this we mean that as long as we cannot exactly estimate or measure the speed of sound, we cannot assess accuracy in the sense of measuring the correct absolute distance. Therefore, the mean value of our measurements might have a small offset with respect to the nominal distance. This will be corrected in a calibration step for estimating the speed of sound once the overall localization system is complete.

We consider four scenarios:

1) Influence of the distance between transmitter and receiver on the noise for a single active piezo in ETF mode,
2) Influence of the number of active piezos on the noise for a fixed distance and being in ETF mode,
3) Influence of the distance between transmitter and receiver on the noise for a single active piezo in CPH mode,
4) Superposition of the carrier signals for multiple active piezos for a fixed distance and being in CPH mode.

The distance is defined by the position of the highest mode (see Figure 4 where the highest mode leads to a distance estimation of approximately 100 cm). For later use in a particle filter based multilateration algorithm, the entire pdf can be used. For showing measurement results in this section, we consider the position of the highest mode as the true distance. In our implementation, we use a parabola fit of the pdf for calculating the position of the maximum.

The parameters used throughout this contribution are depicted in Table I.

TABLE I

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_c$</td>
<td>carrier frequency</td>
<td>40</td>
<td>kHz</td>
</tr>
<tr>
<td>$f_s$</td>
<td>envelope sampling freq.</td>
<td>16</td>
<td>kHz</td>
</tr>
<tr>
<td>$f_{code}$</td>
<td>Gold code order</td>
<td>8</td>
<td>–</td>
</tr>
<tr>
<td>$f_{code}$</td>
<td>Gold code length</td>
<td>255</td>
<td>chips</td>
</tr>
<tr>
<td>$f_{code}$</td>
<td>Gold code freq.</td>
<td>2000</td>
<td>Hz</td>
</tr>
<tr>
<td>$T_{Chip}$</td>
<td>Gold code chip length</td>
<td>0.5</td>
<td>ms</td>
</tr>
<tr>
<td>$c_{sound}$</td>
<td>speed of sound</td>
<td>343</td>
<td>m/s</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>ultrasound wave length</td>
<td>$\approx 8.575$</td>
<td>mm</td>
</tr>
</tbody>
</table>
Fig. 5. Time signal for one transmitter in ETF mode for a nominal distance of approximately 80 cm.

Fig. 6. Time signal for one transmitter in ETF mode for a nominal distance of approximately 400 cm.

Fig. 7. Histogram for one transmitter in ETF mode for a nominal distance of approximately 80 cm (sum of the bar area normalized to 1).

Fig. 8. Histogram for one transmitter in ETF mode for a nominal distance of approximately 400 cm (sum of the bar area normalized to 1).

Fig. 9. Standard deviation $\sigma$ of the distance signals for one active transmitter in ETF mode over distance.

Fig. 10. Standard deviation $\sigma$ of the distance signals for multiple transmitters (one, two, and three) in ETF mode for a nominal distance of approximately 200 cm between transmitter and receiver.

B. ETF results for multiple transmitters

The transmitter and receiver boards are placed at a distance of (approximately) 200 cm. Again, they are not moved during the measurement and we measure the ETF distance signal for more than 100 s. We enable one, two, and three transmitter piezos and consider the standard deviation of the distance signal in dependence on the number of active transmitters. The results are shown in Figure 10. One can see that the standard deviation $\sigma$ increases as expected when there are more transmitters, but it is still below 5 mm, even when all three piezos are active.

C. CPH results for one transmitter over distance

We do now consider the CPH mode. The transmitter and receiver are placed at nominal distances of (approximately) 80 cm, 100 cm, 120 cm, 150 cm, and 200 cm. Just like in
the ETF case, they are not moved during the respective measurement. We measure the CPH distance signal for more than 100 s. The time signals for 80 cm and 200 cm are depicted in Figures 11 and 12. They also show the minimum/maximum band in the shape of small dashed lines. For the considered time interval, the distance signal stays within those bounds. The corresponding histograms are shown in Figures 13 and 14. Figure 15 shows the standard deviation of the distance signal in dependence of the distance.

Note that the precise location of the mode of the Gaussians in Figs. 13 and 14 does not matter for now. In this contribution, we are interested in the noise of the measurement. The absolute distance value comes into play in the multilateration scenario.

The results show that the carrier phase measurement allows for a precise distance measurement. In Table II, the main results for CPH mode are summarized.

<table>
<thead>
<tr>
<th>Nominal distance</th>
<th>Standard deviation (mm)</th>
<th>Min/Max band spread (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 cm</td>
<td>0.08</td>
<td>0.53</td>
</tr>
<tr>
<td>100 cm</td>
<td>0.15</td>
<td>0.85</td>
</tr>
<tr>
<td>120 cm</td>
<td>0.12</td>
<td>0.55</td>
</tr>
<tr>
<td>150 cm</td>
<td>0.15</td>
<td>0.79</td>
</tr>
<tr>
<td>200 cm</td>
<td>0.10</td>
<td>0.82</td>
</tr>
</tbody>
</table>

**D. CPH results for multiple transmitters**

When there are several transmitters active and the CPH mode is considered, it is interesting to see whether the individual carrier signals’ superposition is as expected. To this end, we perform a complex addition of the phasors associated with the individual transmitters, and compare this with the phasor that we measure when all three transmitters are active. The amplitude of the phasor (complex number) is obtained by the amplitude of the signal envelope, and the phase is obtained by the phase measurement of the CPH mode, see Equation (1). In Figure 16, one can see that the superposition of all three
transmitter is as expected, which shows that the phase can be observed using the envelope of the individual transmitters and the phase of the carrier signals’ superposition, as has been explained in Section IV-B.

Another interesting effect can be observed in Figure 17. When transmitter 1 and 2 are active, there is almost complete destructive interference. This means that the amplitude of the phasor is close to zero, which subjects the carrier phase to noise. This behavior is expected though, and can be used in the carrier phase observer which is subject to our current research. The destructive interference can be seen when looking at the phasor diagram in Figure 18.

VI. CONCLUSION AND FURTHER WORK

In this contribution, we presented current research results of our opto-acoustic system for unilateral distance measurement using spread spectrum technologies and carrier phase measurements, the concept of which we already depicted in [8].

We were able to miniaturize the system’s hardware for further use in the 3D multilateration setup. Furthermore, the
conversion of our code base from Matlab to C enabled us to perform the distance measurement in real-time, which is yet another requirement for the overall indoor localization system.

We showed new experimental results that give an estimation about the noise of the distance signals in both the ETF and the CPH mode. Moreover, we investigated how this noise is affected by the distance between transmitter and receiver. Finally, we showed that the ultrasound carrier superposition is in fact as expected, giving us the possibility to implement a carrier phase observer.

Further work is dedicated to improving the ETF mode by correlating the received envelopes with a code replica that takes into account the bandwidth of the piezos. This means, the local code replica on the receiver end should not have rising and falling edges, but rather the shape of a pulse that propagated through the transmitter and receiver system. On top of that, the combination and simultaneous use of ETF and CPH mode is subject to further research. This includes a carrier phase observer, which estimates the phase of the individual ultrasound signals based on the overall phase and the signal strength (i.e., code chip value) of the individual transmitting piezos. Of course, the real-time implementation of the multilateration algorithm with a particle filter is on the authors’ agenda as well.

REFERENCES