ACCURATE INDOOR ULTRASONIC POSITION TRACKING

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I. Introduction

In this paper a three dimensional ultrasonic position tracking system will be presented. The position calculation is based on distance measurements from a moving transmitter to multiple fixed receivers.

Indoor position estimation or tracking can be applied in several domains e.g.: mobile robot navigation, robotic arm identification, movement observation of a person [1], automated spotlight control on stages, etc. Position determination is usually based on distance measurements from special points to the target, e.g. in GPS the satellites are transmitters with known position and the receiver's position is to be determined. The distance is calculated with the Time of Flight (ToF) method, which means that the time is measured between transmission and reception of a message. In the case of GPS the message speed is the speed of light. If shorter distances are to be measured, this high speed needs extremely fast electronics if radio waves are used. In short distance applications, like indoor positioning, sound waves are also acceptable for time of flight measurement. The slower speed of the sound makes it possible to measure ToF with simple hardware (e.g. standard microcontrollers).

Besides ToF method there are other ways to measure distance. Alternatively, a phase-shift method [2,3] is used to estimate the distance between the transmitter and the receiver by measuring the phase difference between the transmitted and received signals. The phase-shift method is typically more accurate than the ToF method. However, with the phase-shift method, the maximum range that can be estimated is limited to one wavelength of the transmitted signal. Usually laser range finders use this method. If the modulation of the output signal can be varied, the range can be extended at the cost of the decreased precision.

The third and least accurate method to measure distance is to measure the received signal strength (RSSI)[4]. In general, radio waves are used for this method, but using sound waves are also possible. Since the radio signal strength is a nonlinear function of distance and disturbing objects can be between the transmitter and receiver, exact calculation is not possible. To deal with the problem interpolation between calibrated points is used. The main advantage of this method is that radio waves penetrates walls, thus more rooms can be covered with less radio transmitter (or receiver). For example rough positioning is feasible by measuring the signal strengths of WiFi access points in the building [5].

Considering the previously presented methods a ToF method was chosen which uses ultrasonic waves. The advantages of this approach are the following: **1)** accuracy is satisfying (a 1-3 centimeters error over a 0.1-10 meter range), **2)** a relatively simple hardware is capable for the measurement. Of course there are disadvantages as well: the visibility of the transmitter by the receiver must be provided.

In the following section the hardware considerations will be presented, after that in the third section the position calculation and filtering details will be shown.

II. Hardware structure

Time of flight distance measurement with ultrasonic waves can be performed by ultrasonic transmitters or receivers (or transducers if the device is applicable in both ways). If the transmitter and receiver is in one module the distance measurement can only performed in a reflective way. This method measures the time difference between the sent and received signal, so the distance of a reflective surface could be measured (see Fig. 1 section “A”). The next method (see Fig. 1 section

"B") use separate transmitter and receiver, but a synchronization signal is needed to calculate the ToF. The synchronization signal can be a wired link between the two stations, although wireless links are also possible if the communication delay is known and jitter is not significant compared to the ToF. In the third method the transmitter is not synchronized with the receivers, so absolute distance cannot be measured, however from time difference between the signal incoming to the two (or more) receivers, a distance difference can be calculated (see Fig. 1 section "C"). This last method is promising for our purposes, with the appropriate number of fixed and known positioned receiver modules, the determination of the transmitter's position is possible. If there are no synchronization signals between the transmitter and the receivers, only one transmitter can operate at a time, because the ultrasonic signal does not contain any information about the sender.

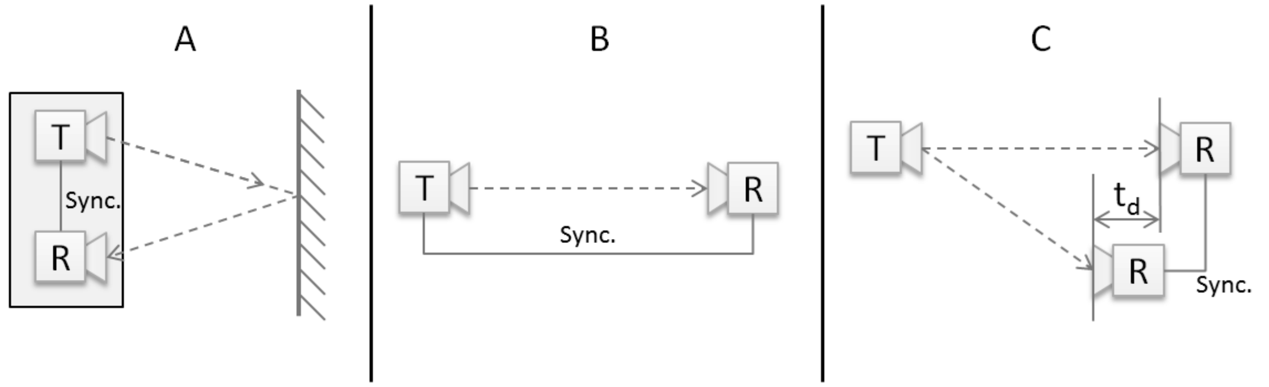

Figure 1: Possible ways to measure distance with ultrasonic waves. "T" means transmitter, "R" means receiver. Dashed lines are ultrasonic signals, continuous lines show (wired) synchronizations.

The ultrasonic signal in question needs further explanation. For generating and detecting ultrasonic signals, piezoelectric crystal based transducers are used. The piezoelectric crystal deforms when a voltage is applied, and the detection is also possible due to the reverse effect: voltage is generated when the crystal is mechanically deformed. The manufactured ultrasonic transducers contain a tuned crystal, shaped for a specific frequency, the typical value is 40 kHz. This is the resonant frequency of the piezoelectric crystal.

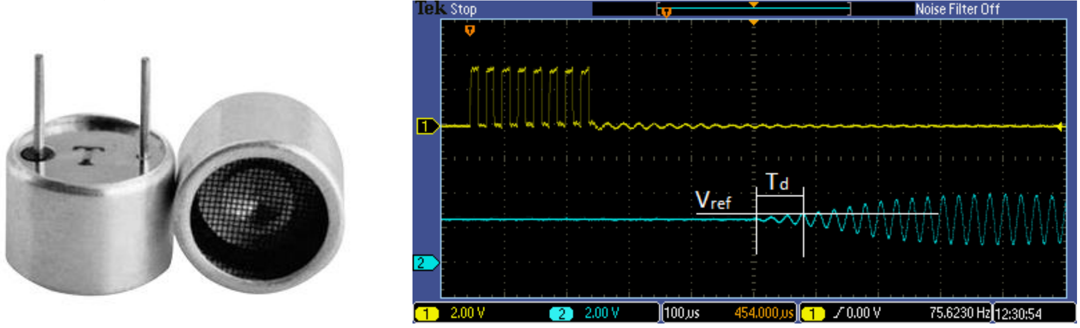

Figure 2: A typical open form piezoelectric ultrasonic transducer on the left; the waveform of an excitation signal and the corresponding received signal. The time delay (T_d) between true reception of the signal and the detection can cause errors.

The transmitter is driven with a few periods (e.g. 8 periods) of a square signal (see Fig. 2), the frequency is 40 kHz. This small burst generates a short ultrasonic "beep". The time between the bursts depends on the distance range to be measured, in closed spaces the interference of reverberated waves should be also taken into consideration. If the bursts are controlled such a way that they are far enough from each other in time, the reverberated waves can eliminated from the measurement (on usual surfaces in a room the ultrasonic wave is suppressed after 1-2 reflections).

The detection of an incoming burst needs more components than the generation. The voltage generated by the ultrasonic receiver is a few millivolts, therefore significant amplification of the signal is required. An instrumentation amplifier circuit was chosen to amplify the voltage between the two poles of the receiver crystal. The gain is approximately 1000. For the measurement of the ToF only the start time of the incoming burst should be measured, thus the amplified signal is compared to a reference voltage. The receiver modules are in a wired RS-485 network. The master of the network sends a synchronization message in every measurement cycle (see Fig. 3). The comparator's output triggers a timer, and the time elapsed from the synchronization message is stored. When all the receivers stored the time or set a flag when no incoming burst was detected, the master starts to request the measured times from the receivers.

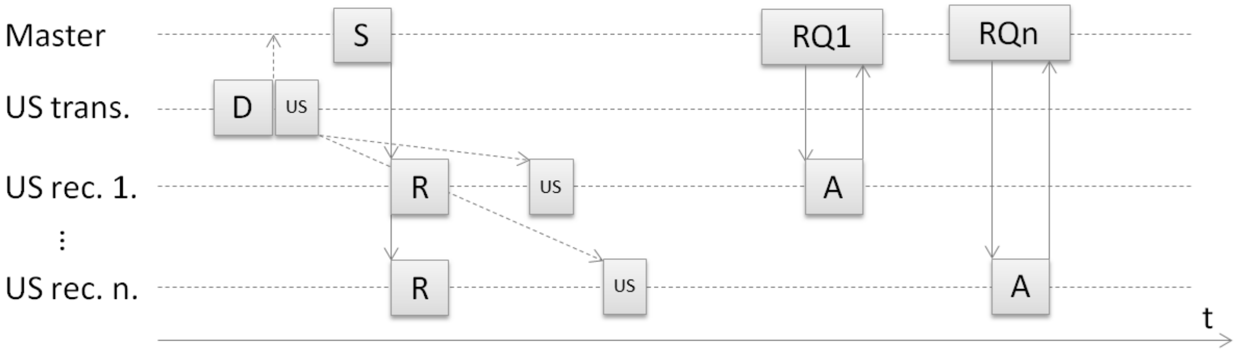

Figure 3: The timing diagram of a positioning cycle. Abbreviations: "D": data transmission, "US": transmission or reception of an ultrasonic burst, "S" synchronization message, "R": resetting timers, "RQn": requesting time data from device n, "A" answering request.

An additional synchronization between the US transmitter and the master unit (D in Fig. 3.) enables the system to measure absolute distances to the receivers. This synchronization signal is transmitted via radio frequency, the advantages of this: 1) the position can be determined from fewer sensors due to absolute distance measurement; 2) additional information can be added (e.g. transmitter ID), so the system will be capable of handling multiple transmitters with time multiplexing.

III. Position calculation

In order to determine the position (coordinates) of the unknown point several approaches are possible. If only distance differences are known it is called multilateration, in this case 4+1 receivers are necessary for three dimensional positioning. If absolute distances are known, 4 receivers are enough (trilateration) [4]. The following problem is given: there are a number of fixed three dimensional points (receivers):

$$R_1,\ R_2, \dots, R_n \in \mathbb{R}^3$$

and one point with unknown coordinates:

$$U \in \mathbb{R}^3$$

and the distances:

$$d_1,\ d_2, \dots, d_n \in\ \mathbb{R}$$

between the R_i and U are known as $\overrightarrow{UR_i}$ vectors. The following equation system should be considered:

$$\sqrt{(U_x - R_{ix})^2 + (U_y - R_{iy})^2 + (U_z - R_{iz})^2} = d_i \text{ where } i = 1, 2, \dots, n \qquad (1)$$

As it is expected this is a three dimensional second order equation system describing spheres. Consider the following: one receiver defines a sphere where U is a point on the surface of the sphere. Two receivers define two spheres where U is on the intersection circle of the spheres (if the spheres intersect each other). If a third sphere is defined by a third receiver and intersects the circle, U can be only in 2 points (see Fig. 4). The fourth receiver can define that which point is U. If additional information is given (e.g.: a range where U is possible) U can determined with 3 receivers. If $n = 3$ the equation (1) forms a second order equation system. there can be three kinds of result: 2 different solutions, 2 identical solutions or no solution (if at least two of the spheres do not intersect each other).

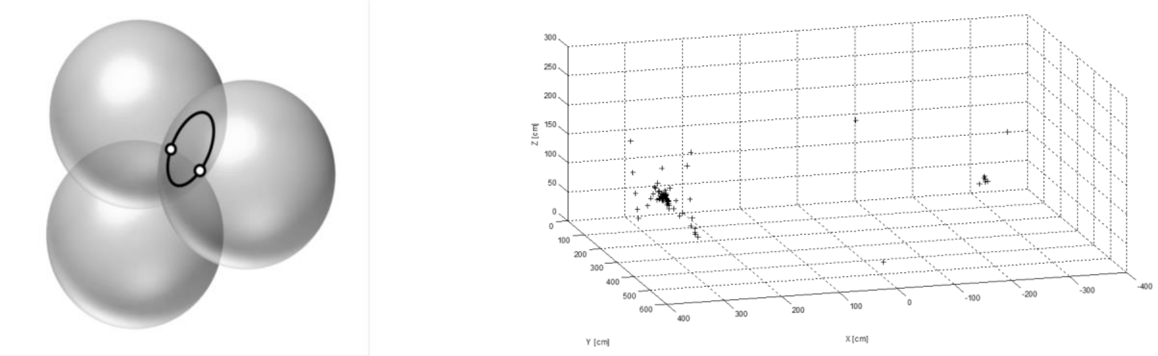

Figure 4: The illustration of the three spheres' intersection on the left, 3D plot of the possible position candidates on the right.

To conclude the reasoning above, the position can be determined from 3 receivers: if the receivers are placed on one plane (e.g. each one in each corner of the room and in the same height) one of the solutions (if exist) will not be in the room, so it can be discarded. Thus 3 receivers are enough for positioning, nevertheless the accuracy can be improved by using more receivers. The following filtering method is used: all possible three receiver subsets are selected from the set of the receivers; then $\widehat{U_k}$ is calculated for every subset. These estimations have to be aggregated; a final position candidate has to be selected. Simple averaging over the points will distort the result because of the outlier points. The task is similar to the center point selection in clustering problems. In Fig. 4 the estimated points are illustrated, there are clearly some outlier points. The rest of the points are grouped in a sphere which center point is to be determined. The approach is the following: a threshold is specified (e.g. 10 cm), and the number of neighbor points within the threshold distance is calculated for every point. The point with the maximal neighbor count is selected, than those points are averaged which are within the threshold range of this point.

IV. Conclusion

In this paper a method of ultrasonic ranging was presented. Accurate positioning has been achieved by using a filtering method specialized for this type of data. The first tests of the system have shown that ±5 cm accuracy in all the 3 dimensions could be achieved over a 0.1-5 meter range with 6 receivers in the room.

References

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