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Ultrasound positioning based on time-of-flight and signal strength

Sverre Holm
Department of Informatics, University of Oslo,
P. O. Box 1080, NO-0316 Oslo, Norway

***Abstract*— Ultrasound positioning systems for indoor use can be distinguished by what kind of information they extract from the received signal. Time-of-flight (TOF) is measured with reference to a radio signal to get ultrasound time-of- arrival (TOA). Line-of-sight to three or more nodes is required for 3D positioning. Accuracy is in the cm or sub-cm range. A radio-free alternative can be made if time-difference-of-arrival (TDOA) is measured instead. Coding of the pulse is often used in order to allow simultaneous transmission from multiple transmitters. The simplest received signal strength (RSS) systems are binary and will just determine if the ultrasound signal can be detected or not. This is used on its own for room-level positioning. Another important application is in assisting RSS-based RF-systems such as WLAN positioning. The ultrasound RSS-system helps reduce the number of large errors (5-10 m) of the WLAN-system. Such systems have recently been deployed world-wide today by companies like Sonitor and Aeroscout. It has also just been demonstrated that RSS-based ultrasound positioning can be done with accuracies in the 10 cm range. This parallels the ubiquitous RF-based RSS systems and requires a propagation model. For ultrasound the model involves spherical spreading and absorption. There are also hybrid systems where the entire echo structure in the time history of the received signal is analyzed. Both the amplitude and time information are used in order to obtain a position of the node using only a single transmitter.**

I. INTRODUCTION

Ultrasound positioning for use indoors is usually thought of as including a time-of-flight (TOF) measurement. One utilizes the fact that ultrasound travels relatively slowly compared to a reference radio signal in order to measure distances between transmitters and receivers and input the distances into a positioning algorithm.

However, ultrasound positioning can also be done in several other ways which do not require a TOF measurement. In fact ultrasound positioning comes in various flavors and can be distinguished by whether the system measure TOF or received signal strength (RSS).

Here the starting point is the received signal. The various methods can easily be distinguished based on what kind of information they extract from it. Fig. 1 shows a typical transmitted signal (to the left, dotted) and a received signal (solid line). In this case a measurement of TOF requires some sort of flank detector which will in that particular example give a value of about 3.4 ms or a distance of 3.4e-3 * 340 = 116 cm.

However, given a good propagation model and a calibrated system, the maximum value for the RSS of about 1.2 V, can also be used for positioning. In fact even without such a model, just the fact that the ultrasound signal is above the noise floor and can be detected is used in commercial systems for indoor positioning.

There have also been demonstrations of systems using the entire echo structure for positioning. In that case the reverberation properties of the room are used also as it manifests itself in the multiples starting at about 5 ms in Fig. 1.

This paper will outline the main characteristics and models of these different systems.

II. TIME-OF-FLIGHT SYSTEMS

A. Ultrasound and Radio

The most obvious way to measure distance is to measure the difference in TOF between a radio signal and an ultrasound signal. Due to the biomimetic features of ultrasound, animals using ultrasound are often used for inspiration, resulting in systems with names like Active Bat [1] and Cricket [2].

In the Active Bat system active ultrasound transmitters are attached to persons to be located, while in the Cricket system the signal flow is reversed so that the items to be located have receiving nodes. The latter is advantageous for two reasons.

First the system can have as many receiving nodes as desired, as it is not limited by the capacity of the ultrasound channel as is the case if each node to be located needs to transmit. Second, if persons are to be located, they are less exposed to ultrasound, something which in a system built for long range potentially may approach harmful levels.

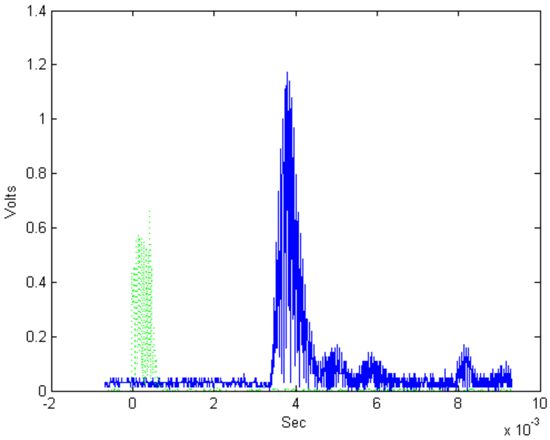

Fig 1. Plot of amplitude of transmitted 40 kHz pulse, length 16 periods (dotted line, green, not to scale), and received echo (solid line, blue). 8-bit resolution measured with an Agilent DSO6014A oscilloscope..

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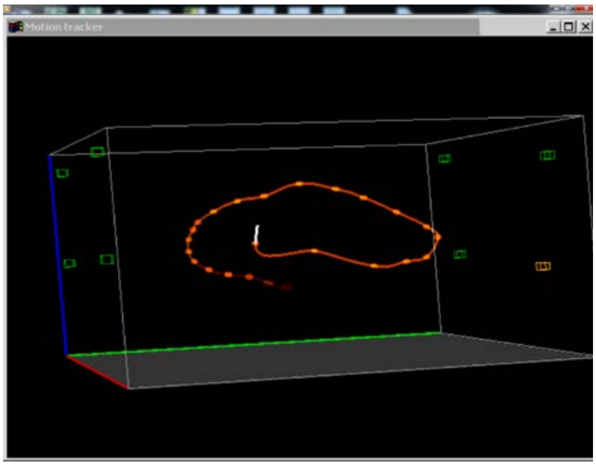

Fig 2. Tracked trace from an active handheld node tracked in a room of size 4 x 4 x 2.4 meters with 8 nodes. Note the white vector at the end of the trace which indicates the current velocity vector estimated from the Doppler shift. The orange color of the receiver node to the lower right indicates an invalid measurement due to shadowing. (Figure courtesy of Sonitor Technologies.)

An analysis of exposure relative to current safety standards can be found in [3].

The disadvantage of having stationary transmitters is that the TOF measurements are taken at slightly different times resulting in inaccurate positions if the target is moving. This disadvantage can be alleviated by using spread spectrum pulse coding, allowing for several transmitters to send simultaneously. The cost is in receiver complexity as it requires a correlation receiver rather than a simple flank detector.

In [4] direct sequence spread spectrum is used and a comparison is made between Kasami, Golay, and Loosey Synchronous coding with respect to noise immunity, simultaneous measurements and accuracy in positioning.

In [5] a system using frequency hopping spread spectrum is described. Frequency hopping is preferred over direct sequence spread spectrum since it is more robust to the near-far problem inherent in spread spectrum. To do a measurement of both location and orientation it uses an 8-element circular receiver array based on MEMS microphones. The coding is done using Kasami codes.

In order to do accurate positioning it is necessary to take into account the variation of sound speed with temperature. If high accuracy is required, even variations with humidity should be taken into account [6].

B. Ultrasound alone

An RF-free ultrasound positioning system is described in [7] based on a set of ceiling mounted ultrasound transmitters and a wearable receiver. They called it a wearable-centric system, which similar to GPS allows the user to position himself. The lack of RF simplifies the system. As it only allows one to estimate time-difference-of-arrival (TDOA), it requires one more node for positioning than a TOF-system. For 3D positioning this means that at least 4 nodes are required vs. 3 for the TOF-system.

A similar RF-free 3D positioning demonstrator, but with a reversed ultrasound direction, was developed by us in collaboration with Sonitor Technologies about 2002 based on the hardware of a room-based positioning system [8] (to be described later). It gave an accuracy of about 2 cm and had the ability to estimate the 3D velocity vector from Doppler shift. Therefore it could give a prediction of where the node was heading, as indicated by the white velocity vector at the end of the trace in Fig. 2. Instead of four receiver nodes, the system used eight for improved accuracy and redundancy. It therefore included a detection of invalid measurements due to e.g. shadowing; see the node to the lower right in Fig. 2 which has been marked as being invalid.

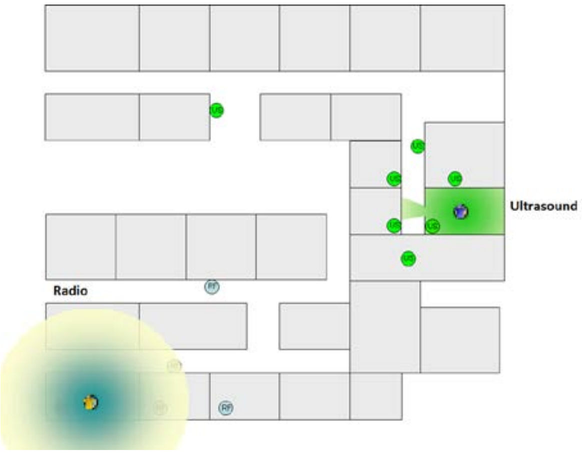

Fig 3. An indoor scenario showing an institution with many rooms. The RF signal in the lower left corner spreads out despite the walls while the ultrasound signal to the right is confined to the room of the transmitter. (Figure courtesy of Sonitor Technologies.)

III. SIGNAL STRENGTH SYSTEMS

A. Binary Signal Strength

The simplest ultrasound systems based on signal strength just output a binary yes/no decision. This is a simple detection of signal or not. The key to understanding the utility of such a simple concept is to consider the difference in how RF and ultrasound propagate indoors. In Fig. 3, which shows the layout of an institution with many rooms, the RF signal in the lower left-hand corner spreads out despite the the floor or ceiling [9]. In addition signal strength will vary with antenna orientation [10]. walls. Propagation models for RF in such an environment need to model spreading, reflections, and attenuation in the wall as well as in

The ultrasound signal to the right in Fig. 3 is confined to the room of the transmitter except for some leakage out through an open door. It will therefore be a simple and reliable indicator of whether a device is inside a room or not.

The importance of a binary indication of inside or outside a room is also illustrated in Fig. 4. Here a hospital room is shown with two beds. Two devices are located with similar error circles. However there is a certain probability that device #2 will be located in the adjacent room as the error circle crosses the wall between rooms. The figure illustrates that RMS positioning error does not always correlate well with how a user experiences an error. A 1 meter error in the same room often does not have much consequence for a user of the positioning system (device #1). On the other hand a 1 meter error which means that the incorrect room is indicated may have a large negative impact on the user's experience of the system (device #2). This is where the binary ultrasound positioning system finds its role and usage.

The binary system has two main uses in practice. First it can be used as a stand-alone system with one node per room simply outputting which room the tracked device is located in [8]. The Sonitor system of [11] has been tested against more conventional RF-based systems with good results in a clinical setting [12], [13]. The

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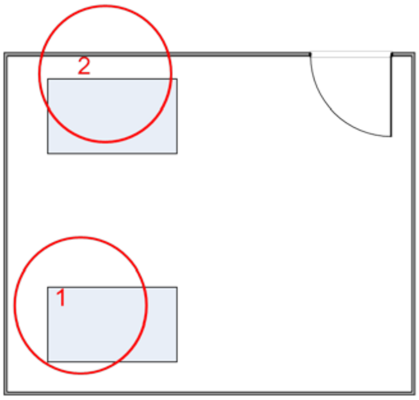

Fig 4. This figure shows a room with two hospital beds. Two devices are positioned in the room. Device #1 is located with an error circle which is contained entirely inside the room, while device #2 has an error circle of the same size which is partly in the adjacent room.

system consists of wearable ultrasound transmitters and fixed ultrasound receivers.

The second usage is in resolving the room-ambiguities of RF-based positioning systems. WLAN-based positioning systems utilizing existing infrastructure and RSSI fingerprinting are very attractive from an economic point of view. However, there is a limitation on how well such systems perform in practice. There seems to be a fundamental limitation on accuracy. A median error around 3 m and a 97th percentile around 10 m is typical [14]. There seems to be strong evidence that these limitations are fundamental. Some improvements may be obtained with more complex environmental models, but still there is a certain chance for large outliers which will result in errors that place the node in an adjacent room or even on a different floor.

One way to resolve the room-ambiguities is to add localization infrastructure in the form of an ultrasound or infrared system. Infrared has similar room-confinement properties as ultrasound but it is more sensitive to interference from sunlight or fluorescent lamps. Neither does IR cope so well with lack of line of sight as ultrasound, which can do binary position detection based entirely on reflections. Therefore ultrasound seems to be preferable. An example of a WLAN-system with wearable tags that include ultrasound receivers for room-level resolution is [15] from Aeroscout. In that system ultrasound transmitter nodes must be placed in each room where the ambiguity is particularly important to resolve.

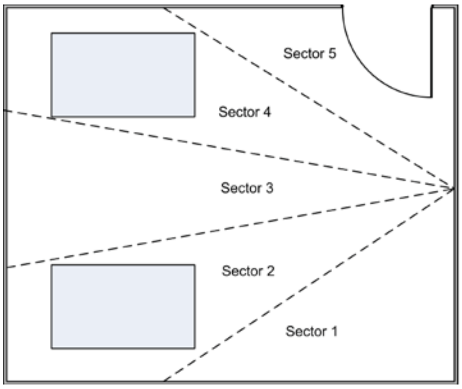

Fig. 5. Determination of sectors in a multi-bed hospital room using an ultrasound array sending unique coded beams into each sector and where the receiver node does relative signal level comparisons.

Both of these applications require an ultrasound link with communications capability so that each tag or each room transmits a unique signature. This will be described in the next chapter. But first some more complex amplitude-based systems will be given.

B. Relative Signal Strength

The next step up in complexity after a binary signal strength decision is to do relative comparisons of amplitude. No propagation model is really required other than the knowledge that level falls monotonically with range.

The system of [8], [11] compares signals received on several stationary base stations. This enables the detection of which part of a room a tag is located in.

A single-node system is presented in [21] where a transmitter array was used to send beams in different directions, each at a different time and with different coding. A receiver measures the received signal strength. The RSS values for each beam are then compared in order to figure out which sector the receiver was located in. A possible application of such a system is bed-level resolution in a hospital as shown in Fig. 5.

C. Absolute Signal Strength

In order to go beyond binary detection or relative signal strength comparisons and use the actual signal strength value one needs a propagation model. As long as there are line-of-sight conditions, spherical propagation combined with absorption is an accurate model. The amplitude loss is then:

$$\text{Amplitude Loss} = \frac{10^{\frac{-\alpha}{20}R}}{R}$$

where R is the range. The absorption α (dB/m) is a function of temperature, humidity, and pressure [20]. The absorption has been plotted in Fig.6. The absorption factor is usually neglected at audible frequencies, except for at high frequencies and a long range such as at concert and outdoor venues. But at 40 kHz it gives a significant contribution to the loss. Fig. 6 shows that the maximum value at 40 kHz is 1.33 dB/m at 55% relative humidity.

A system using absolute values of signal strength requires the full propagation model just given. We did a feasibility study and a test of such a system in [22]. Special measures had to be taken in order to get good absolute calibration of amplitudes. Therefore compensation for

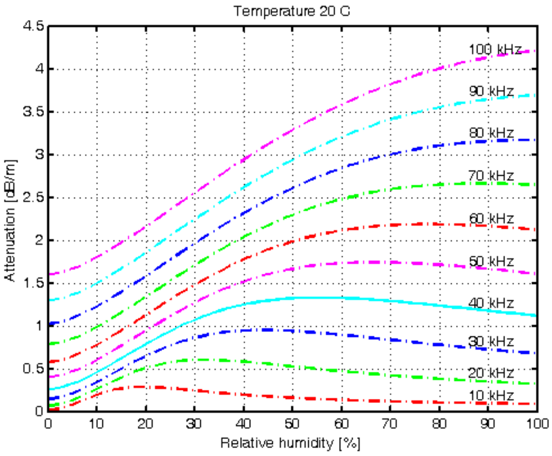

Fig. 6. Absorption in dB/m as a function of frequency and humidity.

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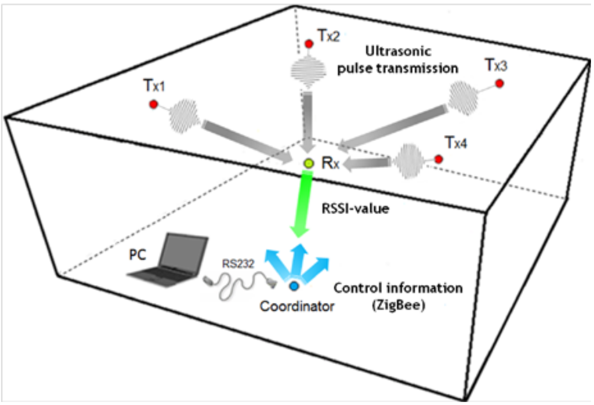

Fig. 7. Architecture of ultrasound RSSI-based positioning, from [22]

changes in battery voltage and orientation of the transducers had to be included. When this was done accuracies in the order of 10 cm were obtained in a room where four transmit transducers cover an area of 2.5 by 2 meters as shown in Fig. 7.

IV. Link Design and Doppler Estimation

All of the signal strength systems just described require an ultrasound link so that each tag or each room transmits a unique signature. This makes it possible with multiple transmitters and receivers in the same room. As a side-effect, potentially useful movement information from the Doppler shift can also be extracted.

1) Ultrasound Communications Link

A system using a communications link was described in [8] and [16]. A simplified version using a three bit code was described in [3]. The received pulse from that system is shown in Fig. 8. Each bit is sent using Frequency Shift Keying (FSK) in the band around f_0=40 kHz and with a symbol length of 40 ms. The reason for the long pulse is to make it possible to use a low bandwidth for detection, in the order of 1/40ms = 25 Hz. This decreases the noise pickup and thus increases the range.

The link budget for estimating range is given in [3], [16] and shows that a reliable range in the order of 10 m is achievable even in a high-noise background such as in an industrial setting. Further in [17] we showed that the maximum range of the low bandwidth system is comparable to that of a system using pulse coding. This is because the reduction in range due to the increased bandwidth of the coded system approximately is made up for by the processing gain of the coding. Such link budget considerations are important in order to assess the robustness to interference of the various systems.

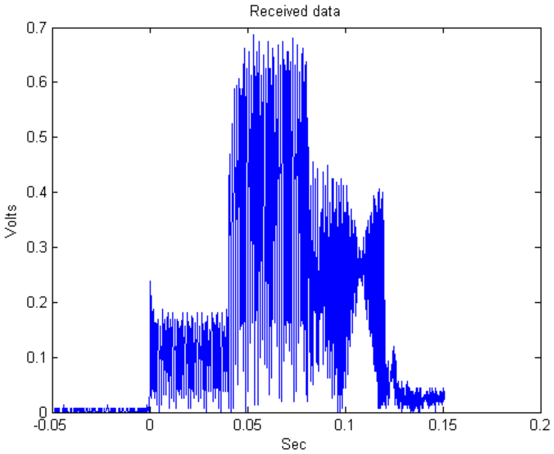

Fig. 8. Amplitude of received signal when a three bit code is sent. Each symbol is 40 ms long.

A low-bandwidth system has its own challenges due to Doppler shifts. If the maximum velocity is ±v, the maximum Doppler shift is

$$f_D = \pm f_0 v/c$$

Here v is the velocity component along the ultrasound beam. For v=6 km/h or 1.67 m/s, fast-paced walking, and c=340 m/s, this gives a Doppler shift of ±200 Hz. In the system of [3] we derived frequencies from a master clock running at 8 MHz. Thus division by factors 195, 197, …, 205 results in frequencies of 39.024, 39.409, 39.801, 40.201, 40.609, and 41.026 kHz, i.e. about 400 Hz apart. Thus it is possible to separate 0s from 1s even when there is maximal Doppler shift. These three frequency pairs are then used for signaling, where the first two frequencies are used for 0 and 1 respectively for the first bit and so on.

In order to reap the benefit from a small detection bandwidth, the Doppler bandwidth has to be subdivided. In [3] it was divided into bins of size 35 Hz, resulting in about 2*400 Hz/35 Hz = 23 bins which have to be checked using an FFT-based processor. A detection in the lower half of the bins will be detected as a 0 and a detection in the upper half will be detected as a 1. As a side result an estimate of the Doppler shift will be obtained from the actual bin which had the maximum signal. This is similar to FSK communications in underwater acoustics which also is a medium with high relative Doppler shifts [18], [19].

If more than 3 bits are required for the data transmission, reuse of frequencies may be necessary. This is because there are a finite number of frequencies available due to the low bandwidth of the transducer (typically 10% relative bandwidth). As long as the reuse interval is longer than the typical reverberation time of the room, this works fine. In [8] such a system is described which uses four frequency pairs, the same symbol length of 40 ms, and reuse after four symbols or 160 ms. Although the data rate of these systems is only 25 bits/s, this is adequate for many applications in indoor location.

2) Doppler Estimation

The Doppler estimation principle has been outlined above. Fig 9 shows a measured example (from [3]). This experiment was done in a typical office with dimensions 2.60 m (width), 5.60 m (length), and 2.70 m (height). The receiver was stationary and the transmitter

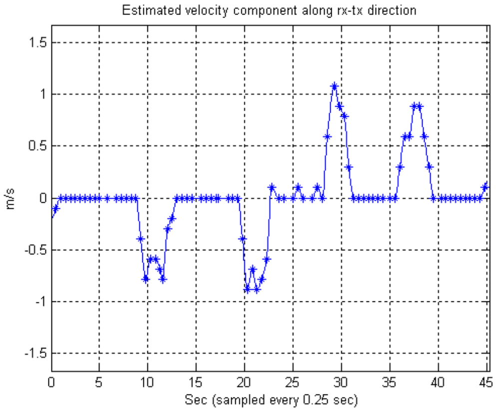

Fig. 9. Measured velocity component along ultrasound beam during experiment (negative velocity is away from transmitter), [3].

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moved. The transmitter started at a distance of about 0.4 m from the receiver, then it was moved a distance of 2 m to about 2.4 m away, stopped, then moved another 2 m to about 4.4 meters, stopped and then moved back in the same steps. Note in Fig. 9 how one can see first a movement out to 2 m, then out to 4 m (negative velocity), then the same positive velocities as the transmitter is moved back in two steps. Given a starting distance, the velocity curve is accurate enough to be integrated in order to get a good estimate of the distance between receiver and transmitter [3]. This property could potentially be used to enhance other forms of position information.

When a flank detector is combined with the data decoder and Doppler detection just described one gets the 3D tracking system of section II.B and Fig. 2. Because of the many receivers (up to 8), the full velocity vector can be found from the Doppler estimates.

V. HYBRID SYSTEMS

With reference to Fig. 1, the methods discussed so far utilize only the most important parts of the received waveform for positioning: the timing of the pulse flank or the maximum amplitude. In [23] an approach is proposed where the full echo structure is used. The idea is that the signal contains reflections from the walls, floor and ceiling and if this information can be utilized it is in principle possible to do 3D positioning with only a single receiver. Each location in the room will have a unique signature and positioning takes place by signature matching.

In order to do this matching it is necessary to characterize the room first. This can be done according to several different approaches:

1. By computation of signatures from an acoustical model that describes both the transmitter and receiver and the acoustics of the room.
2. By measurement of signatures on a fine grid throughout the room.
3. By a learning algorithm

In [23] a signature matching method based on the first approach was tested. The method consists of trying a set of candidate 3D positions in the room by computing their expected signatures and comparing them to the measured signature. An integral part of the method is to estimate the line-of-sight distance by finding the time of the first arrival. This is done in the usual way with by synchronization with an integrated RF system. The preprocessing of the data involves several steps, not the least compensation for attenuation.

Their initial results were obtained using 40 kHz ultrasound in a room measuring 3.7 x 7.7 m and with height 2.9 m with the base station transmitter near the ceiling. 20 measurements were taken at different positions with the receiver at a height of 1.3 m. The accuracy was in most cases better than 20 cm.

A related 2D system was described in [24]. Here the application is very different as the target is to make an acoustic touch panel on a glass plate using a single microphone. The source is a finger knock giving a signal in the 0.1-5 kHz range. The method is calibrated by measuring the resulting echo structure on a grid covering the entire target region. Thus this system uses approach 2, but as this is only a 2D system it is more feasible to do than in the 3D case. The echo signature is also richer than in room acoustics as there are several wave modes in a solid that travel with very different wave speeds in the medium.

An interesting acoustic system was also described in [25] where a microphone next to a keyboard is used to eavesdrop on what is being typed. This system used approach 3 as it generated its own set of target echo structures based on the statistics of the different characters in typical text.

The systems based on echo structure described here both rely on comparison with a complete echo structure. One could think of simplified systems where only the main features of the received echo are used. In Fig. 1 that would mean that one or more of the three secondary peaks are detected and their position in time and possibly also the amplitude is used instead of the entire echo signal.

VI. CONCLUSION

An overview has been given of ultrasound positioning systems in terms of what kind of information from the received signal that they utilize. This has covered TOF-systems which use the arrival time, RSS-systems which use received signal strength, and hybrid systems which use the entire echo structure, i.e. both time and amplitude information in order to do positioning.

There are two main areas of applications for these systems. The first is in positioning of objects in a single room within a limited range. A typical case is for robotics. For this application, TOF-systems are well suited with their accuracies in the cm or sub-cm range. They may be enhanced by using spread spectrum coding.

The other application is personnel or logistics tracking in a large institution such as hospitals. In that case room-level positioning often gives high enough accuracy and the binary RSSI-system is suited. It may also be enhanced with a comparison of relative signal strengths. These applications require good coverage and robustness even if distances approach 10 m. If sub-room accuracies in the 1-3 m range are required, a combination of WLAN with a binary RSSI ultrasound system is well suited.

The systems based on absolute signal strength and hybrid systems based on the entire echo structure are not mature enough to have reached applications yet.

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