USRPS - Ultrasonic Short Range Positioning System

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Abstract: A short range positioning system under development is described. A hybrid ultrasonic – RF link is established between three or more transmitters of known positions and a multi-channel receiver fitted to a mobile vehicle. The described system exploits the enormous propagation speed difference between electromagnetic and sound waves to obtain synchronization without the need of precise (and expensive) clocks. Simulation and preliminary experimental results are presented.

Keywords: Positioning systems, spread spectrum, range measurement

I. INTRODUCTION

The present work was motivated by the need to obtain precise positioning of a mobile vehicle within the limits of a play-yard, where the distance between the mobile and the transmitters would not exceed 40 meters. Three objectives should be fulfilled:

a) The position estimate should be available at all times, with prescribed minimum accuracy.
b) The position estimate should be precise within 1 cm. or less.
c) The complete system should not be expensive.

Early experiments with moderate priced GPS showed that requirement a) and b) were difficult to fulfill. Even in differential configuration, the precision was far beyond specifications.

Several authors reported experimental results using GPS both in simple and differential configurations (DGPS) and for different applications (Land, Marine, Car Navigation, Vehicle Tracking, and Consumer). Nebot (1999) show different types of GPS implementation for Autonomous Navigation. In this case, for DGPS, the most notorious problems that affect the accuracy are the satellite geometric configuration and the multipath reflection. Johnson (1998) demonstrated that combination of GPS and GLONASS (the Russian GPS system) increase the probability of detecting multipath and hence, accuracy is increased.

Some newly applications like precision agriculture report limitation to the use of GPS (Wilson, 2000), both of the type of the listed above. But application that involve Real Time Kinematics (RTK) DGPS (Van Zuydam, 1999), show a satisfactory way to measure the actual position. In this type of applications, the common situation is that a position measure over a wide area is required. In this case, the GPS present an inherent advantage.

Another application born with the advent of the GPS is the Personal Locator System (Koshima, 2000). This is, a miniature device attached to one's person that reports one's whereabouts almost instantaneously. An additional motivation en EEUU is the use of the emergency number service, 911, for wireless callers. In areas like city canyons, this type of technology has the problem of satellite availability. A solution is to use at least two satellites and two cellular base stations.

In the case of indoor location of people, technologies such as DGPS lack with the physics of radio propagation rules where the signals from satellites are weak. Some approach to this problem was made using the principle of the LORAN-A system for radio navigation. This approach, called BPS (Building Positioning System) (Reynolds, 1999) determines the position of a small portable receiving unit by measuring the phase of several radio signal sent from fixed positions.

In this work, the short range involved makes it feasible the use of ultrasound. The wavelength of a 50 kHz acoustic wave in air is 6.88 mm. (considering a sound speed of 344 m/sec in dry air at 20ºC).

The conceived positioning system is composed of a series of ultrasonic transmitters and a receiver. The receiver measures its distance with respect to each transmitter and thereafter is able to calculate its own local position.

For an unambiguous position determination, a minimum of three transmitters and a multi-channel receiver able to discriminate each incoming signal is required.

The ultrasonic (US) transmitters broadcast an acoustic wave BPSK modulated by a pseudo-random code of a certain length. All transmitters are basically identical, except for the code used for the modulation.

The mobile ultrasonic receiver has as many channels as transmitters, and obtains code lock to each ultrasonic transmitter. All channels in the receiver will be identical, except for the code used for correlation.

Hence, the analysis that follows will be focused on a single transmitter and a single receiver channel.

Since cost was of paramount importance, the need to avoid independent precise clocks for the transmitters (and eventually the receiver) was evident.

Then, it was conceived the use or an independent RF channel to synchronize transmitters and receivers.
Besides receiving the ultrasonic signals, the receiver also receives the RF signal that marks the common start of all transmitted codes. Due to the enormous difference in propagation speed between the acoustic and electromagnetic signals, and the short distances involved, the "start mark" is assumed to arrive instantaneously to all US transmitters and receivers, supplying a common "synchronization tick".
Once code lock is obtained for each received channel, the elapsed time (T_1, T_2, T_3) between the start mark and the beginning of each local PRBS code is available.
The calculations involved to derive position are well known and will not be described here.

II. EXPERIMENTAL SETUP

As a first step towards the construction of the complete system, a minimal test setup was conceived and built. This set comprises:

- One US spread spectrum transmitter
- One US receiver

No efforts were derived to the construction of the RF link; the distances involved are short and many commercial low power transmitter/receiver sets are available.
For the tests carried out, a baseband pulse was sent through a coaxial wire linking the US transmitter and receiver.
Fig. 1 shows the experimental setup.

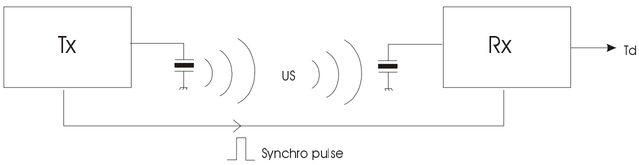

Fig. 1:Experimental setup

2.1 The transmitter

In early stages of the project, several ultrasonic transducers were tested. It soon became evident that piezoelectric transducers (good candidates for their low price) were inadequate since their narrow pass-band could not accommodate the bandwidth of the spreaded carrier.
A sudden phase change in the driver would take tens of cycles before being evident at the transducer output (pressure wave).
An electrostatic transducer (Polaroid Instrument Grade Transducer for Polaroid 6500) was tested with excellent results, both as transmitter (speaker) and as microphone. This is due to the very low Q of these devices.
The transducer requires a DC bias voltage of 150V and admits an AC voltage of 150V peak centered at the bias voltage, when acting as a transmitter. The acoustic power operating at these conditions is 110 dB re 20 µPa at 1 meter.
Fig. 2 shows a simplified sketch of the transmitter. It comprises a carrier generator, a code generator and a power stage to drive the transducer.

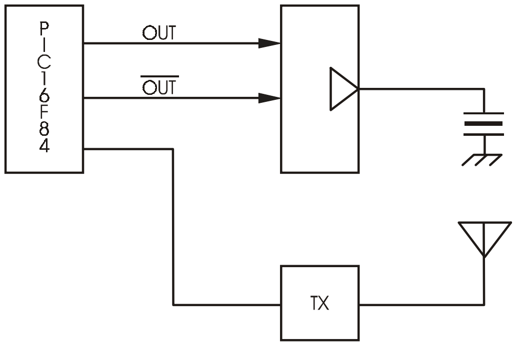

Fig. 2: Simplified sketch of the transmitter

A Microchip PIC16F84 microprocessor generates the spreading code (Kasami sequence, of 255 bits length.), the 50 kHz carrier and a pulse signaling the beginning of the spreading sequence. The spreading code and the carrier are multiplied internally (XOR-ed) and the resulting bit stream applied to an IR2110 FET driver. Two small-power FETs connected to a +300V DC source complete the design.
Notice that even though the output from the PIC is a square-type wave, the driver and the transducer will limit the bandwidth.
The power spectrum of the generated signal has a main lobe of 20 kHz wide as the modulated code has a bit rate of 10 Kb/sec, shown in Fig. 3.

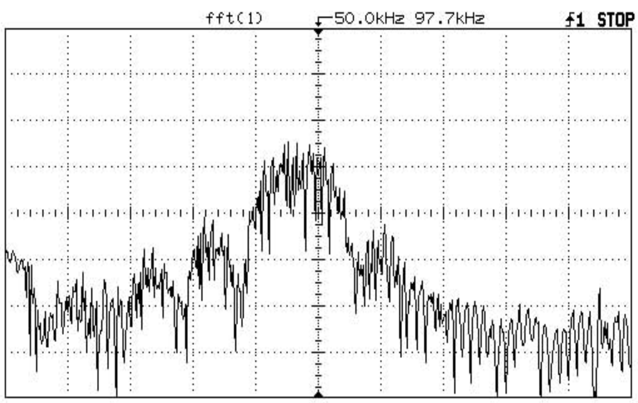

Fig. 3: Power spectrum in dB

Fig. 4 shows the modulating code, the received voltage at the Rx end and the demodulated code. A +30 dB voltage amplifier follows the Rx transducer. In this test, the distance between transducers was approximately 80 cm. Notice that the distance was precisely tuned for the received wave to be exactly in phase with the transmitted wave (remember that the wavelength is approximately 6.88 mm). It is clear that even though the excitation signal is a square wave, the received signal, due to the limited bandwidth, has a much lower harmonic content.

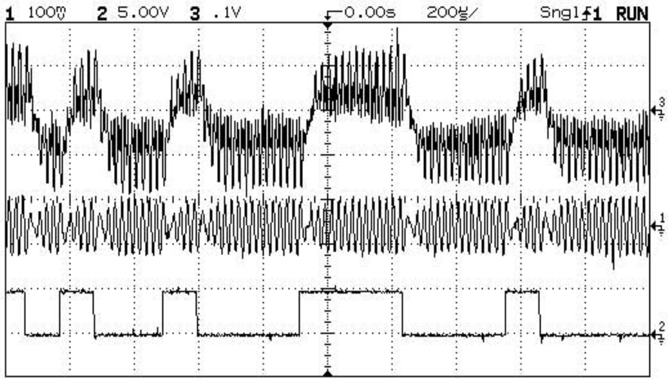

Fig. 4: 1-received signal; 2-modulating code; 3-demodulated code

Fig. 5 shows a similar experiment, except that the carrier phase was changed 180 degrees every five cycles. The phase shift information can be adequately recovered at the receiver end. The distance was not modified; the rms. value of the received signal is app. –3db respect to the received signal without modulation.

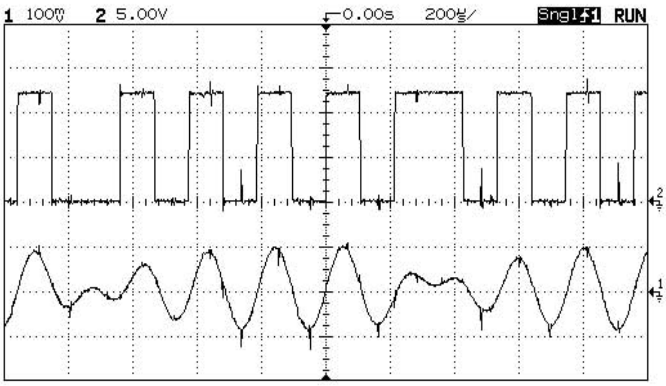

Fig. 5: 1-received signal; 2-transmitted signal

Figures 6 and 7 show the irradiance pattern as obtained experimentally.
This preliminary experiment was actually facilitated by the thin radiation pattern of the used transducer. Indeed if the pattern is omnidirectional the received signal will be considerably smaller; especially jumping from 0.80m to 40m. Because a relatively large area must be covered in all directions, an acoustical mean should be provided to reduce the transducers directivity.
It is known that the acoustic received power is inversely proportional to the square of the distance to the transmitter, and proportional to the transmitter power and the directivity of the transducers.

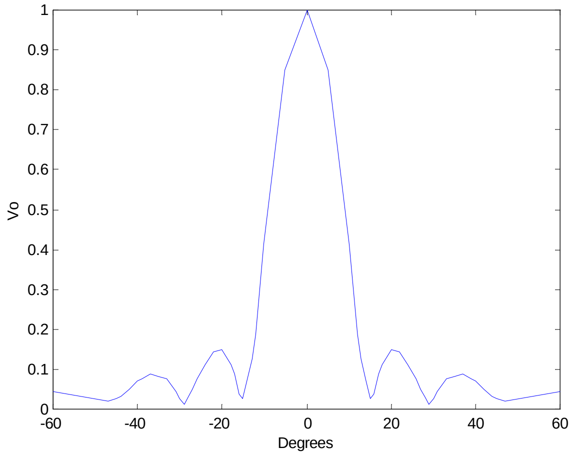

Fig. 6: Irradiance pattern

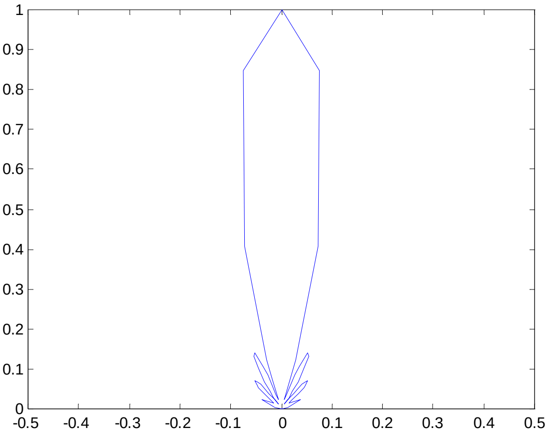

Fig. 7: Irradiance pattern

The received power can be expressed as a function of the received voltage.
Fig. 8 shows the received amplitude (continuous carrier) as a function of distance) obtained experimentally.

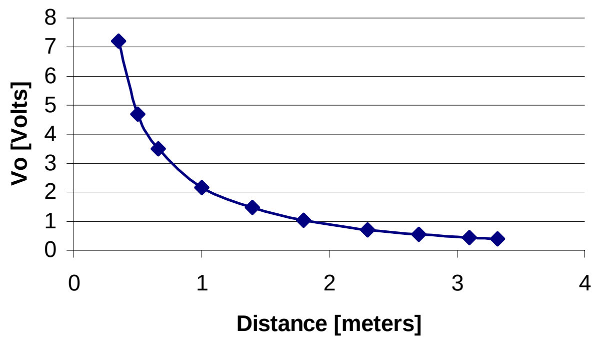

Fig. 8: Received amplitude

2.2 The receiver

Fig. 9 shows the receiver schematics. The Rx transducer is biased with +150 V. The signal from the transducer requires amplification and filtering before demodulation. An automatic gain control (agc) should unavoidably be included in a fully operative version, although it was not used for the initial experiments described in this article.

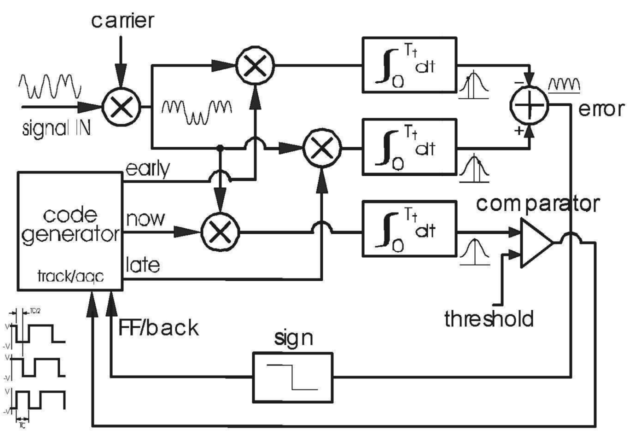

Fig. 9: Receiver Schematics.

The filter bandwidth (centered at 50 kHz) should be greater than or equal to $2/T_c$, where T_c is the chip period of the spreading code. This gives a minimum bandwidth of 20 kHz to reconstruct the original signal. If the filter bandwidth is too wide, the receiver sensitivity to unwanted external noise will be increased.

The conditioned signal is then used to regenerate the original carrier. A phase lock loop (PLL) is used to lock to one of the incoming signals (the one whose modulation codes matches with the demodulating code). This process is well known in CDMA receivers. Fig. 10 shows the loop schematics.

The incoming signal is firstly multiplied by the local code. When this code becomes aligned with the modulating code, the resulting signal will consist of the de-spreaded carrier (a replica of the original carrier prior to multiplication by the spreading code), plus some other unwanted signals that act as disturbances. These signals are the wideband non-correlated signals generated by the other transmitters plus the external noise.

For an adequately long correlation period, the correlation of the unwanted signals with the locally reconstructed carrier will be very low.

Referring to Fig. 9, lock condition will be achieved when two simultaneous conditions are satisfied:

- The mean value of the PLL phase comparator output is zero.
- The correlator output is at its maximum.

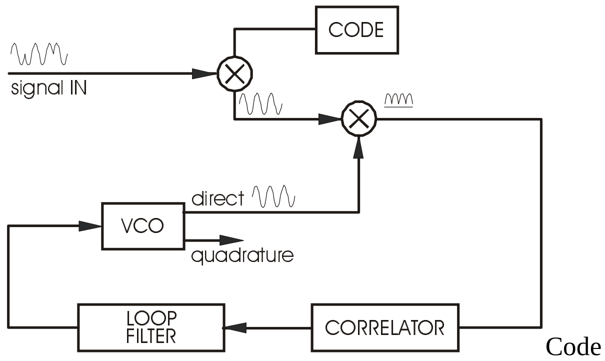

Fig. 10: PLL schematics

Synchronization is achieved in two stages:

1. *Acquisition*: the local (receiver) code is shifted in steps of 1/2 chip until the correlation exceeds a certain threshold.
2. *Tracking*: Code synchronization is maintained. Very small code shifts (forward and backward) are used to attain and retain maximum correlation.

In the acquisition mode, the de-spreaded signal is correlated with the local carrier during a certain time interval T_i. If the resultant correlation does not reach a predetermined threshold after T_i, the local code is shifted ½ chip (always in the same direction) and the process is repeated.

In the tracking mode, the maximum correlation is searched for. Actually, the local code generator has three outputs. One output produces the actual code. The second output produces a replica of the actual code delayed in time ½ chip. This signal is named “late” code. The third output produces a replica of the actual code that is advanced in time ½ chip. This signal is named “early” code.

Let us assume that the incoming spreaded signal is firstly multiplied by the local carrier (the carrier generated by the PLL VCO), and the resulting signal correlated with the late, actual and early versions of the local code, as shown in Fig.9. The actual correlation will be at its maximum when

the difference between the early and late correlations is zero and the actual correlation is above the threshold.
If the difference is not zero, the local code should be slightly shifted (backwards of forward) to null the difference.
The correlation period T_T in the tracking mode should be sufficiently long to reduce the influence of the uncorrelated signals and noise.

$$diff = \int_0^{T_T} sig_{in}.code_{late}\, dt - \int_0^{T_T} sig_{in}.code_{early}\, dt = $$
$$= \int_0^{T_T} sig_{in}\,(code_{late} - code_{early})\, dt \qquad (1)$$

The $code_{late} - code_{early}$ is a three level signal, as a result of being the difference between two two-leveled signals. Since early and late can adopt values of $-V$ and $+V$ their difference can adopt the values $-2V$, 0 and $+2V$. The product of $code_{late} - code_{early}$ with the incoming signal can be easily implemented using analog switches.
As described, the tracking loop can be implemented as depicted in Fig. 11

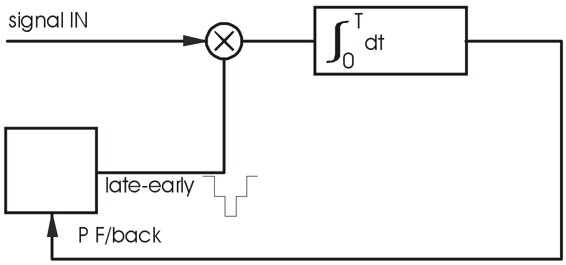

Fig. 11: Tracking loop

A PIC16F84 was used for the practical implementation. The microcontroller generates the late, actual and early codes, and the difference $code_{late} - code_{early}$ encoded in two bits (this is because the $code_{late} - code_{early}$ is a three level signal). One bit carries the signal amplitude and the remaining the sign.
Additionally, the microcontroller can shift the code in both directions either in acquisition or tracking mode, determine the integration periods and generate the in-phase and quadrature local 50 kHz carriers.
The local PLL carrier frequency is achieved acting on the microcontroller crystal oscillator (VXO) from which the instruction cycle time is derived. This way, a slight change in the local carrier period acts proportionally on the local code period.
The PIC generates a pulse signaling the beginning of the local code sequence. The time difference between the pulse generated at the transmitter and the beginning of the local sequence (once lock is reached) is used to compute the distance between transducers.
Figure 12 represents the output of the correlator as a function of the delay between the received code and the generated code. When the codes are aligned, maximum correlation is achieved and when the misalignment is greater than one chip, then correlation is very small. To obtain this figure, a Kasami code of length 255 was used.

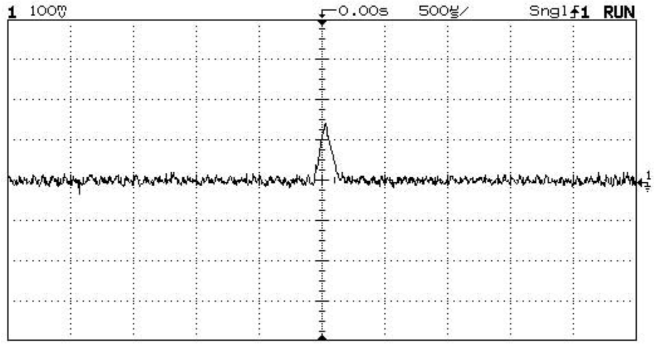

Fig. 12: Correlator output

III. CONCLUSIONS

This article presents the basic aspects of an ultrasonic low range positioning system, able to estimate with good precision (in the order of few millimeters) the position of an object. The basic idea does not differ substantially from the underlying principles in global positioning systems (GPS) except that the enormous difference in speed between electromagnetic and sound waves in air is exploited to avoid the use of precise and expensive clocks.
Even though the system is still in a preliminary phase, experimental laboratory and field results cast enough confidence on the project’s viability.
One of the crucial aspects to be tested is the influence exerted on any channel by the unwanted signals from the uncorrelated transmitters, provided they could be geometrically closer (and consequently be received much louder) than the desired transmitted signal.
All preliminary tests presented here were performed on a static receiver. If the receiver has nonzero speed, the effect of Doppler frequency shifts has to be considered. However, the proposed PLL scheme for each channel is particularly suited to track frequency shifts.
Even at 50 KHz, the attenuation in the air is high, and it may become difficult to reach 40m.
Multipath is quite strong with US unless the area is free of obstacles. Besides, reflections in the floor must be considered.
The wavelength –though “impresively short” only gives an extremely rough idea of what the overall precision might be.
Pressure and temperature changes affect the propagation speed of sound in air. A fully operative version of this system should include adequate compensation mechanisms.

The measurement principle described here could also be applied to liquid or solid media, provided adequate transducers were used and the viability to deliver the electromagnetic synchronization signal.

IV. REFERENCES

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