A low-cost sonar for unobtrusive man-machine interfacing

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Abstract
This paper describes the hardware and the software of a computer-based doppler-sonar system for movement detection. The design is focused on simplicity and low-cost do-it-yourself construction.

Keywords
sonar

INTRODUCTION: SONAR SYSTEMS

Pulse (ranging) sonar
A pulse sonars sends a small-band impulse of ultrasound repetitively and receive the echoes. The distance can be computed from the echo-time, as the speed of sound is almost constant.

The time between emitted pulses must be longer than the longest reflection time, or the measured distance will be wrapped. For a maximum usable range of 5m this requires about 30ms. This limits the time resolution of ranging sonars.

Ranging sonars are used in robotics (Polaroid), intruder alarms, medical imaging, underwater surveillance, and much more. Also numerous electronic music-oriented devices exist: the STEIM SensorLab, the Infusion Systems iCube (FarReach module), and it has been used in the Brain Opera (MIT). Paul Haas describes a simple ranging sonar on his webpage [1] that uses almost only a PIC controller chip.

Doppler sonar
A doppler sonar sends a ultrasound sine wave. Only moving reflecting surfaces cause doppler shifts. The frequency-shift of the received signal depends on the speed of the surface. In the case of a coincident transmitter and receiver this shift equals

$$\frac{\Delta f}{f} = \frac{2v_{object}}{v_{sound}}$$

f is the carrier frequency. 40kHz is a common value for sonars. Δf is the frequency deviation caused by movement speed v_{object}. The speed of sound is approx. 343m/s (depends on temperature). With these values this gives

$$\Delta f = 233m^{-1}v_{object}$$

For human computer interfaces practical speeds will be below 5m/s, which translates in a maximum frequency shift range of ±1165Hz.

The intensity of the frequency-shifted signal depends on the distance from the transmitter, the receiver and their polar pickup pattern, and the surface itself. A surface that distorts or rotates causes a range of frequency shifts (bandnoise).

This principle is applied in fluid current measurement systems, oceanography, and movement detection systems in general.

Quasar Project Kit #3049 is a DIY kit that uses an envelope follower on the received signal and detects changes in the amplitude. Holosound [3] is a more advanced design using a synchronous demodulator and a true-RMS converter in the front-end. Both approaches lose the sign of doppler frequency shift.

Direct sampling of the received signal and decoding it in digital domain was complex and expensive until recently. Almost all consumer systems rely on an analog demodulator.

Hybrid sonars
Emitting band noise, chopped sine, FM or AM signals could possibly combine the properties of pulse sonar and doppler sonar. A compromise must be made between time-, spatial- and velocity-resolution. Decoding involves adaptive filtering or two-dimensional correlation of spectrograms.

Choice
For the purpose of human-machine interfacing in a musical context, movement has a great potential [2]. Few acoustic music instruments sustain forever when the player does not move. This property is interesting to replicate with virtual instruments. Despite this the market of digital musical instruments seems to offer mostly position-sensing input devices for continuous controllers and velocity-sensing input devices for events. From this viewpoint the doppler sonar is ideal.

With fixed ultrasound transmitter and receivers, human movements can be detected, without attaching any device to the human. There is no distinction between different parts of the body, besides caused by the directivity patterns of the transmitter and receiver(s). It is not necessary to eliminate reflections from non-moving surfaces.

The possibilities of complex carrier waveforms appear interesting, but this is future work.

HARDWARE

This design is developed with the following goals in mind:

- Direct sampling, no analog demodulation
- Anyone with basic electronics construction skills must be able to reproduce it. No SMD's, few and mostly standard components...
- Flexible: any of the three sonar types should be usable without modification of the hardware.
- No critical calibration.
- Cheap

The soundcard

Modern times brought us prosumer and consumer soundcards that allow a sample rate of 96kHz. This sample rate catches frequencies up to 48kHz, and allows creating a sonar without an analog computer, voltage to midi converter or specific data-acquisition card. The converters used in soundcards are optimized for sound quality. Noiseshaping is used to push quantisation noise in the upper part of the frequency range. This does not cause problems in this application, since the dynamic range of the converters is big enough.

The soundcard is used both to generate the transmitted signal and to capture the received signal. I tested these cards:

- M-Audio Audiophile 24/96
- RME Hammerfall DSP Multiface
- Echo Layla24

None of these cards seemed to attenuate ultrasonic frequencies too much to allow abuse for sonar applications.

The transmitter

Piezoceramic transmitter elements are suitable for this application. I used part no. 400ST160 for the transmitter. It is directional with an opening angle of approx. 50-60° (-6dB). It produces about 118dB SPL at 12Vrms. A piezoceramic transmitter is a capacitive high-impedance load.

The soundcard delivers a line-level signal. This needs amplification to drive the piezoceramic ultrasound transmitter.

A typical audio amplifier does not fit well for ultrasound abuse, as speakers are a low-resistance inductive load. Many audio amplifiers are protected against ultra-sound too.

A suitable amplifier for this application can be very simple since it does not need to be linear. The piezoceramic element does not produce frequencies over 50 kHz, which is below the harmonics.

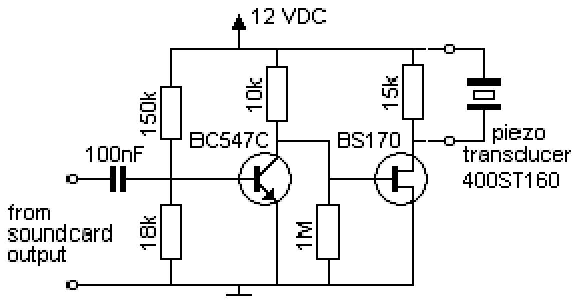

Figure 1. Transmitter amplifier

The first stage (transistor) adds a DC-bias to the input signal, and amplifies its AC voltage to drive the output stage. The signal clips already at this point. The second stage switches the power-supply voltage. This signal drives the transmitter.

The receiver

Few microphones are specified for more than 20kHz, but no doubt some will still pickup 40kHz ultrasound. I have tested a few microphones for this purpose, but none of them showed usable sensitivity at this frequency. Dr. Godfried-Willem Raes suggested me to use MCE-2500 (Monacor) omnidirectional electret microphone capsules, as they reach 60kHz. I did not want to build a complete preamp for this application. Many microphone preamps and mixers with built-in preamps are linear till over 50kHz. I have used the following preamps and mixers successfully:

- Behringer MX2004A
- Mackie 1604 VLZ Pro
- M-Audio DMP-2

To interface this electret microphone capsule to a regular balanced-input microphone preamp with 48V phantom power, some electronics is required though. The easiest solution uses 4 resistors, 3 capacitors, and zener-diode for protection. All the electronics and the capsule fit into a regular XLR cable plug, so no difficult custom casing is required.

You can build a custom pre-amp for an electret capsule, which is less complicated than building a decent phantom-powered balanced microphone pre-amp. Low frequency response does not matter for this purpose.

This electret capsule works also in the audible range, so this ultrasound receiver can even be *abused* as a regular microphone. In software, the ultrasound can be filtered, for simultaneous dual-use.

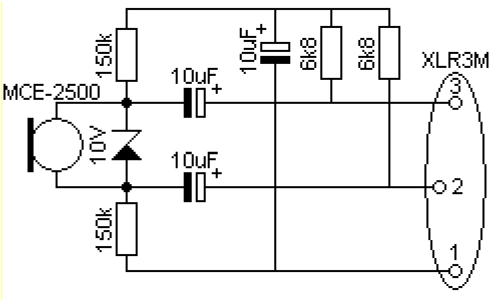

Figure 2. Electret phantom power circuit

Another possibility is using a piezoceramic element designed for the 40kHz operation. I haven't tried this option since the electret capsule gave good results.

Practical setup

It is not necessary to put the receivers at a very specific position. Only the directivity patterns are important to consider. It is best to aim both the transmitter and the receivers to the center of the movement zone. I used them at 2-4 meters distance.

Some common sound sources produce significant ultrasound: e.g. jangling keys, sibilants, hand claps. It is important that those sounds do not confuse the receiver.

SOFTWARE

PD object: dopplersonar~

Pure Data (by Miller Puckette) is used to prototype the software and explore mappings. An external called dopplersonar~ is written for this purpose.

The useful received signal spectrum is contained in the 39kHz – 41kHz range. The carrier is suppressed with an IIR notch filter. The amplitude of the carrier is best ignored since it depends a lot on the placement. Four bandpass filters are used to divide the doppler shifts into:

- fast forward movement (> 0.6m/s)
- slow forward movement (< 0.6m/s)
- slow backward movement (< 0.6m/s)
- fast backward movement (> 0.6m/s)

The logarithm of the energies in these parts is passed to the outputs of the object with a period of 10.66ms. Figure 3 given an idea about the dynamics of the outputs.

The code of the object is freely available [4].

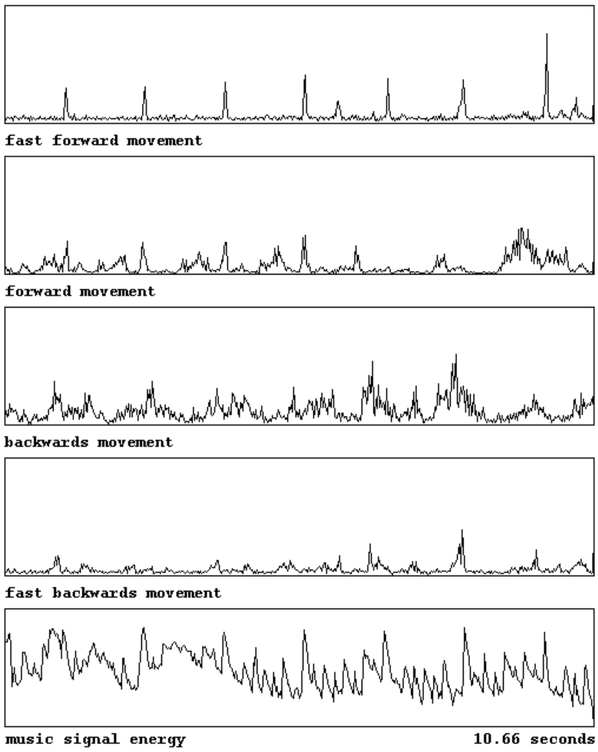

Figure 3. Outputs of dopplersonar~ capturing one person dancing and the energy of the music signal

Application example: Airdrum

The gesture of a sudden standstill or inversion of movement direction induces the idea of a virtual collision. The perceived energy of the virtual hit is related to the speed and duration of the movement before the hit, and is mapped to midi note-on velocity. The movement after the hit (elasticity of the suggested collision) can be mapped to midi note-off aftertouch or midi channel aftertouch. This is suitable for playing virtual percussion instruments.

CONCLUSION

A doppler sonar is a suitable technology for unobtrusive, wireless and low-latency man-machine interfacing. Motions are detected without differentiation between different body parts, while absolute positions are discarded. A digital sonar can be constructed using digital audio workstation components, and a minimum of custom electronics.

The extended possibilities of a bandnoise sonar asks for further investigation. The described hardware is suitable for this.

ACKNOWLEDGEMENTS

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