MEMS ultrasonic time-of-flight innovation: sensors advance user experiences

Steve Taranovich - December 20, 2017

I recently met Dr. Dave Horsley, CTO and co-founder of Chirp Microsystems. This is a company that was created in 2013 after incubating with Skydeck at Berkeley and the government-based SBIR program. Horsley is a professor at the University of California Davis (UCD) where he heads up the MEMS Laboratory.

The history leading up to Chirp Microsystems began in 2008 with a project that Dr. Horsley had as a professor at UCD's Berkeley Sensor and Actuator Center (BSAC). Together with his collaborator, Professor Bernhard Boser, he led a team, including PhD students (and future Chirp co-founders) Stefon Shelton and Richard Przybyla. The team had DARPA funding to research sonar navigation using ultrasound range measurements fused with measurements from a MEMS inertial measurement unit (IMU), a gyro/accelerometer combination. More recently, Chirp is doing virtual reality (VR) applications where they are fusing ultrasound data with IMU data to do tracking of game controllers. DARPA funding lasted until 2011 then they spun out the company in 2013.

[See Junko Yoshida’s article about Chirp Microsystems here: Ultrasound: Can Chirp Usurp UI?]

Help for start-ups

Dr. Horsley wants to acknowledge the excellent initial support they received in their early days from the National Science Foundation (NSF) with a program called the Small Business Innovation Research or SBIR program. Horsley touts this as a fantastic program and that there were many people who helped them along the way to starting their company. He mentioned that Vesper was also an SBIR company. Horsley maintains that there were many other companies that came up and are coming up through these programs.

Dr. Horsley and Chirp co-founders Dr. Przybyla and Dr. Shelton are the perfect team to have come up with a novel design for a tiny MEMS-based solution in an ultrasonic "sonar on a silicon chip," Time-of-Flight (ToF) sensor device. The design has millimeter precision and low power consumption as well.

Time of flight
Figure 1 shows a pulse-echo measurement cycle which begins with the TX burst signal, in this example it is a 200 kHz sinusoid. The TX signal is applied for a duration long enough to excite the piezoelectric micromachined ultrasonic transducer (PMUT) to full amplitude. After the burst ends, the PMUT response decays and the TX/RX switch connects the RX amplifier to the PMUT. The received waveform gets digitized by the ADC and gets stored in memory to be digitized by the DSP. The echo is from an object in the sensor’s field of view. That object’s range is determined by the ToF, $R = c(T/2)$, where $c = 340$ m/s or the speed of sound. $T$ is the ToF and is measured on the time at which the echo crosses a pre-defined threshold. The echo’s bandwidth envelope is shaped by the sensor’s bandwidth (BW).

The shape of the envelope affects the uncertainty in the range measurement since the slope converts the amplitude noise (quantified by the SNR) into range noise represented as $\sigma_r$.

Where:

$$\sigma_r = \frac{c}{2BW} \frac{1}{2\sqrt{SNR}}$$

See Reference 2 for more in-depth analysis.

Three-dimensional ultrasonic imaging has been demonstrated using a phased-array signal processing technique and a monolithic array of PMUTs (Figure 2). Reference 2 also has more analysis details about this.
A 3D location of an object can be done via three range measurements using trilateration. (Image courtesy of Reference 2)

For more details on Time-of-Flight, see my article on Planet Analog.

The first two devices

Chirp is an appropriate name for the company since ultrasonic ToF sensors measure range by emitting an ultrasonic “chirp” and then listening for echoes returning from targets in the sensor’s field-of-view. Each echo travels at the speed of sound, and an echo’s ToF provides a precise measurement of the range to a corresponding target.

Chirp claims the CH-101 and CH-201 are the first commercially available MEMS-based ultrasonic ToF sensors. One main function of both of these first two devices is having both the transmitter and the receiver in a single device.

These devices are in a 3.5×3.5 mm LGA package, and combine a MEMS ultrasonic transducer with a custom low-power CMOS SoC that handles all ultrasonic signal-processing functions. Similar to a MEMS microphone in size, the CH-101 and CH-201 operate on a single 1.8V supply, plus have an I2C interface. The sensor’s on-board microprocessor enables always-on operation for wake-up sensing applications.

**Chirp CH-x01 Block Diagram**

![Chirp CH-x01 Block Diagram](Image courtesy Reference)

**Figure 3** A block diagram of the CH-101 and CH-201 ultrasonic sensors (Image courtesy Reference)
CH-101 vs. CH-201: The CH-101 is recommended for customers that want to sense things closer to the sensor; as close as 1cm and out to 1m range. The CH-201 is recommended for long-range sensing applications up to 5m and as close as 20cm. When an object is closer than 20cm, the sensor knows that the object is there, but an accurate range reading is not possible. The reason for this is common to all ultrasonic sensors which are transmitting and receiving with the same transducer. Looking at the diagram below, we can see that there is one PMUT that has a transmit (TX) and a receive (RX) set of switches, so that when transmitting, the TX switch is closed and a transmit pulse is sent to the PMUT acting as a transducer, then the system changes into receive mode by opening the transmit switch and closing the receive switch. This video explains what these sensors can do and how they work.

Chirp Ultrasonic Sensor - How does it work? from Chirp Microsystems on Vimeo.

The PMUT

The PMUT

Figure 4 A cut-away look at a PMUT where a unimorph PMUT has a single piezo layer on top of an elastic layer. A bimorph would have the elastic layer replaced with a second piezo layer. (Image courtesy of Reference 1)

A bimorph has the advantage of doubling the sensitivity at the cost of increased complexity in fabrication.

‘Ring-down’ phenomenon

There is a period of time in which the transducer is still in the ‘ring-down’ period. Since the transducer was excited with a large pulse, it takes some time before that excitation decays, or ‘ring-down’ such as a bell does when it is struck. So, during that period, the device can perceive sound, but there is more background there and the echo is still a bit large in the transmit section so that objects within that 20 cm will get echoes back while the transducer is still ‘ringing down.’ This prevents an accurate range reading until the ‘ringing’ decays to a low enough level.

In Figure 5, the slope of the phase signal during ‘ring-down’ indicates the frequency offset and is
used to update $f_s$ (The A-to-D Converter sampling rate) and $f_{TX}$ (transmit frequency) before the next measurement. In this implementation, an external clock divider is adjusted up or down by a fixed step of approximately 2 kHz in response to the sign of the frequency offset, so if the initial measurement offset is large it can take several cycles for the tuning loop to lock to the resonant frequency.

**Figure 5** A ‘ring-down’ example (Image courtesy of Reference 2)

**Figure 5** also enables online frequency tracking capability in the 3D Ultrasonic Rangefinder application example below. The average resonant frequency of the ultrasound transducer array may shift due to process and temperature variations. The absolute frequency is fairly unimportant, as long as the transducers are matched and the frequency is known so that the transmitter, receiver, and beamformer can operate at the correct frequency. Frequency tracking is desirable because it means that no programming of the CMOS IC is required for ultrasound chips with different $f_o$ due to process variations.

One way that designers rectify this ‘ring-down’ phenomenon and have the long-range measurement capability, but also want an accurate measurement as close to the 20cm as possible, is using two separate devices—one as a transmit and one as a receive device. In this manner, we can coordinate the measurement and trigger both devices so that one is transmitting and the other is set to receive. With this technique, objects can be measured as close as almost zero distance.

**Infrared (IR) vs. ultrasonic sensing**

A big differentiator between IR and ultrasonics is that ultrasonics works outdoors in sunlight where IR does not. There are some IR data sheets that will publish dramatically reduced range outdoors, even on a cloudy day. If there is LED or fluorescent light indoors, then the IR sensors work fine. If there is halogen or incandescent lighting, then the IR sensors will not work. This is why IR ToF is not in any automotive applications.

Another big differentiator is that ultrasonic sensors are much lower power than IR sensors. An example is when sensors are deployed to detect a human presence or occupancy sensing. Chirp’s ultrasonic devices can sample a 1 sample/second at a power consumption of 15 uW. Today’s IR ToF sensors are in excess of 10 mW. Running off batteries, an ultrasonic sensor can run for a year on a
coin-cell battery.

*Passive infrared (PIR)*

PIR detects a hot object, like a human or a pet, so motion sensing and occupancy sensors use this type of sensor. However, these sensors do not detect small motion—we have all been in a conference room or in front of a PIR spotlight where you have to wave your arms around wildly to get the sensor to recognize you.

Ultrasonic sensors will detect the natural motion of movement like even a person writing on a piece of paper at a table or talking with someone. Small motions can be detected, so a smart TV can sense small movements and remain powered on, for example.

**Shaping the field of view in ultrasonics**

IR ToF has a very narrow field of view, especially those based on a LASER or [Vertical-Cavity Surface-Emitting LASER (VCSEL)](https://en.wikipedia.org/wiki/Vertical-Cavity_Surface-Emitting_LASER) output. If trying to detect a hand gesture, this technology is not well suited. When ultrasound is configured for a wider field of view, it can have the same wide field of view as a camera. Ultrasound can be used to wake up a tablet, PC, or security camera where you want to turn it on when there is motion in the field of view; you only need one ultrasound sensor.

In an ultrasonic sensor design, when the aperture is opened up, a narrower field of view is the result. If the sensor is behind a 0.5mm hole, it will typically have a 180° field of view. If a designer wants to put the sensor in a tablet to see the whole room around a table, then a small opening like this is best. To get a narrower field of view, such as a 60° or less, the opening can be flared to something like 3mm and it will give a narrower field of view.

**Ultrasonic sensor applications**

**3D ultrasound rangefinder**

An example of a 10-channel prototype of an ultrasonic rangefinder was built as a compromise between performance, power, and complexity. A 2015 paper by Chirp co-founders Richard Przybyla, Stefon Shelton, Andre Guedes, Professor Horsley, and colleagues (Reference 2) led to the creation of a MEMS IC design, which we now have in the tiny CH-101 and CH-201 MEMS-based ultrasonic ToF sensors.
How it works

Ultrasound array

This example uses two PMUTs for transmitting and seven PMUTs for receiving in an aluminum nitride (AlN) MEMS array (Figure 6).

High voltage transmitters

The transmitter circuit drives the transducer at resonance which then outputs an excitation pulse. A 1% or 2% duty cycle allows excellent power efficiency and will not need to go into a sleep mode. The narrowband transducer filters the output pressure signal in which linearity is not critical, so a simple inverter is just right for optimal power efficiency here. Figure 7 shows the transmitter schematic.
output transmit signal to the transducer’s top electrode. (Image courtesy of Reference 2)

*Front-end amplifier*

The ADC needs an amplifier in front of it to amplify and buffer its input signal. Good noise figure and proper input and output impedance levels are key characteristics of this amplifier. An open-loop current-reuse operational transconductance amplifier (OTA) was chosen for this prototype design.

*Analog to Digital Converter (ADC)*

The ADCs are switched capacitor bandpass, delta-sigma A to D converters which have built-in continuous time, anti-alias filters.

The 12 kHz BW signal going to the ADC input is centered at 220kHz, so a direct down-conversion (DDC) architecture demodulates that signal to DC and processes the in-phase and quadrature (I and Q) signals via this low speed ADC operating only at a bandwidth of BW/2. A 4th order bandpass delta sigma ADC is chosen here with a 1 bit output sampling at \( f_s = 16f_o \).

![Figure 8](image_url) An electrical/mechanical/acoustical equivalent circuit model of the ultrasonic transducer with an acoustic resonator coupling tube (Image courtesy of Reference 2)

*Digital processing*

Reference 2 shows that after the signal is converted to a bit-stream, it gets converted to the complex-baseband via a digital quadrature mixer.

*Drones/robots*³

Hover stabilization is important, especially with an indoor drone where you may not be able to use GPS to navigate for collision avoidance. Sometimes a side-facing camera is installed into the drone
or a robot. If you are in a conference room with all white walls, 5m distances will look the same as a 5cm distance. Ultrasonic sensors are small enough and have low power dissipation so that they can run off a battery for a reasonable period of time.

**Smartphones**

Chirp’s small size and low power allows product designers to remove the optical proximity sensor from the front of the phone to create a bezel-less display. Because of the wide field-of-view these sensors can measure range even when mounted on the top or bottom sides of the phone. Since this is the location of the microphone and speakers, it’s easy for designers to add another acoustic sensor at these locations.

**Automotive**

Right now, CH-101 and CH-201 are well suited for use inside the automobile cabin for motion sensing and gesture control. I fully expect to see range-finding applications on the outside of the vehicle with new Chirp products in the future that will be in addition to LIDAR and RADAR sensing.

**Gesture recognition**

Reference 2 demonstrates gesture recognition, showing a single frame taken with a single transmit pulse with no averaging. The small transmit array radiates almost isotropically, permitting the system to capture the entire field of view in a single measurement. This system in Reference 2 tracks objects between 45 mm to 1 m away and over an angular range of +/- 45º. Echoes from targets at a range of 1 m return after 5.8 ms. This sets the maximum measurement rate of the system.

![Echo from user's head and hands](image.png)

**Figure 9** Here we see the echo from Chirp co-founder Richard Przybyla’s hands and head when he
poses as seen in this image. The color axis shows the $y$-angle position of the targets. Beamformed data is thresholded at 12 dB SNR (Image courtesy of Reference 2)

Gesture recognition with Chirp's Sensor from Chirp Microsystems on Vimeo.

Medical monitoring

Although Chirp is not working on medical ultrasound, this could be a future application area for their technology. This kind of medical ultrasound would require different transducers from the air-coupled transducers that Chirp makes. One excellent example of a medical monitoring application that can be done on the brain externally and non-invasively is cerebrovascular autoregulation (CA) status monitoring. CA is a protective mechanism of the brain to regulate its blood supply while maintaining stable cerebral blood flow when arterial blood pressure (ABP) or cerebral perfusion pressure are changing within physiological ranges. The impairment of CA has a strong impact on the outcome of patients with traumatic brain injury (TBI). Therefore, for the optimal patient’s treatment, the CA status has to be monitored continuously in real time over a long period, and the individualized treatment strategy should be re-evaluated regularly over the time course of the CA status.


**Figure 10** This is the non-invasive monitor for continuous real-time monitoring of CA (a). The mechanical frame mounted on the patient’s head fixes the ultrasonic transducers in position to ensure ultrasound wave transmission through the brain’s parenchyma or the functional tissue parts of the brain made up of neurons and glial brain cells (b). (Image courtesy of Reference 4)

There are many high-profile companies working to commercialize MEMS ultrasound transducers for medical applications – one is Butterfly Network.

**Smart home products, VR and AR**

We certainly will be seeing these sensors in smart speakers and other smart home products. In VR and AR applications, ultrasonic sensors can provide accurate tracking of objects such as hand-held gaming controllers.

Combined with Chirp’s embedded software library, these sensors advance user experiences with VR/AR, wearables, robotics, drones, and occupancy detection. For more information, please visit Chirp Microsystems.

*Steve Taranovich* is a senior technical editor at EDN with 45 years of experience in the electronics industry.
References


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