MEE303 Sensor Systems

L09
Position sensing: Time of Flight

Position Sensing

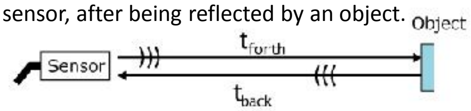
Time of flight measurement systems

Position Sensing

Position tracking devices are used to measure the change in an object's position and orientation over time.

Time of flight -based distance measurement often serves as a way of positioning parts, navigating automated vehicles like stacker cranes, and measuring the dimensions of objects like boxes

Time-of-Flight principle (ToF) is a method for measuring the distance between a sensor and an object, based on the time difference between the emission of a signal and its return to the sensor, after being reflected by an object.

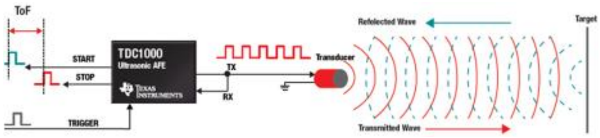


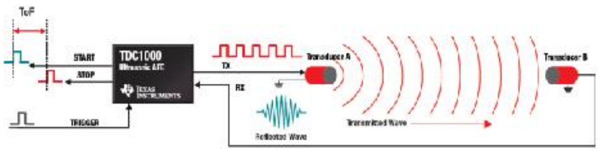
The parameters required to calculate range are simply

- speed of sound in air or =343.2 metres per second
- the speed of light = 299792458 metres per second

Time-of-flight (TOF) systems may be of the "round-trip" (i.e., echo, reflection) type or the "one-way" (i.e., cooperative target, active target) type.

Round-trip systems effectively measure the time taken for an emitted energy pattern to travel from a reference source to a partially reflective target and back again. The returned signal follows essentially the same path back to a receiver located in close proximity to the transmitter.





One-way systems transmit a signal at the reference end and receive it at the target end or vice versa. Some form of synchronizing reference must be available to both ends in order to establish the time of flight

Position Sensing

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Sources of Waves

All noncontact, active ranging devices employ some form of energy. They are based on the principles that energy propagates at a known, finite, speed (e.g., the speed of light, the speed of sound in air).

Therefore, various types of signals (also called carriers) can be used with ToF, the most common being sound and light. .

Depending on whether radio frequencies, light frequencies, or sound energy is used, these devices go by names such as *radar, lidar, and sonar*

Sound: Ranging systems based on sound energy employ carrier frequencies in the so-called “ultrasonic” (beyond audible) range of frequencies. . (+40Khz)

Besides being inaudible, ultrasonic frequencies are more readily focused into directed beams and are practical to generate and detect using piezoelectric transducers

sound, unlike light, propagates at not only much lower speeds, but with considerably more speed variation, depending on the type and state of the carrying media.

Radio Frequency: Echo-type TOF ranging systems based on the band of the electromagnetic spectrum between approximately 1 m and 1 mm wavelength are known as RADAR (Radio Detection And Ranging).
Radio waves can be used for long-distance detection in a variety of atmospheric conditions

Light: Beyond the radio portion of the electromagnetic spectrum are the infrared, visible, and ultraviolet frequencies.
These frequencies can be produced by lasers and detected by solid-state photosensitive devices and are useful for both TOF and active triangulation ranging

A basic trade-off in the choice of frequency is that while high frequencies can be shaped into narrower beams, and therefore achieve higher lateral resolution, they tend to fade more quickly with distance.

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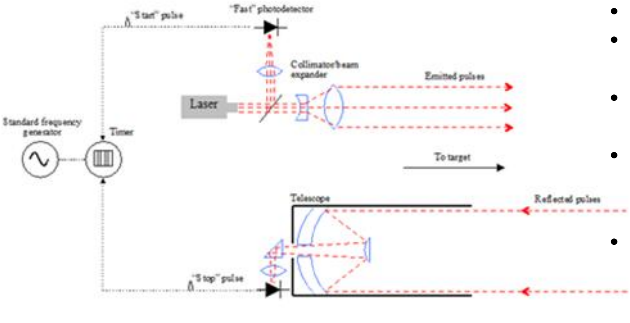
Light Detection And Ranging (LIDAR)

Light Detection And Ranging (LIDAR) is a classic TOF system (both direct and indirect versions exist) for remote depth sensing

In direct TOF, the time jitter of the clock and of the photo-detectors used to control it limit the smallest measurable distance,

whereas the strength of the returned light limits the largest distance.

Direct time of flight: In the direct TOF techniques, the time of flight is measured directly with a clock.



The laser emits pulses of light

- duration tp, and repetition period T.
- A beam splitter directs some fraction of the light to a "fast" photodetector
- the output pulse of the photodetector provides the "start" pulse to a timer (clock).
- The remaining fraction of light passes through the beam expander optics and travels to the target in a medium with index of refraction *n*.
- After reflection from the target, some fraction of the light is collected by the telescope and directed towards the second "fast" photodetector.
- The photodetector produces the "stop" pulse to the timer.

$$d = \frac{cT_f}{2}$$

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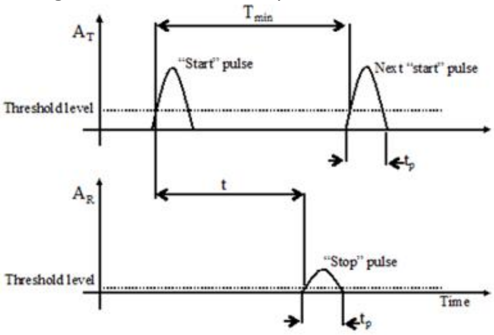
Time of flight measurement systems

Light Detection And Ranging (LIDAR)

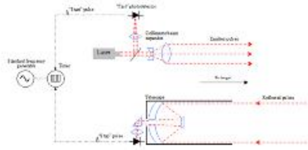
Direct time of flight: In the direct TOF techniques, the time of flight is measured directly with a clock.



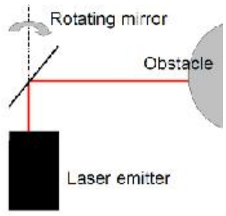
A_T of the start pulse voltage or current produced by the photodetector is controlled by the amount of light siphoned to the detector by the beam splitter.

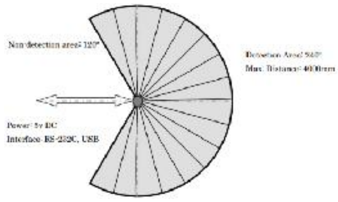
The amplitude A_R of the stop pulse depends on the amount of reflected light collected by the telescope.

the repetition period T of the laser pulses should not be smaller than Tmin = t + tp or the maximum repetition frequency not be greater than fmax = 1/Tmin.



Increasing spatial resolution





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Time of flight measurement systems

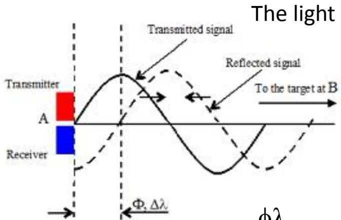
Light Detection And Ranging (LIDAR)

Phase comparison method (Indirect time of flight)

the concept of measuring distance to a target using the phase shift ϕ between the intensity modulated transmitted and received waves.

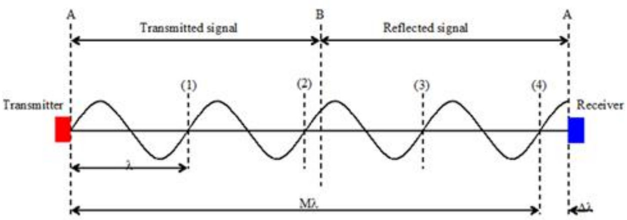
The light does not need to be monochromatic and polarized

The transmitter emits light whose intensity is modulated (sinusoidal modulation is common) by either the transmitter itself (if it is a laser or LED) or an optical system such a mechanical shutter.



The light reflects from the target and arrives at the receiver having a phase shift with respect to the transmitted wave of ϕ, which can have a value between 0 and 2π

$$\Delta\lambda_m = \frac{\phi\lambda_m}{2\pi} = \frac{\phi c}{2\pi\lambda_m} \qquad d = \frac{1}{2}(M\lambda_m - \Delta\lambda_m)$$



f_m is the frequency of modulation and M is an integer that is equal to the number of full modulation wavelengths in the distance 2*d*.

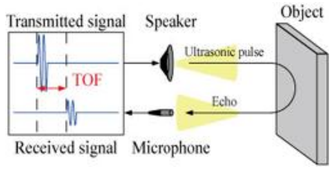
As illustrated in Figure, there are four full modulation wavelengths (***M* = 4**) in the roundtrip distance from the transmitter to the target and back to the transmitter.

Position Sensing
Time of flight measurement systems

Ultrasonic TOF Systems

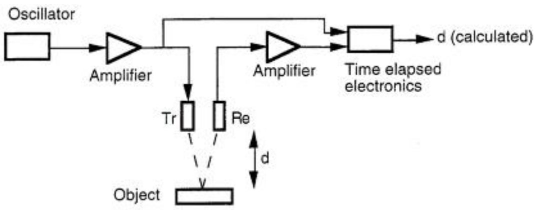
This is the most common technique employed on indoor mobile robots

Ultrasound waves are transmitted in a medium. When the pulse reaches an another medium, it is totally or partially reflected, and the elapsed time from emission to detection of the reflected pulse is measured



$$d = \frac{VT_f}{2}$$

This time depends on the distance and the velocity of the sound. When sound travels with a known velocity Vs Tf time elapsed between the outgoing signal and its incoming echo is a measure of the distance d to the object causing the echo



The transmitter and the receiver could be the same device, but they are separated for clarity.
The oscillator generates an electric signal with a typical frequency of 40 kHz.
This electric signal is transformed into mechanical vibrations of the same frequency in the transmitter. These vibrations generate sound waves that are reflected by the object.

Position Sensing
Time of flight measurement systems

Ultrasonic TOF Systems

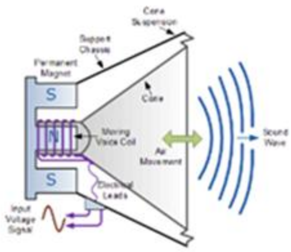
Sound is a vibration in matter. It propagates as a longitudinal wave, i.e., the displacement in the material is in the direction of the sound wave propagation.

Most ultrasound transducers convert electric energy to mechanical energy and vice versa. The most common types of in-air transducers are:
Mechanical, Electromagnetic, Piezoelectric, Electrostatic, Magnetostrictive.

Electromagnetic transducers such as loudspeakers and microphones can be used for ultrasonic wave generation used up to approximately 50 kHz, but they are mainly suited for lower frequencies.

Loudspeakers and microphones are normally audio sound transducers that are classed as “sound actuators” but their micromechanical analogies can reach higher sound frequencies.

The loudspeakers and microphones can be built up as basic moving coil transducers



When an analogue signal passes through the voice coil of the speaker, an electro-magnetic field is produced and whose strength is determined by the current flowing through the “voice” coil,

The electro-magnetic force produced by this field opposes the main permanent magnetic field around it and tries to push the coil in one direction or the other depending upon the interaction between the north and south poles.
As the voice coil is permanently attached to the cone/diaphragm this also moves in tandem and its movement causes a disturbance in the air around it thus producing a sound.

IKCU\Mechatronics Engineering\MEE303 Sensor Systems Dr.Levent ÇETİN

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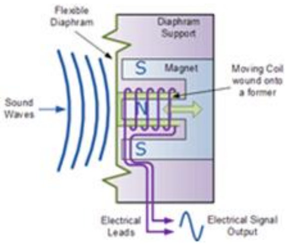
Ultrasonic TOF Systems

The loudspeakers and microphones can be built up as basic moving coil transducers



The construction of a dynamic microphone resembles that of a loudspeaker, but in reverse. It has a very small coil of thin wire suspended within the magnetic field of a permanent magnet

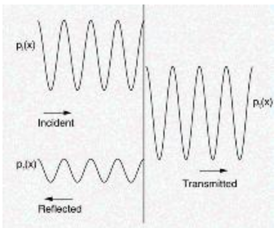
As the sound wave hits the flexible diaphragm, the diaphragm moves back and forth in response to the sound pressure acting upon it causing the attached coil of wire to move within the magnetic field of the magnet

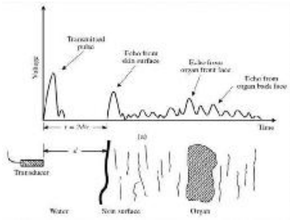
The movement of the coil within the magnetic field causes a voltage to be induced in the coil as defined by Faraday's law of Electromagnetic Induction.

The resultant output voltage signal from the coil is proportional to the pressure of the sound wave acting upon the diaphragm so the louder or stronger the sound wave the larger the output signal will be, making this type of microphone design pressure sensitive.

Operation Principle

An acoustic wave has an intensity and a usually unwanted phenomenon arises when the sound wave has to pass from one medium to another medium **with different characteristic impedance**, a part of the wave intensity will reflect at the boundary between the two media





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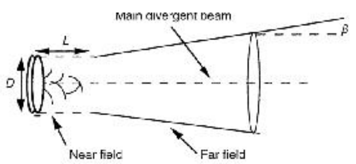
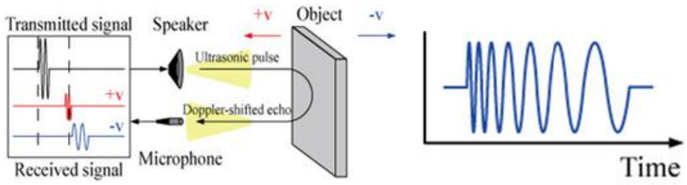
Ultrasonic TOF Systems

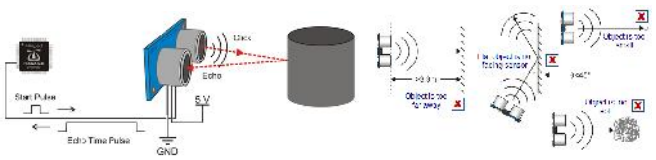
The electric energy is converted into mechanical vibrations of a membrane in the transmitter. The vibrations (the sound wave) have to pass through the boundary between the membrane (usually a solid material) and free air.



The method of velocity measurement using ultrasonic waves is based on the pulse-Doppler method. When the object is moving, due to the Doppler effect introduced by the motion of the object, the reflected echo is Doppler-shifted.



Because the transmitter membrane and the free air have different characteristic impedances, some of the acoustic intensity is reflected. Therefore ultrasonic tof displacement sensors have a minimum measurement limit as can be seen in figure



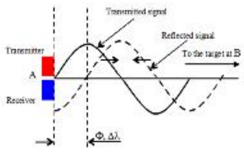
Position Sensing

Time of flight measurement systems

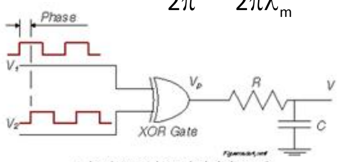
Methods for calculations

direct TOF setup, a clock measures this time, while in an indirect TOF setup, the time is inferred from, for example, the phase relationship between intensity-modulated emitted and detected wave.

Phase-Shift Measurement



$$\Delta\lambda_m = \frac{\phi\lambda_m}{2\pi} = \frac{\phi c}{2\pi\lambda_m}$$

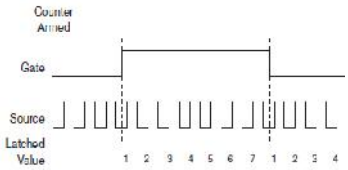


At low frequencies typical of ultrasonic systems, a simple phase-detection circuit based on an *exclusive-or* gate will generate an analog output voltage proportional to the phase difference seen by the inputs. (Adapted from [Figueroa and Barbieri, 1991].)

The time measurement can be done by using counters. Counters are excited with oscillators which generates square waves with relatively high frequencies

The counters can be triggered via external pulses.

The first trigger to counter makes it start the register the number of pulses incrementally until second trigger comes.



The total number of pulses logged in register is multiplied via oscillator period to calculate the total amount of time passed between two triggers.

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GPS

An example of a TOF one-way (active receiver) system that uses radio frequencies is the global positioning system (GPS).

GPS is a space based satellite navigation system that provides location and time information.

The Global Positioning System allows a GPS receiver to determine its position by using a simple formula: Velocity x Time = Distance. GPS satellites continuously transmit digital radio pulses at precise, known times. So by measuring the exact instant when the pulses arrive, the receiving GPS equipment can determine the distance to each satellite

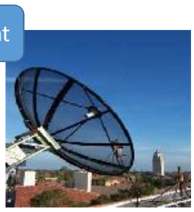
the GPS receiver have to get its own clock synchronized with the satellite clocks. For this purpose, GPS sattelites send a time codded pulse array to receiver. The receiver arranges its clock if there is a difference between durations on received codded signal and the information provided from satellite about that signal. By this means, a receiver can calculate its distance to the specific satellite

A constellation of 24 Satellites that transmits signals that gives the current GPS position & time

Space segment

Worldwide control stations to maintain satellite in orbit & adjust satellite clocks

Control segment



GPS receivers which receive signals from satellite to calculate users position & time

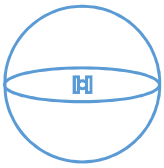
User segment

Position Sensing

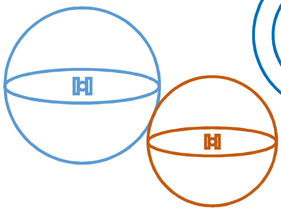
Time of flight measurement systems

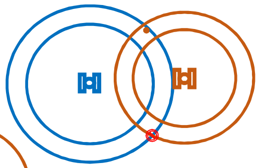
GPS

Position calculations:

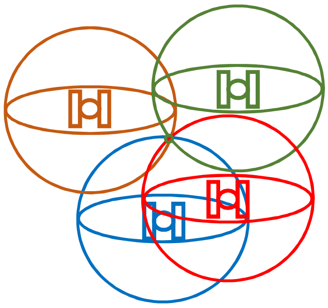


The receiver is somewhere on this sphere.





The tangential point on perfect spheres is actually where the reciever is but due to measurement uncertainties, their intersenstion is not a point



The third sattelite to overcome uncertainties and the fourth for cross check and time correction

$$\left\{\begin{array}{l}(x_0-X_1)^2+(y_0-Y_1)^2+(z_0-Z_1)^2=d(\Delta t_1,\varepsilon)^2\\(x_0-X_2)^2+(y_0-Y_2)^2+(z_0-Z_2)^2=d(\Delta t_2,\varepsilon)^2\\(x_0-X_3)^2+(y_0-Y_3)^2+(z_0-Z_3)^2=d(\Delta t_3,\varepsilon)^2\\(x_0-X_4)^2+(y_0-Y_4)^2+(z_0-Z_4)^2=d(\Delta t_4,\varepsilon)^2\end{array}\right\}$$