Application Report

SLAA783–July 2019

PGA460 Array of Ultrasonic Transducers for Triangulation and Tracking

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ABSTRACT

This document discusses various triangulation solutions to compute and track an object's location using at least two ultrasonic transducers. The Texas Instruments PGA460 ultrasonic sensor signal conditioner and driver-integrated circuit is used in each solution due to its built-in support for broadcast commands to ensure the transmitter and receiver transducer elements are all synchronized for accurate triangulation. The Texas Instruments MSP430 micro-controller is loaded with the triangulation algorithm because the PGA460 is a slave device only capable of returning time-of-flight (ToF) data for a single channel. The performance, cost, algorithm complexity, and size advantages/disadvantages of each solution will be discussed in comparison for the user to select the most appropriate triangulation solution for their system.

Contents

1 Introduction 1
2 Triangulation 2
3 PGA460 Triangulation Solutions 2

List of Figures

1 Simplified Ultrasonic Time-of-Flight Concept 2
2 Triangulation Block Diagram Solution for a Transceiver and Receiver Combination 2
3 Triangulation Block Diagram Solution for a Multi-Transceiver Combination 2

List of Tables

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1 Introduction

A single ultrasonic sensor pinged to perform a time-of-flight measurement can be used to estimate the distance between the sensor and the targeted object. However, a single ultrasonic sensor is also likely to have a wide beam angle because the pulsed echo propagates in a conical shape rather than a narrow straight line. Due to the wide area coverage of a single sensor, the exact position and incoming angle of the echo reflected from the target cannot be precisely determined. For systems that only require a binary indication of an object's presence without regard to position, such as an occupancy sensor, triangulation is not necessary. For systems that require knowledge of the object's detailed position for virtual mapping of the environment, such as an autonomously mobile robot, triangulation is recommended.

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2 Triangulation

Triangulation uses the coordinates of three known points to form a virtual triangle. The law of cosines computes the internal angles of the virtual triangle given the length of all sides. Ultrasonic time-of-flight triangulation is enabled by incorporating at least two synchronized receiver elements to capture the time-of-flight information of a single echo reflected from one object. In this configuration, the two receiver elements serve as known points, therefore the leg length between the two receiver elements is always given. The length of the two remaining legs from the target can be calculated by converting the receivers' time-of-flight measurements to distance. Using the law of cosines, the equation to solve for the transmitter's angle between the target and complementary receiver is shown in Equation 2.

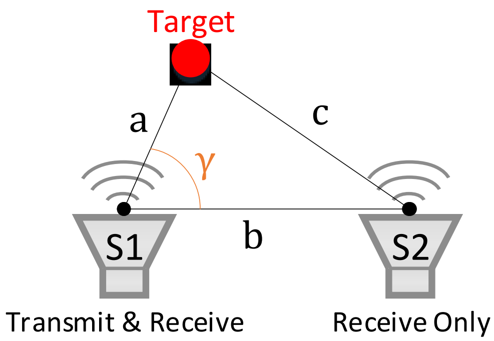

Figure 1. Simplified Ultrasonic Time-of-Flight Concept

$$c = \sqrt{a^2 + b^2 - 2ab\cos(\gamma)} \quad (1)$$

$$\gamma = \cos^{-1}\left(\frac{a^2 + b^2 - c^2}{2ab}\right)$$

where

- a = distance between $XDCR_{S1}$ and target
- b = distance between $XDCR_{S1}$ and $XDCR_{S2}$
- c = distance between $XDCR_{S2}$ and target
- y = angle between both target and $XDCR_{S2}$ (2)

3 PGA460 Triangulation Solutions

All of the proposed solutions require each ultrasonic sensor (either mono or bistatic) to be paired with an independent PGA460 device. Triangulation cannot be achieved through multiplexing or return path switching without resolution losses. A single PGA460 can only be connected to multiple receiver elements for binary presence detection.

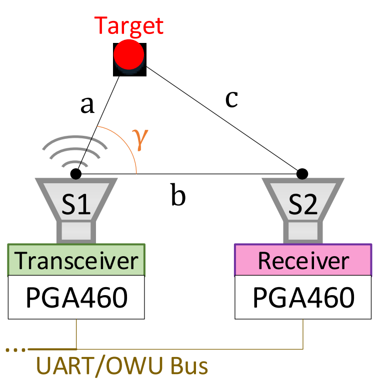

Figure 2. Triangulation Block Diagram Solution for a Transceiver and Receiver Combination

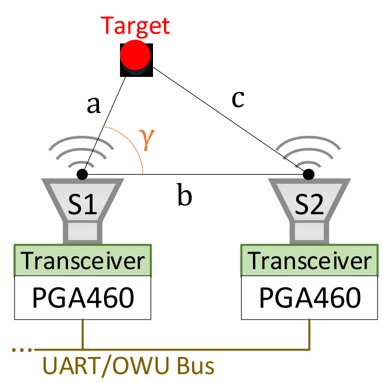

Figure 3. Triangulation Block Diagram Solution for a Multi-Transceiver Combination

3.1 Transceiver and Receiver

If a system is dedicated solely to triangulation, then the transceiver and receiver module implementation is recommended. In this configuration, the transceiver module can transmit the ultrasonic echo and listen for a return, while the receiver module should only be capable of listening for a returning echo. For both modules to be synchronized, a bus communication interface is required. The PGA460's USART or OWU interfaces enable a shared bus connection for up to eight PGA460 devices. By limiting the physical connection of the receiver module's sensor to the PGA460's return path, the burst-and-listen command

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can be executed at the receive module without transmitting a disruptive echo. In this scenario, only the transceiver module should transmit an echo. By executing a broadcast burst-and-listen command, the transceiver module will transmit and begin to listen for a return echo, while the receive module will only be capable of listening for a return echo due to its floating driver (OUTA and OUTB). The transceiver module can be either a monostatic or bistatic configuration based on the system's range requirement.

The triangulation algorithm for the transceiver and receiver solution is as follows:

1. Send broadcast threshold bulk write command (CMD25).
2. Send broadcast burst-and-listen command (CMD17/18).
3. Wait until the preset record length time expires.
4. Send an ultrasonic measurement result command (CMD5) to read back the time-of-flight data from each device.
5. Convert time-of-flight data to one-way distance, and calculate the internal angles using the law of cosines.
6. Repeat steps 2–5 to track the object's position.

3.2 Dual Transceivers

If multiple ultrasonic modules in a system are to independently capture time-of-flight data, and triangulation must be enabled as a secondary or advanced feature, then all modules must be of the transceiver type. All modules should be able to transmit and receive, therefore the triangulation algorithm will either require additional steps and time-compensation techniques, or the resonant frequency of the transducers installed on each module should be out-of-band from one another. This section will discuss the option of using a software or hardware workaround for dual-transceiver triangulation.

3.2.1 Software Workaround – Offset Time-of-Flight

Because the broadcast burst-and-listen command would generate two echoes, and the command does not include exclusion for specific addresses to listen-only, the transceiver and receiver algorithm is not compatible in the dual-transceiver mode. Instead, the algorithm must be updated such that all devices are initialized with a broadcast listen-only command, immediately followed by a sole transceiver to burst-and-listen. Because the transmitted echo is generated after the listen-only command has already been executed, the transceivers operating in the listen-only mode will report the return echo time-of-flight to be greater than the actual value. This user-created time-of-flight lag can be offset and compensated if the time between the broadcast listen-only command and singe device burst-and-listen command is known. The offset time will be dependent on the USART/OWU baud rate, along with the amount of master controller delay introduced between both commands. The master controller can track the offset time by logging timer values immediately before each of the aforementioned commands are executed. The master controller then computes the difference between the two timer logged values to correctly offset the listen-only time-of-flight data by a negative value.

The triangulation algorithm for the dual-transceiver software workaround is as follows:

1. Send the broadcast threshold bulk write command (CMD25).
2. Wait for the master controller to log the initial timer value.
3. Send the broadcast listen-only command (CMD17/18). Sending a broadcast listen-only command enables up to eight PGA460 devices to listen for a return echo. The more devices listening for an echo, the more accurate and precise the triangulation. In a dual-transceiver configuration, a single address listen-only command (CMD2/3) can also be sent.
4. Wait for the master controller to log the offset timer value.

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5. Send a single address burst-and-listen command (CMD0/1) immediately after sending the previous listen-only command. The burst-and-listen command is a no-response command, therefore if the listen-only command is aborted, the burst-and-listen command is served at the designated address.
6. Wait until the burst-and-listen preset record length time expires.
7. Send an ultrasonic measurement result command (CMD5) to read back the time-of-flight data from each device.
8. Convert time-of-flight data to one-way distance.
9. Subtract the timer logged initial value from the timer logged offset value. Then subtract this difference from the listen-only devices' time-of-flight value to compensate for the command lag.
10. Calculate the internal angles using the law of cosines.
11. Repeat steps 2–10 to track the object's position.

The PGA460 device does not support echo signature coding. If coding were supported, all devices would be able to burst-and-listen simultaneously, without the worry of echo cancellation or interference from one another.

3.2.1.1 Time Decouple Synchronization

A more accurate alternative to logging the timer offset between the initial listen-only broadcast command and subsequent burst-and-listen command is to repurpose the PGA460's DECPL pin as a synchronization-interrupt pin. When the DECPL pin is set to time decouple mode, the DECPL pin will only hold logic-high during the burst-and-listen command execution. The command execution is equal to the preset's record time length, therefore the time decouple duration should be set equal to the preset's record time length value.

The PGA460's DECPL pin in time decouple mode will only toggle during a burst-and-listen command, and not for a listen-only command. Therefore, the initial listen-only broadcast command described in Section 3.2.1 must be substituted with a broadcast burst-and-listen command with the designated preset's pulse count set to 0. For the remainder of this example, assume that preset-1 is intended to be used for listen-only broadcast purposes, and has a pulse count of 0. When a preset's pulse count is 0, the PGA460's OUTA will still sink current during a burst-and-listen command to produce a single-ended one pulse equivalent toggle. If feasible, a single-ended transformer should be used in this type of triangulation configuration, where only the OUTB is connected to the transformer and the OUTA remains floating. This single-ended driver connection effectively disables any echo transmission for a pulse count of 0. If a push-pull transformer driver method must be used, preset-1's driver current limit should be minimized to 50 mA to limit the amount of sound pressure level generated by the listen-only sensors.

When the PGA460 receives a burst-and-listen command, the PGA460 will wait a consistent 50 µs after the end of the incoming UART packet before the device toggles the low-side gate drivers and processes the incoming data through the digital signal processor. Once the wait period to process the command has expired, the DECPL pin will toggle from low-to-high logic. The external master controller can monitor the state of the DECPL pin for each of the PGA460 devices connected to a bus and will flag when an interrupt occurs whenever the DECPL pin transitions from low-to-high logic. This flag indicates that the burst-and-listen command was received and processed by that particular PGA460 device. A timer should log the interrupt time for this low-to-high logic DECPL transition for the burst-and-listen broadcast command with a 0 pulse count, and then again for the subsequent single address burst-and-listen command with a non-0 pulse count.

One option is to only monitor the DECPL pin of the sensor that will transmit, because the record length logic-high time will be extended by the start time differences of the two burst-and-listen commands. The broadcast command will be processed by all devices simultaneously, therefore the offset between the initial and subsequent burst-and-listen commands is assumed to be identical for all devices on the bus.

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