Real-time multi-object localization and tracking using frequency-modulated continuous-wave radar

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Problem statement

Radar technology is widely used in automotive applications. For example, adaptive cruise control (ACC) uses a radar to measure the speed of the vehicle in front in order to keep a safe distance while blind spot assistance uses a radar to detect the presence of a vehicle in the blind spot of the driver. Recent advancements in autonomous vehicles also make heavy use of radar technology. In this case, the radar, along with an array of other sensors must detect as well as track the many objects that can enter or exit the path of the vehicle.

In this project, we will use the TI IWR6843 FMCW radar module [1] for multi-object detection and localization. Building upon the works of the previous project group, we will extend their algorithms to work with multiple objects. Furthermore, we will implement the algorithms on the DSP chips and microcontrollers embedded into the radar module, which enables the system to do real-time processing in an online setting. The final system should function as a simplified autonomous vehicle radar or early-warning system, where the range and speed of the objects moving in and out of the region of interest can be measured in real-time.

Stretch goals

In addition to localizing the objects, in many applications it is also important to be able to track the objects over time. This requires the system to correctly associate measurements from different times with some persistent objects. As a stretch goal for this project, such a tracking system. In [2, 3], Kalman filters are used on the radar detection output to update parameters for existing objects as well as removing ghost targets.

Technical approach

FMCW radar is a relatively mature technology. As such, there are standard algorithms for processing the raw radar output. We base our technical approach on these standard techniques, which are discussed in [4, 5, 6].

In a FMCW radar, electro-magetic waves (usually in the millimeter-wave range) are continuously emitted, with varying frequency contents (chirp signal). This enables us to measure the range (distance from radar) of the object by computing the difference between the instantaneous frequency of the reflected wave and the emitting wave (beat signal). Using the frequency slope of the chirp, we can translate the beat to a time delay, which corresponds to the round-trip propagation delay. Combining with the speed of light, this in turn gives us a distance measure. Furthermore, if there are multi-objects at different distances, the beat signal will in fact have multiple frequencies that can be separated out after taking the Fourier Transform. The relation between the distance and the "beat" frequency is given by: $d = \frac{f_b c}{2S}$, where c is speed of light and S is the slope of the chirp signal. However, if the objects are close to each other in range, we would not be able to separate them since the FFT would not be able to resolve the different peaks close in frequency. In fact, the range resolution is given by: $d_{res} = \frac{c}{2B}$, where B is the bandwidth of the chirp, i.e. the difference between the minimum and maximum frequency in the chirp. Finally, the maximum range that can be unambiguously measured is $d_{max} = \frac{F_s c}{2S}$, where F_s is the sampling frequency of the ADC that digitizes the beat signal.

A FMCW radar can also measure range rate, or velocity towards/away from the radar, even if the objects are at the same range. This is because small motions in the objects will not change the beat frequency very much, but will lead to significant phase differences in their respective beat signals. By sending a sequence (frame) of chirps, the phase difference will vary in the echo of each chirp, i.e. the phase difference changes like a phasor which can be resolved using another FFT. Suppose we send a frame that contains N chirps spaced T_c apart. The relation between the velocity and the phase difference is given by: $v = 2\pi\lambda_0$, where λ_0 is the wavelength associated with the initial chirp frequency, ω is the phase shift frequency obtained from the FFT. The velocity resolution is $v_{res} = \frac{\lambda_0}{2NT_c}$. Finally, the maximum velocity we can measure is $v_{max} = \frac{\lambda_0}{4T_c}$.

Finally, in order to localize objects, we require the angle of the object with respect to the radar face in addition to its range. This is possible if we have multiple receiving antennas separated by some distance, because the echoing waves travel different distances to each antenna, this gives us another phase difference that we can use to measure the angles of objects. We can estimate the angle using the phase difference between every pair of receiving antennas. With an array of equally spaced antennas, we can also perform FFT to separate the objects. The relation between the angle of the object relative to the radar normal is given by: $\theta = sin^{-1}\left(\frac{\lambda\omega}{2\pi d}\right)$, where ω is the phase difference between antennas, and d is the separation between antennas. The angular resolution is $\theta_{res} = \frac{\lambda_0}{Nd\,cos(\theta)}$. Note that the angular resolution actually depends on the angle itself, where the angle of objects orthogonal to the radar face can be resolved much more easily compared to the angle of objects near the edge of the field of view. Finally, the maximum angle that can be measured is theoretically $\pm 90^{\circ}$, however, due to the fact that the angular resolution quickly deteriorates near the edge, this limit is empirically much lower.

To summarize, the digital signal processing routine for multi-object localization is as follows:

1. The multiplicative-mixed beat signals from a frame of chirps are laid out along the rows of a matrix. The x-axis represents time, while the y-axis represents the chirp index.
2. We take FFT along each row to separate different frequencies in the beat signals. The magnitude peaks show objects at different ranges. (Range-FFT)
3. We take FFT along each column to separate the phase variation between chirps. The magnitude peaks show objects at different velocities. (Doppler-FFT)
4. Every receiving antenna would produce a range-velocity map from steps 1-3 above. The peaks in these maps would be approximately the same. We take FFT across the array of receiving antennas (Angle-FFT) to obtain angle-of-arrival estimate for each of the range-velocity peaks.

Literature Review of Previous Work

The ECE113D F/W 2019-2020 group [7, 8, 9] has implemented the standard 3DFFT algorithm to extract range, velocity and angle of arrival information. They were successful in accomplishing several localization tasks for offline data using MATLAB, including range, velocity and angle of arrival estimation, for one object in the field of view. We plan to use their project as a starting point for our extension.

Gao *et al.* [10] has successfully incorporated similar range, velocity, and angle information. They have also used RA (Range Angle) and STFT (Short time Fourier Transform) heatmap to help perform further data processing. This data is then concatenated or stacked, and passed into a VGG Neural Network for object classification (pedestrian, car, etc.)

Kim and Hong [2] has also used Monte Carlo simulations in matlab to simulate the expected radar behavior, which could be helpful for testing our algorithms before moving onto the hardware platform.

Hyun et al. [3] has proposed two methods to remove clutter for multi-target range and velocity detection. The first method proposed is based on fast ramp trains (which essentially require taking 2D FFTs). The drawback for this method however, is that it is computationally expensive and generally challenging for digital synthesizers to implement a linear fast ramp. The second proposed method uses slow ramp trains, which is computationally less expensive but faces the issue of "ghost targets" in multi-target detection.

Who does what

- We will both understand the algorithms and what each other are doing on a high level at least.
- Justin will focus more on the hardware, which include real-time implementations (data transmission, online signal processing, etc) of the algorithms as well as basic interface.
- Jingbin will focus more on software prototypes of the algorithms, involving preliminary tests on MATLAB using offline data.

Project timeline

The tasks listed should be completed by the end of the week specified.

- Week 1
    - Understand/annotate code from previous group
- Week 2
    - Obtain example data and replicate previous group's results
- Week 4
    - Real-time
        - Implementation of single-object localization from previous team
    - Offline
        - Revision/improvements to previous algorithms
        - Algorithm for multi-object localization
- Week 7
    - Real-time
        - Implementation of multi-object localization
    - Offline
        - GUI for displaying localization data
- Week 10
    - Full system integration

Reference

1. Texas Instrument, Single-chip 76-GHz to 81-GHz automotive radar sensor integrating DSP, MCU and radar accelerator, [https://www.ti.com/product/AWR1843]

2. Kim, D., Hong, S., *Multiple-target tracking and track management for an FMCW radar network*, [https://asp-eurasipjournals.springeropen.com/articles/10.1186/1687-6180-2013-159]

3. Hyun, E., Oh, W., Lee, J., *Detection and tracking algorithm for 77GHz automotive FMCW radar*, [https://ieeexplore.ieee.org/abstract/document/6087125]

4. Rao, S., *Introduction to mmWave Sensing: FMCW Radars*, Texas Instrument

5. Iovescu, C., Rao, S., *The fundamentals of millimeter wave sensors*, Texas Instrument

6. Briggs, D., *Introduction to the radar project*

7. Zeger, E., *Radar Project*, [https://emi4053.wixsite.com/mysite]

8. Pan, Y., *Radar Project* [https://ucla113dradar.wixsite.com/radar]

9. Oh, J., *Radar Project* [https://joelpig123.wixsite.com/radarproject]

10. Gao, X., Xing, G., Roy, S., and Liu, H., *Experiments with mmWave Automotive Radar Test-bed*, [https://arxiv.org/pdf/1912.12566.pdf]