Vehicle wheel detection using micro doppler effect

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Abstract. With the advent of autonomous driving, safety have become the top priority. To adhere vehicle safety standard for autonomous vehicle, the sensors play the primary role in sensing the environment. With high frequency resolution radar, micro motions of the vehicle wheel can be detected. Time-Frequency distribution is used to detect the frequency changes with respect to time. MUSIC is a high resolution direction finding algorithm, which can estimate the direction of arrival of echo signals. Micro Doppler effect provides the vehicle wheel information related to the number of spokes and its spoke size. With this information, it is possible to detect the exact position of the wheels in the vehicle.

Keywords: Micro Doppler effect, Time-Frequency, MUSIC (MUItiple SIgnal Classification).

1. Introduction

Automakers are developing new vehicles with diverse technologies to meet the ever growing consumer demands. The consumers are looking for improved safety, comfort and energy efficient vehicle. ADAS applications incorporates various sensing technologies along with advanced processing and communication. For the development of autonomous vehicle, SAE has defined six levels of automation for the driving scenarios.

- LEVEL 0 - No Driving Automation (Example: ABS)
- LEVEL 1 - Driver Assistance (Example: ACC, AEB)
- LEVEL 2 - Partial Automation (Example: Automated Parking)
- LEVEL 3 - Conditional Automation (Example: Stop and Go)
- LEVEL 4 - High Automation (Example: Stop and Go in Urban)
- LEVEL 5 - Full Automation (Example: Autonomous Parking)

1.1. Automotive Radar

Automotive RADAR and LIDAR are the primary sensors of the self-driving cars. Radars systems are mainly used in vehicle safety and comfort systems. A typical automotive radar sensor updates the safety systems at the rate of 30 frames per second. When the vehicle velocity is the same as that of radar mounted vehicle, then it is quite difficult to detect the movement of the moving vehicle. The change in frequency of the echo signal that is caused by the micro movements of the vehicle wheel can be detected using micro Doppler effect. The Doppler frequency is calculated using the equation (1).

\[ f_d = \frac{2V}{\lambda} \cos(\theta) \] (1)
As the vehicle is receding from the radar its Doppler shift becomes negative and its velocity is positive. Similarly when the vehicle moves towards the radar, its Doppler shift becomes positive and in turn its velocity is negative [8]. Micro movements of the vehicle wheel introduces Doppler frequency modulations in the frequency spectrum. A varying Doppler shift is generated by the varying velocities of the points in the wheel. The figure 1 indicates the different velocities of points in the rotating wheel of the vehicle. Detection of the micro motions of the vehicle wheel is explained in this paper.

1.2. Literature Survey
The Micro Doppler effect detects the rotational and vibrational motions in the target. The Inverse Synthetic Aperture Radar use Micro Doppler Signature for the classification of targets [5]-[7]. An Empirical Mode Decomposition (EMD) method is used for detecting the micro movements in the vehicle motion. EMD method distinguish the tracked and wheeled vehicles and also splits the signal into number of functions [5]. The translational motion of the target introduce constant Doppler shift with side bands known as micro Doppler signatures. Micro Doppler Analysis of rigid bodies such as Vehicle wheel, Helicopter blades, and non-rigid bodies such as motion of limbs in human bodies in joint time frequency domain is studied [6]. Radar Cross Section (RCS) of time varying targets such as vehicle wheel is studied [7]. The micro movements of the vehicle is detected based on time frequency transform using micro Doppler analysis. Mathematical model for micro Doppler analysis is derived [8]. Dynamic Time Warping (DTW) Algorithm is applied to detect the micro motions in the target. Micro Doppler signature depends on the rotation rate and DTW method is able to classify the targets [9]. Software Defined Radio (SDR) is based on FMCW radar, which can be used to detect the target and also to control air traffic radar system [3]. Constant False Alarm rate (CFAR) uses an adaptive threshold level, which is determined by the clutter or noise in the echo signal [1].
Motion Estimation is based on Doppler velocity over azimuth angle using Orthogonal Distance Regression (ODR) is proposed [4]. The vehicle wheel velocity is calculated based on the velocity of the points on the wheel and its axis of rotation. This is an improved method compared to temporal filtering and the position of all the vehicles' wheels are detected [2].

2. Wheel Detection
2.1. General Motion
Each point of a body in pure translation undergoes same motion, whereas each point of rotating body about a fixed axis undergoes pure circular motion. When a body undergoes translation and circular motion then its resultant velocity is sum of its two velocities. The magnitude of the velocity of the center of a wheel rolling on a stationary plane surface equals the product of the radius and the magnitude of the angular velocity. For pure rolling the point of contact has zero velocity and the top most point has two times of its linear velocity [2]. So these velocity variation of points across spokes introduces change in Doppler frequency. The figure 2 indicates the movement of the spokes with varying velocities at different points in the rotating wheel.

\[ V_{A/O} = R_{A/O} \times \omega \]  

\[ V_R = 2V \sin \theta / 2 \]

Figure 2. Position of spokes in a rotating wheel

Euler’s theorem allow us to express the body’s change in position relative to the axis of rotation.

2.2. Radar Cross Section
The RCS is used to determine the characteristics dimension of the wheel and also to represent the strength of the radar returns from the vehicle wheel. When the wavelength of the radar signal
is larger than the target’s dimension, then it is in Rayleigh region. The RCS in rayleigh region depends on the volume of the scatterers rather than its physical shape. When the wavelength of the radar signal is smaller than target’s dimension, then RCS is of optical region. The RCS in optical region depends on the physical shape of the scatterers rather than its volume. Each individual scatterers of vehicle wheel introduces an echo signal, which is characterized by its amplitude and its phase. The RCS of target varies as much as 15db due to its motion.

2.3. Range Doppler Response
The Matched filter increases the output signal to the mean noise ratio. when the input s white noise then the The frequency response function of white noise spectral density is

\[ H(f) = G_a S^*(f) \exp(-j2\pi ft_m) \] (4)

The received signal spectrum is expressed in the form of amplitude spectrum and phase spectrum

\[ S(f) = |S(f)| \exp[-j\phi_s(f)] \] (5)

The Matched filter frequency response function is expressed in the form of amplitude spectrum and phase spectrum

\[ H(f) = |H(f)| \exp[-j\phi_m(f)] \] (6)

Equating equation (4) by the values of equation (5) and equation (6)

\[ |H(f)| \exp[-j\phi_m(f)] = |S(f)| \exp[j\phi_s(f) + 2\pi ft_m] \] (7)

By solving equation (7), it is found that the amplitude spectrum of the echo signal and the Matched filter frequency response has the same magnitude. The phase shift of the matched filter frequency response is equal to the negative phase shift of the received echo signal and also dependent on the frequency of the received signal. The fast time and slow time data is calculated using Matched Filter. Space time adaptive algorithm is applied on the two dimensional angle-Doppler data for each range bin to calculate the velocity of the target and its angle.

2.4. MUSIC Algorithm
The model is assumed to be constant velocity model. At each pulse the car moves along its trajectory while the spoke of the wheel introduces additional displacement and angular speed. MUltiple SIgnal Classification (MUSIC) algorithm is used to detect the direction of the receiving signals from the vehicle wheel. MUSIC algorithm is capable of detecting the velocities of different points on the wheel. MUSIC algorithm process the received echo signal in two subspaces. The signal subspace is based on the largest eigen values in the received echo signal. The largest eigen vectors of the signal will span the signal subspace. The noise subspace receives the echo signal having lower eigen values. The directions of reflections are calculated based on the azimuth and elevation of the vehicle wheel.

3. Simulation Results
Simulation of the system design is used to predict the behavior of the system under certain conditions. In this simulation model, the car is modeled by six scatterers.
- Rotation Center
- 5 Spokes of the wheel

The rotation center moves along the chassis of the vehicle and it is assumed that each spokes of the wheel are 72 degree apart from each other. The wheel is rotating at the constant speed of 4 revolutions per second. It is assumed that the spoke size of the wheel to be 18 cm and all
Table 1. Shows the scattered positions of the spokes and the rotation center from the radar.

| COORDINATES | CENTER | SPOKE 1 | SPOKE 2 | SPOKE 3 | SPOKE 4 | SPOKE 5 |
|-------------|--------|---------|---------|---------|---------|---------|
| X           | 40.0000| 40.1800 | 40.0556 | 39.8544 | 39.8544 | 40.0556 |
| Y           | 0      | 0       | 0.1712  | 0.1058  | -0.1058 | -0.1712 |
| X           | 40.0030| 40.1830 | 40.0584 | 39.8572 | 39.8572 | 40.0584 |
| Y           | 0      | 0.0002  | 0.1713  | 0.1056  | -0.1060 | -0.1711 |
| X           | 40.0060| 40.1860 | 40.0612 | 39.8601 | 39.8601 | 40.0621 |
| Y           | 0      | 0.0005  | 0.1713  | 0.1054  | -0.1062 | -0.1710 |
| X           | 40.0090| 40.1890 | 40.0640 | 39.8630 | 39.8630 | 40.0653 |
| Y           | 0      | 0.0007  | 0.1714  | 0.1053  | -0.1063 | -0.1710 |

Table 2. Shows the scattered velocity of the spokes and the rotation center from the radar.

| COORDINATES | CENTER | SPOKE 1 | SPOKE 2 | SPOKE 3 | SPOKE 4 | SPOKE 5 |
|-------------|--------|---------|---------|---------|---------|---------|
| X           | 60.0000| 60.0000 | 55.6975 | 57.3409 | 62.6591 | 64.3025 |
| Y           | 0      | 4.5239  | 1.3980  | -3.6599 | -3.6599 | 1.3980  |
| X           | 60.0000| 59.9943 | 55.6958 | 57.3455 | 62.6637 | 64.3007 |
| Y           | 0      | 4.5239  | 1.3926  | -3.6632 | -3.6566 | 1.4034  |
| X           | 60.0000| 59.9886 | 55.6940 | 57.3501 | 62.6683 | 64.2990 |
| Y           | 0      | 4.5239  | 1.3871  | -3.6666 | -3.6532 | 1.4088  |
| X           | 60.0000| 59.9829 | 55.6923 | 57.3547 | 62.6729 | 64.2972 |
| Y           | 0      | 4.5239  | 1.3817  | -3.6699 | -3.6499 | 1.4142  |

Table 3. Shows the scattered angle of elevation of the spokes and the center from radar.

| COORDINATES | CENTER | SPOKE 1 | SPOKE 2 | SPOKE 3 | SPOKE 4 | SPOKE 5 |
|-------------|--------|---------|---------|---------|---------|---------|
| phi         | 0      | 0       | 0.2499  | 0.1521  | -0.1521 | -0.2499 |
| phi         | 0      | 0.0003  | 0.2450  | 0.1518  | -0.1524 | -0.2448 |
| phi         | 0      | 0.0006  | 0.2450  | 0.1516  | -0.1526 | -0.2446 |
| phi         | 0      | 0.0010  | 0.2451  | 0.1513  | -0.1529 | -0.2445 |

the five spokes have identical reflectivity. At each pulse the car moves along its trajectory and introduces Doppler shift in radar return.

The Time-Frequency analysis gives more information about micro Doppler effects. The figure 3 shows the micro Doppler modulation caused by wheel spokes around the constant Doppler frequency shift. Each wheel spoke introduce sinusoid like Doppler modulation and within each period there is additional four sinusoids appear. This infer that the wheel is designed with five spokes. The varying position of the rotating spokes is observed in the table 1, the varying velocities of the spokes is observed in table 2 and the angle of elevation of the spokes is observed.
in table 3. The figure 4 indicates the micro Doppler modulation which is caused by the movement of the rotating wheel. The figure 5 indicates the range Doppler response using the first 128 pulses of the radar return signal. Though the radar return looks like they are from different targets, but actually they all are from the same target. This intensity is due to the reflection being stronger from the chassis of the car than the spokes of the wheel.

**Figure 3.** Micro Doppler shift produced by the spoke tip of rotating wheel.

**Figure 4.** Micro Doppler shift produced by different points on rotating wheel.
4. Conclusion
Inferred from the simulation result, the micro Doppler modulation is due to the movement of the spokes which resides in rotating wheel. The rotational motion of wheel in addition to the chassis movement of the vehicle introduces the change in frequency of the echo signal. The period of each sinusoid is about 250ms. It shows that the spoke tip velocity is 4KHZ away from constant Doppler introduced by the chassis. The exact spoke tip velocity with relative orientation of the wheel is obtained. Based on exact spoke tip velocity and spoke spinning rate, spoke length is determined. These micro motions detection can be integrated with ACC functionality for the safe driving of the vehicles in urban scenarios. For the further research, vehicle can be classified as heavy or light vehicles based on the estimated spoke length.

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Figure 5. Range Doppler Response.