Design Analysis of an Indoor Localisation System integrated with FMCW Radar for Emitter Tracking Applications

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Abstract. An indoor localisation system is designed based on passive tracking and a localisation system assisted with an active FMCW radar system. The system covers a sixty-meter point-to-point radius. The designed system operates within the UWB band at a frequency of 3.6GHz. The simulated system has four passive receivers as well as an integrated FMCW active radar and multiple transmitters that are tracked. A parametric sweep is utilised to optimize the results for the desired frequency. Simulations are performed within the Matlab simulation software environment.

Keywords: FMCW, Indoor localisation, Passive localisation, Active localisation, short-time Fourier transform (STFT)

1. Introduction

For detecting, tracking, and localizing single and numerous moving objects, radar sensors are best suitable and efficient option, radars provide trustworthy and precise tracking by determining the distance to and bearing of the target by using a modulated or pulsed signal in conjunction with narrow beams. Even though this method offers the advantages of high antenna gain and immediate object localization, they are relatively inexpensive and need phased array or mechanically guided antennas and advanced signal processing techniques, this raises both the financial burden and the level of computing difficulty. As a result, there are still certain restrictions, particularly those caused by the many signal pathways received. Several pieces of research have proposed implementing a Received Signal Strength Indication (RSSI)-based Indoor Positioning System (IPS) to localize objects found within. The RSSI measures the strength of a received radio signal and ascertains the distance between the transmitter and the target. The distance must be measured to establish an approximation of the target's position using three-dimensional trilateration. There is evidence that RSSI-based IPSs can accurately approximate interior locations; nevertheless, the average accuracy only goes up to roughly two meters. When it comes to locating more minor objects, an accuracy of two meters could be more helpful since the walls in the rooms of average homes are often a few meters in height. FMCW, or frequency-modulated continuous wave is utilized for indoor object localization to resolve this problem. To achieve high precision across a wide range and high-resolution positioning, it uses a technique known as time of flight (ToF). The time required for a radio signal to go from a transmitter to a receiver is called ToF. Because radio waves move at a constant speed, ToF is

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used to determine the transmitter's and receiver's geographical separation. After the distance has been determined, trilateration may be used conventionally to determine the location of a particular item of interest. Fig.1 depicts the essential components of a typical Multiple Object Detection and Tracking system.

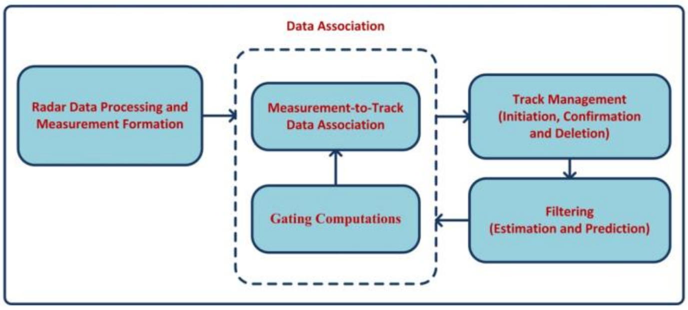


Fig. 1. Track Management for Localization

2. Passive Radar Detection

There is a subset of bistatic radar systems known as passive radars. These radars do not make use of a separate transmitter but rather make use of signals coming from various sources in order to shed light on the targets to be tracked. These sources are often called emitters of opportunity (EoO), including additional radars, communications systems, broadcasting systems, etc. It is argued that EoOs are "non-cooperative" because the PCR operator does not have any control over their transmissions and does not need the EoOs' participation to use them. Passive Emitter Tracking (PET) and Passive Coherent Location (PCL) are the two distinct techniques this radar system may use. PET requires a target to send the signal. After the signal has been sent, PR detects it and conducts signal processing based on an exponential function of the time the signal has been delayed.

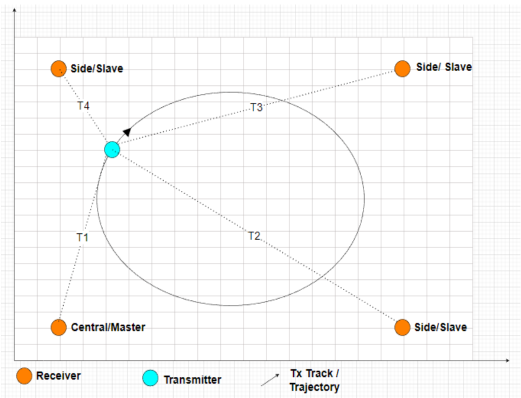


Fig. 2. PET Locator System

PCL uses broadcast emitters as reference signal and for the radar transmitter, the signal hits target and reflected to the system, target location is determined at echoes received.

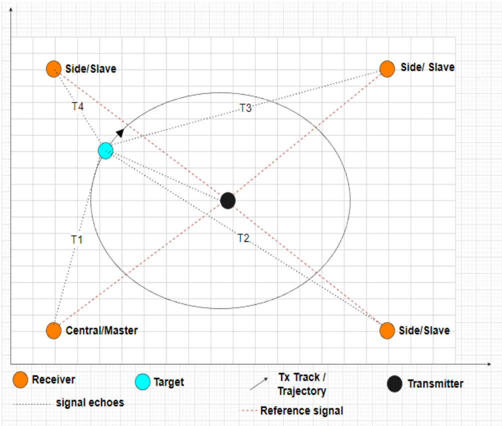


Fig. 3. PCL Locator System

In this research, novel PET localization is proposed. PET Localization using Time Difference of Arrival in conjunction with FMCW to locate the target as well as position on 3-dimensional locations. The relations between TDoA with the target position are calculated by using:

$$\sqrt{(x_t - x_1)^2 + (y_t - y_1)^2 + (z_t - z_1)^2} - \sqrt{(x_t - x_2)^2 + (y_t - y_2)^2 + (z_t - z_2)^2} = c\,(t_1 - t_2) \quad .1$$

$$\sqrt{(x_t - x_1)^2 + (y_t - y_1)^2 + (z_t - z_1)^2} - \sqrt{(x_t - x_3)^2 + (y_t - y_3)^2 + (z_t - z_3)^2} = c\,(t_1 - t_3) \quad .2$$

$$\sqrt{(x_t - x_1)^2 + (y_t - y_1)^2 + (z_t - z_1)^2} - \sqrt{(x_t - x_4)^2 + (y_t - y_4)^2 + (z_t - z_4)^2} = c\,(t_1 - t_4) \quad .3$$

The system employs omnidirectional broadcast antennas with directional receiver antennas oriented in different directions. For example, the initial system that was implemented, called Chain Home, utilized a pair of linear antennas positioned orthogonally to receive signals, with each antenna connected to a distinct display unit. The optimal detection of maximum return can be achieved by aligning the antenna perpendicular to the target. In contrast, the minimum return can be obtained when the antenna is directed directly towards the target. The operator could ascertain the direction of a target through the rotation of the antenna, wherein one display would indicate a maximum value. In contrast, the other would indicate a minimum value. A notable drawback of this particular approach is the omnidirectional nature of the broadcast, resulting in the examined direction containing only a fraction of the transmitted energy. In order to achieve a sufficient level of power directed towards the intended "target," it is necessary for the transmitting antenna to possess a directional characteristic.

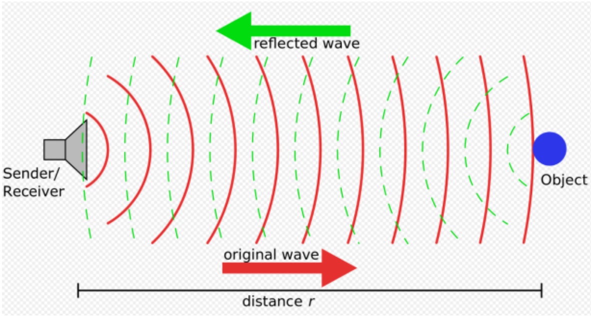


Fig. 4. Active Radar Working Principles

FMCW Radar system is a specialized radar that can determine the distance between moving objects and their velocities by modulating the signal being delivered constantly to shift its frequency continually. Changing the frequency pattern of an emitted radio wave by several frequency modulation techniques, the most common of which are sawtooth modulation and triangular wave modulation. Other frequency modulation techniques include sine wave modulation, square wave modulation, and stepped modulation. Sawtooth and triangular wave modulations are utilized the most frequently.

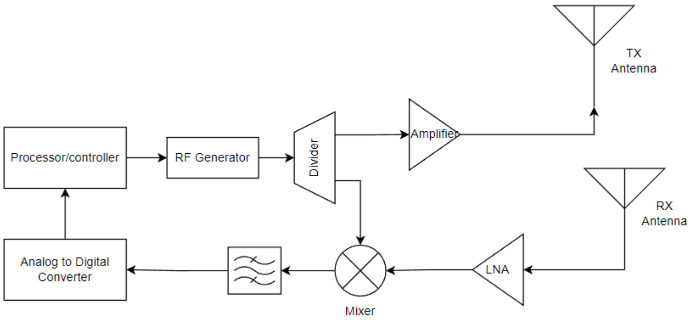


Fig. 5. FMCW Radar Block Diagram

In the FMCW system, the transmitting antenna sends out continuous radio waves, and the receiving antenna picks up the signal reflected from the target. Through a preamplifier, the signal picked up by the receiving antenna is sent to the next step of the receiver, the mixing stage. In the mixer circuit, a portion of the broadcast frequency-modulated signal is mixed with the received signal to produce a new signal. This new signal may then calculate the distance (R) and the velocity at which the moving item travelled. The term "beat frequency" refers to the difference in frequency between the frequency of the signal being broadcast and the frequency of the signal being received (reflected).

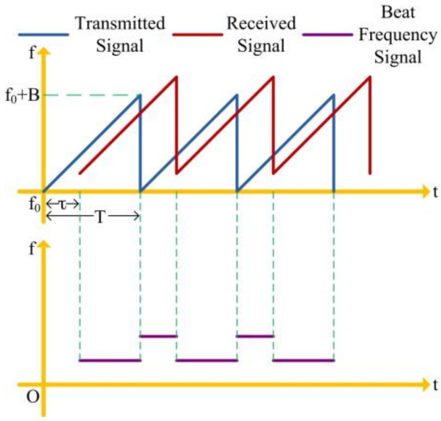


Fig. 6. Time-Varying FMCW Sawtooth Waveform Model

Regarding FMCW radar, the range resolution is determined by the bandwidth of the broadcast signal. In contrast, the chirp time interval may determine the maximum range. Figure 3 depicts a linear progression of the transmitted frequency from fo to fo + B, where B represents the signal's bandwidth. This progression begins at fo and continues until fo + B. The signal sweep time is denoted by the symbol T, and the maximum range is represented by the expression c*T/2, where c is the speed at which light travels. The signal that is being broadcast may be written as:

$$S_T(t) = A_T \exp\left\{-j2\pi\left[f_0 t + \frac{B}{2T}t^2\right]\right\} \quad .4$$

3. Proposed Passive Radar Detection

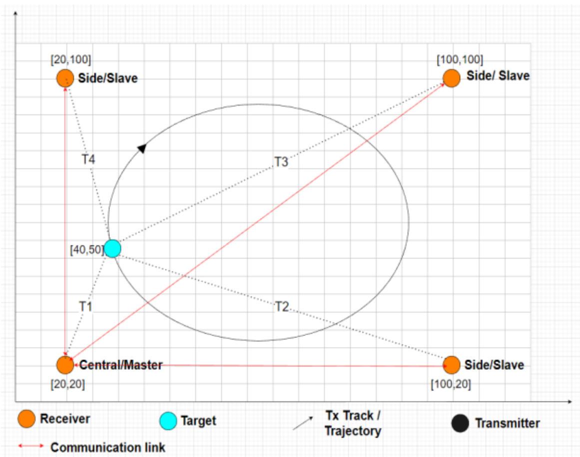


Fig. 7. Proposed Scenario of Passive Detection

In this passive radar detection scenario, the target transmits an FMCW signal, and then the transmitted signal is detected by 4 receivers. The scenario has following specification: Centre Frequency of the transmitted pulse 3.6 GHz, Bandwidth 500 MHz, sweep time 1ms, Speed of the target is 4 m/s, Position of the target is on [40,50], The Central/master receiver is on [20,20], The side receiver are on [100,20], [100,100], [20,100], The target emits the signal with omnidirectional antenna, so it will have same level in any direction. For object detection, each receiver can digitalize the received signal from the target, and then send it to the central/master receiver. Then on the central receiver, there is a signal processing process, from mixing the signal to get the low frequency before doing the FFT to get the exact beat frequency value. After we get the beat frequency, we can predict the time difference between the master and the wide receiver. After making the direction of arrival based on the TDOA, the position is as Figure 8 below.

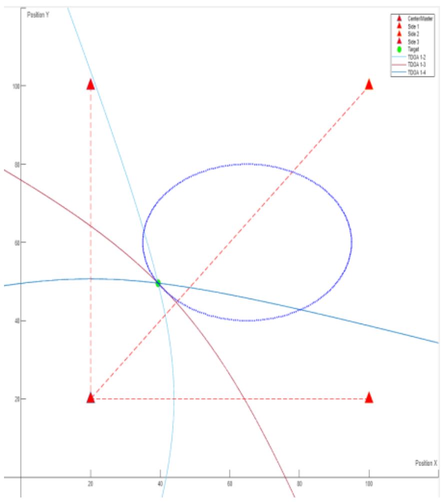


Fig. 8. TDOA of Passive Detection System

4. Proposed Active Radar Detection

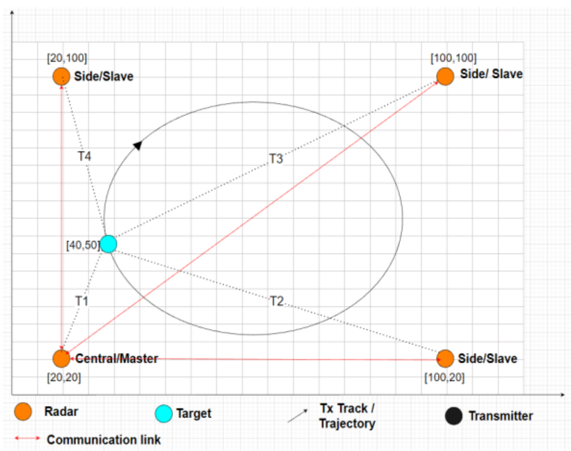
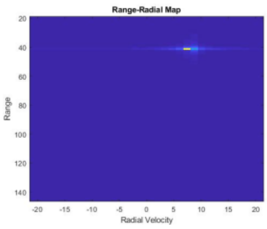
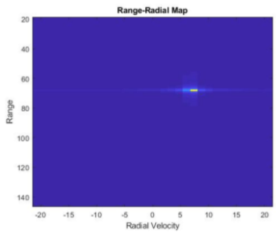
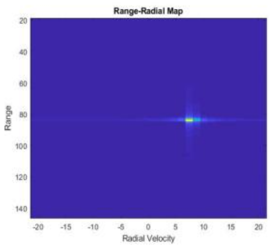


Fig. 9. Proposed Scenario of Active Detection System

In this active radar detection scenario, the target transmits an FMCW signal, and then the transmitted signal is detected by 4 receivers. The scenario has the following specification: Centre Frequency of the Radar 1 is 3.1 GHz, Centre Frequency of the Radar 2 is 3.6 GHz, Centre Frequency of the Radar 3 is 4.1 GHz, Centre Frequency of the Radar 4 is 4.6 GHz, Bandwidth 500 MHz, sweep time 1ms, Speed of the target is 4 m/s, Position of the target is on [40,50], The target emits the signal with omnidirectional antenna, so it will have same level in any direction. For active radar detection, we use 4 radars with different Centre frequencies, the center of frequency must be different because we must ensure that the signal does not interfere between them. For localization of active radar, the need for ADC speed is much lower than passive detection, it is because we do the mixing of the signal to get beat frequency on the analog side, so it has a low frequency like several Mhz. After processing and getting the range, each side radar then sends the data (target range from the radar) to the master, to do final processing to get the specific position of the target. The exact position of the target is calculated by eq.1,2,3, object detections using FMCW Radar, following FFT results are attained:

Radar No	FFT-Map	Expected Range Result
1	 **Fig. 10.** Range Radial Map of Radar Master	36
2	 **Fig. 11.** Range Radial Map of Radar Side 1	67
3	 **Fig. 12.** Range Radial Map of Side Radar 2	78

4 54

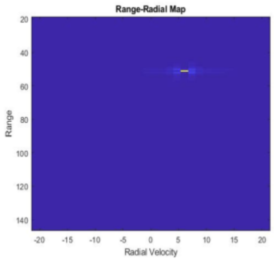


Fig. 13. Range Radial Map of Side Radar 3

As we can see, the result from radar range measurements is nearly the same as the expected result. Then all of the range data of each radar is sent to master/center processing to get the exact position. As we know the exact position of the radar, we can draw a hyperbolic of each radar range difference, then we can get the intersection within 3 hyperbolic lines and get the exact position.

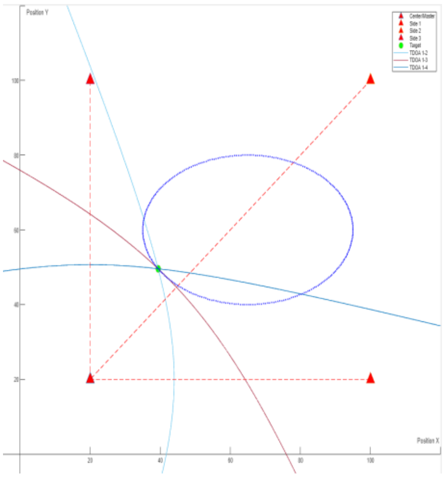


Fig. 14. Final Localization of Active Radar System

5. Radial Velocity Measurement

In order to determine the radial velocity of an object concerning all receivers, the process involves conducting a short-time Fourier transform (STFT) after obtaining the beat signal on each radar. The figure illustrates the manifestation of the Doppler frequency shift resulting from the motion of an object. The Doppler shift can be used to calculate radial velocity using the standard equation.

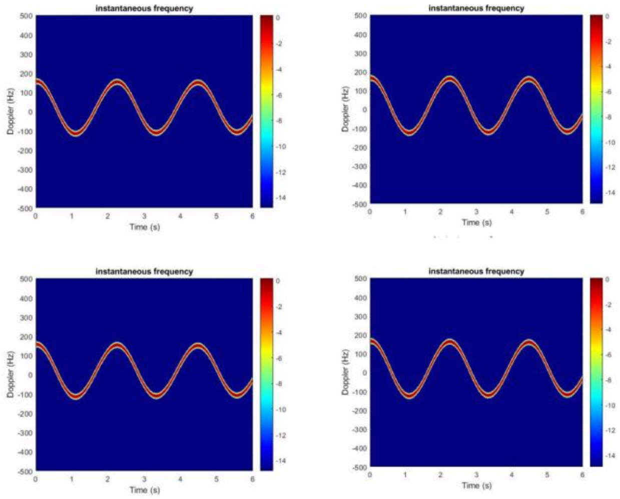


Fig. 15. Radial Velocity Measurement at Radar Master, Side1-3

6. Conclusion

After several investigations for IPS based on an FMCW radar system, IPS use either a Passive system or an active system, both have the same performance for localization of the target if using an FMCW signal. Each system needs to send the data to the central/master to do localization either based on TDOA or different measurement ranges. For passive system, will have higher hardware specifications, especially for the master, because all of the processing (Mixer, FFT, etc.) is on the master. Both passive and active detection systems must have time synchronization, as the signal is collected on master/central.

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