

## **A RADAR BASED RANGING SYSTEM FOR POSITIONING AND VITAL SIGN DETECTION**

### **CROSS-REFERENCE TO RELATED APPLICATION(S)**

[0001] This application claims the benefit of Singapore Patent Application No. 10201803588X, entitled “A radar based ranging system for positioning and vital sign detection” and filed on April 30, 2018, which is expressly incorporated by reference herein in its entirety.

### **TECHNICAL FIELD**

[0002] Various aspects of this disclosure generally relate to ranging of a target object, and more particularly, to positioning or ranging of a target object over a fine distance displacement of the target object.

### **BACKGROUND**

[0003] Ranging/positioning is an essential technology that is needed in many applications from smart nation to smart factories. In an open-air environment, the global navigation satellite system (GNSS) provides a good solution to ranging/positioning. However, many demands in the smart nation and smart factories are in the indoor environment, where the GNSS is invalid. For wireless ranging/positioning, its accuracy is in general proportional to the signal bandwidth and sampling rate. For example, the ultra-wideband (UWB) system can achieve <10mm positioning accuracy, but it requires more than 500MHz signal bandwidth and special sampling techniques and complicated clocking requirements. The Wi-Fi system (802.11g) occupies narrower radio frequency (RF) bandwidth and uses lower sampling rate. However, the ranging accuracy of a Wi-Fi time-of-arrival (ToA) method is as poor as a few meters. This is because that most of the ToA ranging/positioning solutions use the detection of signal edge. The edge detection is directly related to the signal bandwidth and sampling speed for the signal. Since RF bandwidth is a valuable resource and high sampling speed usually results in high complexity and high power consumption, a ranging system having high accuracy but occupying narrow

bandwidth with low sampling speed in internet-of-things (IoT) applications is desirable. Multi-frequency continuous wave (CW) radar was introduced for long distance ranging depending on phase information. However, only the phase of the beat between two carrier frequencies is used while the phase information of respective carrier are not be used.

**[0004]** Vital sign detection application in human centric smart home, smart building and smart factory are gaining traction. Vital sign detection can be achieved by radar technology. Various conventional radar sensors for noncontact healthcare monitoring focus primarily on the radar sensor. Software defined radio (SDR) based radar system with universal software radio peripheral (USRP) transceiver was also introduced. However, the principle and hardware used in weather surveillance can only identify distance resolution in kilometres. Hence, traditional application is not suitable for vital sign detection. In a traditional SDR based radar system for medical imaging, 950MHz bandwidth was occupied by the stepped frequency continuous wave radar for imaging.

## SUMMARY

**[0005]** The following presents a simplified summary of one or more aspects in order to provide a basic understanding of such aspects. This summary is not an extensive overview of all contemplated aspects, and is intended to neither identify key or critical elements of all aspects nor delineate the scope of any or all aspects. Its sole purpose is to present some concepts of one or more aspects in a simplified form as a prelude to the more detailed description that is presented later.

**[0006]** In one aspect of the disclosure, a radar interferometry based phase detection for ranging of a target object is provided. The method of ranging or positioning is based on a phase of a carrier frequency and a plurality of phases of beats among all frequencies. In operation, the method may identify finer distance differences or displacements compared to the edge detection used in the common discrete time ToA/TDoA (time difference of arrival) solutions. The method occupies a narrower RF bandwidth. Since the phase detection is not directly related to the sampling speed, high ranging accuracy may be achieved even with a low sampling rate. After ranging, positioning may be determined by multi-station trilateration or mono-station cooperating with direction of arrival (DoA) detection. This makes it possible for a low cost, low power consumption IoT device to include fine or granular positioning function.

[0007] The method may be also suitable for vital sign detection because of its high sensitivity to distance changes, and in one example, detect the respiration rate of a moving object. A multi-mode radar system based on the above method may be implemented readily using a SDR platform and advantageously, reconfigurable.

[0008] In an aspect of the disclosure, a method, a computer readable medium, and an apparatus for ranging a target object are provided. The apparatus may transmit a plurality of signals with different frequencies towards the target object. The apparatus may receive the plurality of signals as a result of the plurality of signals being reflected back from the target object. The apparatus may estimate the phase of the basis carrier frequency signal of the plurality of signals and the number of periods traveled by the plurality of signals. The apparatus may determine the distance to the target object based on the phase of the basis carrier frequency signal and the number of periods traveled by the plurality of signals. The apparatus may estimate the moving speed of the target object or the vital sign frequency of the target object through monitoring the changing of the distance over time.

[0009] To the accomplishment of the foregoing and related ends, the one or more aspects include the features hereinafter fully described and particularly pointed out in the claims. The following description and the annexed drawings set forth in detail certain illustrative features of the one or more aspects. These features are indicative, however, of but a few of the various ways in which the principles of various aspects may be employed, and this description is intended to include all such aspects and their equivalents.

### BRIEF DESCRIPTION OF THE DRAWINGS

[0010] FIG. 1 is a block diagram illustrating an example of a radar system.

[0011] FIG. 2A is a diagram illustrating an example of multiple frequencies being a sequence of frequencies changing along time.

[0012] FIG. 2B is a diagram illustrating an example of multiple frequencies emitted simultaneously.

[0013] FIG. 2C is a diagram illustrating an example of frequency synthesizer output.

[0014] FIG. 3 is a diagram showing the signal phases in different stages and different periods.

[0015] FIG. 4 is a diagram illustrating an example of the synchronization and initial  $p_1^1$  calibration.

- [0016] FIG. 5 is a chart illustrating mean ranging errors versus the signal to noise ratio of the method of one embodiment and the discrete time time-of-arrival method.
- [0017] FIG. 6 is a chart illustrating the relationship of the ranging accuracy and the updating period.
- [0018] FIG. 7 is a chart illustrating the mean ranging errors versus the signal to noise ratio of the method of one embodiment and the multi-frequency radar.
- [0019] FIGS. 8 and 9 show the cumulative distribution functions of the method of one embodiment and the discrete time time-of-arrival method, respectively.
- [0020] FIG. 10A is a diagram illustrating an example of positioning using a mono station equipped with an antenna array for directional arrival estimation.
- [0021] FIG. 10B is a diagram illustrating an example of positioning using three stations with trilateration.
- [0022] FIG. 11 is a diagram illustrating an example of sensing human respiration rate using a radar of some embodiments.
- [0023] FIG. 12 is a diagram illustrating the real detection results for the human respiration in time and frequency domains compared with that from a clinic-grade respiration sensor.
- [0024] FIG. 13 is a diagram illustrating the detection results for a person walking from the radar to the place two meters in front of the radar, stopping for two seconds, and then walking back to the radar.
- [0025] FIG. 14 is a signal processing block diagram in accordance with one embodiment of the present disclosure.
- [0026] FIG. 15 is a signal processing block diagram in accordance with another embodiment of the present disclosure.
- [0027] FIG. 16 is a flowchart of a method of ranging a target object.
- [0028] FIG. 17 is a conceptual data flow diagram illustrating the data flow between different means/components in an exemplary apparatus.
- [0029] FIG. 18 is a diagram illustrating an example of a hardware implementation for an apparatus employing a processing system.

## DETAILED DESCRIPTION

[0030] The detailed description set forth below in connection with the appended drawings is intended as a description of various configurations and is not intended to represent the only configurations in which the concepts described herein may be practiced. The detailed description includes specific details for the purpose of providing a thorough understanding of various concepts. However, it will be apparent to those skilled in the art that these concepts may be practiced without these specific details. In some instances, well known structures and components are shown in block diagram form in order to avoid obscuring such concepts.

[0031] Several aspects of a ranging or positioning technique will now be presented with reference to various apparatus and methods. These apparatus and methods will be described in the following detailed description and illustrated in the accompanying drawings by various blocks, components, circuits, processes, algorithms, etc. (collectively referred to as “elements”). These elements may be implemented using electronic hardware, computer software, or any combination thereof. Whether such elements are implemented as hardware or software depends upon the particular application and design constraints imposed on the overall system.

[0032] By way of example, an element, or any portion of an element, or any combination of elements may be implemented as a “processing system” that includes one or more processors. Examples of processors include microprocessors, microcontrollers, graphics processing units (GPUs), central processing units (CPUs), application processors, digital signal processors (DSPs), reduced instruction set computing (RISC) processors, systems on a chip (SoC), baseband processors, field programmable gate arrays (FPGAs), programmable logic devices (PLDs), state machines, gated logic, discrete hardware circuits, and other suitable hardware configured to perform the various functionality described throughout this disclosure. One or more processors in the processing system may execute software. Software shall be construed broadly to mean instructions, instruction sets, code, code segments, program code, programs, subprograms, software components, applications, software applications, software packages, routines, subroutines, objects, executables, threads of execution, procedures, functions, etc., whether referred to as software, firmware, middleware, microcode, hardware description language, or otherwise.

[0033] Accordingly, in one or more example embodiments, the functions described may be implemented in hardware, software, or any combination thereof. If implemented in software, the functions may be stored on or encoded as one or more instructions or code on a computer-readable medium. Computer-readable media includes computer storage media. Storage media may be any available media that can be accessed by a computer. By way of example, and not limitation, such computer-readable media may include a random-access memory (RAM), a read-only memory (ROM), an electrically erasable programmable ROM (EEPROM), optical disk storage, magnetic disk storage, other magnetic storage devices, combinations of the aforementioned types of computer-readable media, or any other medium that can be used to store computer executable code in the form of instructions or data structures that can be accessed by a computer.

[0034] FIG. 1 is a block diagram illustrating an example of a radar system 100. In the example, the radar system 100 may be used to detect the distance to a target 102. The radar system 100 may include a Tx (transmission) antenna 104, a Rx (receive) antenna 106, an RF front-end 120, and a software defined radio 110. For fine distance or displacement detection, the emitted signal by the Tx antenna 104 may be represented as:

$$T(t) = \cos(\omega_1 t) \sin(\omega_2 t + \theta) + \sin(\omega_1 t) \cos(\omega_2 t + \theta) \quad (1)$$

where  $\theta$  is the initial phase at the emission start moment.

[0035] The emitted signal hits the target 102, and the reflection is received by the Rx antenna 106 after the round-way travelling time  $\tau$ . Thus, the received signal is:

$$R(t) = p[\cos(\omega_1 t - \omega_1 \tau) \sin(\omega_2 t + \theta - \omega_2 \tau) + \sin(\omega_1 t - \omega_1 \tau) \cos(\omega_2 t + \theta - \omega_2 \tau)] + n(t) \quad (2)$$

where

$p$  is the propagation loss compared with the emitted signal,

$n(t)$  is the additive white Gaussian noise (AWGN).

[0036] As  $\tau$  is caused by the round-trip travelling of the electromagnetic (EM) wave, and the travelling speed is a constant, light speed, the distance between the radar and the target 102, namely ranging, may be directly obtained through estimating  $\tau$ . Moreover, if the target 102 moves or includes vital signs,  $\tau$  will be a time varying signal. Through monitoring the changing of  $\tau$ , moving speed and vital sign frequency may be estimated. Thus, the following signal processing focuses on  $\tau$  estimation.

[0037] The intermedia angular frequency signal from the RF front-end 120 is

$$\begin{aligned}
 I &= \frac{p}{\sqrt{2}} [\cos(\omega_1 t - \omega_1 \tau) \sin(\omega_2 t + \theta - \omega_2 \tau) \\
 &\quad + \sin(\omega_1 t - \omega_1 \tau) \cos(\omega_2 t + \theta - \omega_2 \tau)] \cos(\omega_2 t + \theta) \\
 &\quad + \frac{1}{\sqrt{2}} n(t) \cos(\omega_2 t + \theta) \\
 &= \frac{p}{2\sqrt{2}} [\sin((2\omega_2 + \omega_1)t + 2\theta - (\omega_1 + \omega_2)\tau) + \sin(\omega_1 t - (\omega_2 + \omega_1)\tau)] + \\
 &\quad \frac{1}{\sqrt{2}} n(t) \cos(\omega_2 t + \theta) \tag{3}
 \end{aligned}$$

$$\begin{aligned}
 Q &= \frac{p}{\sqrt{2}} [\cos(\omega_1 t - \omega_1 \tau) \sin(\omega_2 t + \theta - \omega_2 \tau) \\
 &\quad + \sin(\omega_1 t - \omega_1 \tau) \cos(\omega_2 t + \theta - \omega_2 \tau)] \sin(\omega_2 t) \\
 &\quad + \frac{1}{\sqrt{2}} n(t) \sin(\omega_2 t + \theta) \\
 &= \frac{p}{2\sqrt{2}} [\cos(\omega_1 t - (\omega_1 + \omega_2)\tau) - \cos((2\omega_2 + \omega_1)t + 2\theta - (\omega_1 + \omega_2)\tau)] + \\
 &\quad \frac{1}{\sqrt{2}} n(t) \sin(\omega_2 t + \theta) \tag{4}
 \end{aligned}$$

[0038] With the low pass filter 124 in the RF front-end 120, all high frequency components are removed before AD converter 126.

$$I' = \frac{p}{2\sqrt{2}} \sin(\omega_1 t - (\omega_1 + \omega_2)\tau) + \frac{1}{\sqrt{2}} n'(t) \tag{5}$$

$$Q' = \frac{p}{2\sqrt{2}} \cos(\omega_1 t - (\omega_1 + \omega_2)\tau) + \frac{1}{\sqrt{2}} n'(t) \tag{6}$$

where  $n'(t)$  is the AWGN after the low pass filter 124.

[0039] Let

$$\begin{aligned}
 Y &= Q' \sin(\omega_1 t) - I' \cos(\omega_1 t) \\
 &= \frac{p}{2\sqrt{2}} \cos(\omega_1 t - (\omega_1 + \omega_2)\tau) \sin(\omega_1 t) + \frac{1}{\sqrt{2}} n'(t) \sin(\omega_1 t) \\
 &\quad - \frac{p}{2\sqrt{2}} \sin(\omega_1 t - (\omega_1 + \omega_2)\tau) \cos(\omega_1 t) - \frac{1}{\sqrt{2}} n'(t) \cos(\omega_1 t) \\
 &= \frac{p}{4\sqrt{2}} [\sin(2\omega_1 t - (\omega_1 + \omega_2)\tau) + \sin((\omega_1 + \omega_2)\tau)] + \frac{1}{\sqrt{2}} n'(t) \sin(\omega_1 t) \\
 &\quad - \frac{p}{4\sqrt{2}} [\sin(2\omega_1 t - (\omega_1 + \omega_2)\tau) - \sin((\omega_1 + \omega_2)\tau)] - \frac{1}{\sqrt{2}} n'(t) \cos(\omega_1 t) \\
 &= \frac{p}{2\sqrt{2}} \sin((\omega_1 + \omega_2)\tau) + \frac{1}{\sqrt{2}} n''(t) \tag{7}
 \end{aligned}$$

where  $n''(t) = n'(t)[\sin(\omega_1 t) - \cos(\omega_1 t)]$ .

[0040] Similarly

$$\begin{aligned}
X &= Q' \cos(\omega_1 t) + I' \sin(\omega_1 t) \\
&= \frac{p}{2\sqrt{2}} \cos(\omega_1 t - (\omega_1 + \omega_2)\tau) \cos(\omega_1 t) + \frac{1}{\sqrt{2}} n'(t) \cos(\omega_1 t) \\
&\quad + \frac{p}{2\sqrt{2}} \sin(\omega_1 t - (\omega_1 + \omega_2)\tau) \sin(\omega_1 t) + \frac{1}{\sqrt{2}} n'(t) \sin(\omega_1 t) \\
&= \frac{p}{4\sqrt{2}} [\cos(2\omega_1 t - (\omega_1 + \omega_2)\tau) + \cos((\omega_1 + \omega_2)\tau)] + \frac{1}{\sqrt{2}} n'(t) \cos(\omega_1 t) \\
&\quad + \frac{p}{4\sqrt{2}} [-\cos(2\omega_1 t - (\omega_1 + \omega_2)\tau) + \cos((\omega_1 + \omega_2)\tau)] + \frac{1}{\sqrt{2}} n'(t) \sin(\omega_1 t) \\
&= \frac{p}{2\sqrt{2}} \cos((\omega_1 + \omega_2)\tau) + \frac{1}{\sqrt{2}} n'''(t) \quad (8) \\
&\quad \text{where } n'''(t) = n'(t)[\sin(\omega_1 t) + \cos(\omega_1 t)].
\end{aligned}$$

[0041] Thus the estimation of  $\tau$  can be obtained by

$$\begin{aligned}
(\omega_1 + \omega_2)\hat{\tau} &= \text{atan} \frac{Y}{X} \\
\hat{\tau} &= \frac{1}{\omega_1 + \omega_2} \text{atan} \frac{Y}{X} \quad (9)
\end{aligned}$$

[0042] Since  $\tau$  is caused by the round-trip travelling from the radar to the reflecting target 102 in the distance of  $d$ .

$$\tau = 2d/c \quad (10)$$

where  $c$  is the light speed.

[0043] Thus the estimation of distance  $d$  is

$$\hat{d} = \frac{c}{2(\omega_1 + \omega_2)} \text{atan} \frac{Y}{X} \quad (11)$$

[0044] Equation (11) is the finest level of distance estimation. It is based on interferometry. The detection accuracy is related to the signal frequency instead of its bandwidth. In addition, the signal parts of  $Y$  and  $X$  in equations (7) and (8) do not include “ $t$ ” whose accuracy is effected by sampling speed. Instead, they include only “ $\tau$ ” which is independent to “ $t$ ”. In other words,  $Y$  and  $X$  are not effected by sampling rate. Accordingly, the estimation of  $\tau$  is not related to sampling rate. As a result, high accuracy wireless positioning may be achieved without occupying large RF bandwidth and high sampling rate.

[0045] However, the distance estimation in Equation (9) will periodically repeat in any multiple of the signal wavelength. Thus,  $d$  detection has the following range

$$-\frac{\lambda}{4} \leq d \leq \frac{\lambda}{4} \quad (12)$$

where  $\lambda = \frac{2\pi c}{(\omega_1 + \omega_2)}$  is the wavelength of signal  $(\omega_1 + \omega_2)$ .

[0046] Let the  $\delta$  (degree per unit distance) is the sensitivity of detection.

$$\delta = \frac{360}{\lambda/2} = 720/\lambda \quad (13)$$

[0047] From above equation, it may be observed that the higher the carrier frequency, the higher the detection sensitivity for the changing of the distance. However, higher frequency has narrower detection range due to shorter wavelength.

[0048] Table 1 summarizes the detection sensitivities and ranges for different carrier frequencies. These sensitivities are enough for detecting most of vital signs. The weak vital sign such as heart beat may use high carrier frequency, for example 60GHz, while for the respiration detection, low carrier frequency such as 2.4GHz may be used.

Table 1. Numerical results of detection sensitivity and range for different frequencies

| Signal frequency $(\omega_1 + \omega_2)/(2\pi)$ | 1GHz  | 2.4GHz | 5.8GHz  | 28GHz  | 60GHz |
|-------------------------------------------------|-------|--------|---------|--------|-------|
| $\delta$ (degree per 1 mm)                      | 2.4   | 5.76   | 13.92   | 67.2   | 144   |
| Range of $d$ estimation                         | 150mm | 62.5mm | 31.25mm | 5.36mm | 2.5mm |

[0049] Equation (11) gives the estimation of short distance within half signal wavelength. The distance detection range is not enough for most positioning applications. For longer distance than half signal wavelength, multiple frequencies may need to be used. When the radar system 100 emits multiple frequencies, the range between the radar and the target 102 may be derived from the different phase shifts corresponding to different frequencies.

[0050] The distance estimation of some embodiments is as follows. Recalling the output  $X$  and  $Y$  for emission signal  $(\omega_1 + \omega_2)$ , they may be represented in the complex format

$$F = X + jY = \frac{p}{2\sqrt{2}} [\cos((\omega_1 + \omega_2)\tau) + j \sin((\omega_1 + \omega_2)\tau)] + n_c(t)$$

$$F = \frac{p}{2\sqrt{2}} e^{j(\omega_1 + \omega_2)\tau} + n_c(t) \quad (14)$$

where,  $n_c(t)$  is the complex AWGN from radar branches  $X$  and  $Y$ .

[0051] Assuming the radar emission including  $W$  stages with different frequencies for local oscillator (LO) 112,

$$F = \begin{cases} \frac{p}{2\sqrt{2}} e^{j(\omega_{11}+\omega_2)\tau+\theta_1} + n_c(t) & \text{stage 1} \\ \frac{p}{2\sqrt{2}} e^{j(\omega_{12}+\omega_2)\tau+\theta_2} + n_c(t) & \text{stage 2} \\ \vdots & \\ \frac{p}{2\sqrt{2}} e^{j(\omega_{1W}+\omega_2)\tau+\theta_w} + n_c(t) & \text{stage } W \end{cases} \quad (15a)$$

where

$\omega_{1i}$  is the value of  $\omega_1$  in stage  $i$ ,

$\theta_1$  to  $\theta_w$  are the fixed phase differences among multiple frequencies caused by the frequency synthesiser.

[0052] However, these phase differences may be calibrated:

$$F = \begin{cases} \frac{p}{2\sqrt{2}} e^{j(\omega_{11}+\omega_2)\tau} + n_c(t) & \text{stage 1} \\ \frac{p}{2\sqrt{2}} e^{j(\omega_{12}+\omega_2)\tau} + n_c(t) & \text{stage 2} \\ \vdots & \\ \frac{p}{2\sqrt{2}} e^{j(\omega_{1W}+\omega_2)\tau} + n_c(t) & \text{stage } W \end{cases} \quad (15)$$

[0053] FIG. 2A is a diagram 200 illustrating an example of multiple frequencies being a sequence of frequencies changing along time. In the example, the frequency increases from stage 1 to stage  $W$  in a period, i.e.,  $\omega_{11} < \omega_{1i} < \omega_{1W}$ , then repeating the same pattern in subsequent periods.

[0054] FIG. 2B is a diagram 220 illustrating an example of multiple frequencies emitted simultaneously. In the example, the frequency increases from stage 1 to stage  $W$ , i.e.,  $\omega_{11} < \omega_{1i} < \omega_{1W}$ .

[0055] FIG. 2C is a diagram 240 illustrating an example of frequency synthesizer output. In the example, the frequency increases from stage 1 to stage  $W$  in a period, i.e.,  $\omega_{11} < \omega_{1i} < \omega_{1W}$ , then repeating the same frequency pattern in subsequent periods.

[0056] FIG. 3 is a diagram 300 showing the signal phases in different stages and different periods. Note that the phase differences among different stages increase along with distance increasing. This information may be used to estimate the distance. Let the phase in stage 1 in period 1 is  $p_1^1$ , then the phase in stage  $i$  in period 1 is

$$p_i^1 = \text{mod} \left( p_1^1 \frac{\omega_{1i} + \omega_2}{\omega_{11} + \omega_2}, 2\pi \right) \quad (16)$$

[0057] In period  $N$ , the phase in stage 1 is still

$$p_1^N = p_1^1 \quad (17)$$

[0058] The phase in stage  $i$  in period  $N$  is

$$\begin{aligned} p_i^N &= \text{mod} \left\{ p_1^1 \frac{\omega_{1i} + \omega_2}{\omega_{11} + \omega_2} + \frac{2\pi \left[ (N-1) \left( \frac{2\pi c}{\omega_{11} + \omega_2} - \frac{2\pi c}{\omega_{1i} + \omega_2} \right) \right]}{\left( \frac{2\pi c}{\omega_{1i} + \omega_2} \right)}, 2\pi \right\} \\ &= \text{mod} \left\{ p_1^1 \frac{\omega_{1i} + \omega_2}{\omega_{11} + \omega_2} + 2\pi(N-1) \frac{\omega_{1i} - \omega_{11}}{\omega_{11} + \omega_2}, 2\pi \right\} \end{aligned} \quad (18)$$

[0059] Thus, range estimation consists of the estimate to  $N$  and the estimate to  $p_1^1$  in one period. Both estimates may be jointly achieved by using the least-square approach.

[0060]  $F$  may be represented as a function of,  $p_1^1$  and stage  $i$

$$F(N, p_1^1, i) = \frac{p}{2\sqrt{2}} e^{j \left( p_1^1 \frac{\omega_{1i} + \omega_2}{\omega_{11} + \omega_2} + 2\pi(N-1) \frac{\omega_{1i} - \omega_{11}}{\omega_{11} + \omega_2} \right)} + n_c(t) \quad (19)$$

[0061] A  $W \times W$  diagonal matrix  $L$  may be defined to denote all stages' phase shifting effects caused by large delays as

$$L = \begin{bmatrix} 1 & & \\ & \ddots & \\ & & e^{j2\pi(N-1) \frac{\omega_{1W} - \omega_{11}}{\omega_{11} + \omega_2}} \end{bmatrix},$$

[0062] A  $W \times 1$  column vector  $S$  may be defined to denote all stages' phase shifting effects caused by small delays as

$$S = \begin{bmatrix} e^{jp_1^1} \\ \vdots \\ e^{jp_1^1 \frac{\omega_{1W} + \omega_2}{\omega_{11} + \omega_2}} \end{bmatrix}.$$

[0063] A  $W \times 1$  column vector  $F$  may be defined to denote all stages' observed phases as

$$F = \begin{bmatrix} F_1 \\ \vdots \\ F_W \end{bmatrix}.$$

[0064] Obviously,

$$F = LS + N$$

where  $N$  is a  $W \times 1$  column vector consisting of AWGN in  $W$  stages.

[0065] Then, the estimator for  $N$  and  $p_1^1$  is

$$\begin{aligned} [\hat{N}, \hat{p}_1^1] &= \underset{\substack{0 \leq N \leq \beta \\ 0 \leq p_1^1 \leq 2\pi}}{\text{argmin}} \|LS - F\|^2 \end{aligned} \quad (20)$$

where

$F_i$  is the observation of  $F$  in stage  $i$ ,

$\beta$  is the least common multiple between two frequencies having smallest frequency difference among  $W$  stages.

[0066] However, in a real application,  $\beta$  is defined by the maximum possible round-trip distance divided by signal  $\lambda$  of stage  $W$  in the working area. For example, if the maximum consider distance is 100 meters, and the basis frequency is 2.4 GHz,

$$\beta = 100 \times \frac{2}{0.125} = 1600.$$

[0067] Compared with the multi-frequency CW radar in Equation (9), Equation (20) includes  $p_1^1$ , and jointly estimates  $N$  with all phase information, while the one in Equation (9) separately estimates the phase of the beat between two frequencies without the phase estimation for the basis carrier frequency.

[0068] The solution to Equation (20) requires heavy computation due to two-dimension search. The estimation accuracy is also restricted by the search step-size for  $p_1^1$ . Thus, it is not practical.

[0069] A much simpler solution is to estimate  $p_1^1$  and  $N$  separately. First,  $p_1^1$  may be estimated as

$$\widehat{p}_1^1 = \text{atan} \frac{Y_1}{X_1} \quad (21)$$

where  $X_1$  and  $Y_1$  are the radar outputs of  $X$  and  $Y$  in stage 1.

[0070] Then the estimate of  $N$  is

$$\widehat{N} = \underset{0 \leq N \leq \beta}{\text{argmin}} \left\{ \sum_{i=1}^W \|F(N, \widehat{p}_1^1, i) - F_i\|^2 \right\} \quad (22)$$

where  $F_i$  is the observation waveform at stage  $i$ .

[0071] Since Equation (22) is one-dimension integer search, the computation is much less than that of Equation (20).

[0072] When the frequency differences among different stages are the same,  $\Delta$ ,  $N$  may be calculated without searching. Since  $\tau(\omega_{11} + \omega_2) = p_1^1 + 2\pi N$ ,  $\tau = (p_1^1 + 2\pi N)/(\omega_{11} + \omega_2)$ . On the other hand,  $e^{j\tau\Delta} = e^{j(\omega_{11} + \omega_2)\tau} e^{-j(\omega_{11} + \omega_2)\tau} = F_i F_{i-1}^*$ , Thus,

$$p_1^1 + 2\pi N = \angle \left( \frac{1}{W-1} \sum_{i=2}^W F_i F_{i-1}^* \right) \cdot (\omega_{11} + \omega_2) / \Delta$$

[0073] Thus,

$$\widehat{N} = \text{round} \left\{ \left[ \angle \left( \frac{1}{W-1} \sum_{i=2}^W F_i F_{i-1}^* \right) \cdot (\omega_{11} + \omega_2) / \Delta - \widehat{p}_1^1 \right] / 2\pi \right\} \quad (23)$$

where  $\text{round}(\cdot)$  means rounding to the nearest integer.

[0074] The estimation for  $N$  using Equation (22) is more accurate in theory, but Equation (23) is simpler.

[0075] When  $N$  and  $p_1^1$  are estimated, the distance from the radar to the reflection target is

$$\hat{d} = \left( (\hat{N} - 1) \frac{2\pi c}{\omega_{11} + \omega_2} + \frac{\hat{p}_1^1 c}{\omega_{11} + \omega_2} \right) / 2 \quad (24)$$

[0076] Note that it is assumed that the Tx signal phase in every stage is 0. This may be achieved through synchronization. Namely, LO 112 and LO 128 in FIG. 1 must be coherent. After that, the fixed initial phase difference has to be calibrated out.

[0077] The software defined radio clock is synchronized to carrier frequency  $\omega_2$  through the phase-locked loop (PLL) so as to secure that  $\omega_{1i}$  and  $\omega_2$  have fixed phase difference in Equation (15a). They are all coherent to each other thanks to the mechanism. The remained fixed phase errors among different local frequencies may be calibrated.

[0078] During system initialization, insert the self-loop signal so as to find the initial value of  $p_1^1$  when the distance is 0. Then calibrate out this initial phase value from LO 112. This is for the calibration of the fixed system delay in the ranging process. In principle, when the distance is 0,  $p_1^1$  in Equation (24) should be 0. However, the initial  $p_1^1$  is non-zero due to system delay. The 0-distance calibration is to find out the value of  $p_1^1$  when distance is 0 so as to remove the initial  $p_1^1$  bias from the ranging.

[0079] FIG. 4 is a diagram 400 illustrating an example of the synchronization and initial  $p_1^1$  calibration. In the example, the radar may include a software defined radio 410 and an RF front-end 420. In some embodiments, the software defined radio 410 and the RF front-end 420 may be the software defined radio 110 and the RF front-end 120, respectively, described above with reference to FIG. 1.

[0080] The RF front-end 420 includes an LO 428 and a PLL 422. The software defined radio 410 includes a phase shifter 416 and an LO 412. The LO 412 and the LO 428 may be synchronized through the PLL 422.

[0081] Since the targeted applications here are that the radio wave propagates over air. In this environment, the reflection wave has 180 degrees flipping when the radar incident wave hits the object with dielectric constant larger than 1. Thus, the phase shifter 416 needs to have a fixed 180 offset.

[0082] The performance of the ranging of an embodiment is simulated and compared to discrete-time based ToA method. The radar system of the embodiment emits 2.4 GHz and 2.401 GHz sequentially. The filter bandwidth in RF front-end is 2 MHz. The sampling rate is 5 MHz. The compared discrete-time ToA method has RF bandwidth of 20MHz and sampling speed of  $20\text{M Hz} \times 8 / 7 = 22.87\text{ MHz}$ , which simulates IEEE802.11g signal for ToA estimation. In the comparison, each ranging reading took 10 ms unless stated otherwise. The signal to noise ratio (SNR) is defined dB of the signal power divided by the noise power in the respective signal bandwidth for different systems. The distance for estimations in the simulation was randomly generated from 0 to 100 meters.

[0083] FIG. 5 is a chart 500 illustrating mean ranging errors versus SNR of the method of one embodiment and the discrete time ToA method. As shown, the discrete time TOA method have the error floor, which means that no matter how high SNR is, the ranging accuracy cannot be improved. In contrast, the method of one embodiment has smaller ranging error when SNR is larger than -10 dB even the signal bandwidth is one tenth of the discrete time TOA method. Moreover, the ranging error may be improved with increased SNR.

[0084] FIG. 6 is a chart 600 illustrating the relationship of the ranging accuracy and the updating period. As shown, the method of one embodiment has improved accuracy by increasing the ranging updating period. However, due to the error floor, the discrete time ToA method cannot be improved in the practical SNR range.

[0085] Since the method of some embodiments utilizes the finest phase shift information of the carrier frequency as well as the phase shift of the beats among different stages, the distance estimation outperforms the conventional multi-frequency CW radar, especially when SNR is high and accumulation time is long for accurate distance estimation. FIG. 7 is a chart 700 illustrating the mean ranging errors versus SNR of the method of one embodiment and the multi-frequency radar (update period 10 s). As shown, the method of one embodiment achieves much more accurate ranging if the time accumulation is long enough.

[0086] FIGS. 8 and 9 show the cumulative distribution functions (CDFs) of the method of one embodiment and the discrete time ToA method, respectively. The updating period here is 10 ms. As shown, the method of one embodiment achieves 0.7 meter accuracy with 95% probability when the SNR is 10 dB. While in the same condition, the discrete time ToA

method achieves only 3.2 meter accuracy. If the SNR is increased to 20 dB, 95% ranging accuracies for the method of one embodiment and the discrete time ToA are 0.3 meter and 3.2 meters, respectively.

**[0087]** Some embodiments of the ranging method may be at least used in wireless positioning. Positioning may be achieved by using mono station equipped with an antenna array for direction of arrival (DoA) estimation or multiple stations with trilateration. Each station may be equipped with a radar described above with reference to FIGS. 1-9 to performing ranging. FIG. 10A is a diagram 1000 illustrating an example of positioning using a mono station 1002 equipped with an antenna array for direction al arrival estimation. FIG. 10B is a diagram 1050 illustrating an example of positioning using three stations 1052, 1054, and 1056 with trilateration.

**[0088]** The target to be positioned may be passive, which require the station emits relative larger power to secure enough reflection strength. In most focused applications, the positioned targets may be active reflectors. The station emits the signal for ranging including the called target ID. When the target received the call, and the ID is matched, the target will resend the received signal back after a fixed delay. This makes the radar receiving strong enough reflection signal. Moreover, in this way, the system may position multiple targets sequentially.

**[0089]** The ranging method of some embodiments may also be used in vital sign detection. Since the interferometry in Equation (11) may detect very fine distance turbulence. This may be used to test the vital sign such us respiration rate and moving speed. The radar system of some embodiments may be used to detect the human respiration rate by facing the radar's Tx and Rx antennas to a human's chest.

**[0090]** FIG. 11 is a diagram 1100 illustrating an example of sensing human respiration rate using a radar 1102 of some embodiments. With the radar architecture of some embodiments implemented in the GNU radio and processing with Equation (11), accurate detection may be achieved.

**[0091]** FIG. 12 is a diagram 1200 illustrating the real detection results for the human respiration in time and frequency domains compared with that from a clinic-grade respiration sensor. The measured respiration rates were 0.2601 Hz by the system of one embodiment and 0.25 Hz by of the clinic-grade respiration sensor, respectively. Comparing the results by

two approaches, the difference of two detections for the respiration rate was less than 5%. The radar emission power was -14 dBm.

[0092] The radar system of some embodiments may be used to detect the moving object and its speed. In Equation (7), if the reflection is from a moving object,  $\tau$  will be a time-varying variable as follows

$$\tau = 2(d - St)/c \quad (25)$$

where  $S$  is the speed that the object approach to radar.

[0093] Replacing  $\tau$  in Equation (7) with Equation (24), we have

$$\begin{aligned} Y &= \frac{p}{2\sqrt{2}} \sin\left(\frac{2(\omega_1 + \omega_2)(d - St)}{c}\right) + \frac{1}{\sqrt{2}} n''(t) \\ &= \frac{p}{2\sqrt{2}} \sin\left(\frac{2(\omega_1 + \omega_2)d}{c} - \frac{2(\omega_1 + \omega_2)S}{c} t\right) + \frac{1}{\sqrt{2}} n''(t) \end{aligned} \quad (26)$$

[0094] Similarly,

$$X = \frac{p}{2\sqrt{2}} \cos\left(\frac{2(\omega_1 + \omega_2)d}{c} - \frac{2(\omega_1 + \omega_2)S}{c} t\right) + \frac{1}{\sqrt{2}} n'''(t) \quad (27)$$

[0095] Representing Equations (24) and (25) in the complex format

$$F(t) = X + jY = \frac{p}{2\sqrt{2}} e^{-j2\pi f_d t + \theta} + n_f(t) \quad (28)$$

where

$$f_d = \frac{2(\omega_1 + \omega_2)S}{\pi c} \quad (29)$$

is the Doppler frequency,

$\theta = 2(\omega_1 + \omega_2)d/c$  is a fixed phase offset,

$n_f(t)$  is the complex noise caused by branches  $X$  and  $Y$ .

[0096] Thus, the Doppler frequency can be estimated as

$$\hat{f}_d = \underset{f}{\operatorname{argmax}} |\mathcal{F}(f)| \quad (30)$$

where,  $\mathcal{F}(f)$  is the Fourier transform of  $F(t)$ .

[0097] Accordingly, the moving speed estimation is

$$\hat{S} = \frac{\pi c \hat{f}_d}{2(\omega_1 + \omega_2)} \quad (31)$$

[0098] FIG. 13 is a diagram 1300 illustrating the detection results for a person walking from the radar to the place two meters in front of the radar, stopping for two seconds, and then walking back to the radar. In a real application, a threshold may be set for the output of the Doppler frequency detection, e.g., 3 Hz, so as to filter out the random noise. The Tx emission power is -3.5 dBm.

[0099] FIG. 14 is a signal processing block diagram 1400 in accordance with one embodiment of the present disclosure. As shown, each of signal parts  $X$  and  $Y$  goes through a first-in-first-out (FIFO) queue 1402 and 1404, respectively. The outputs of FIFO queues 1402 and 1404 may be sent to a Cartesian-polar coordinate converter 1406, which outputs  $\widehat{p}_1^1$ . The output of the Cartesian-polar coordinate converter 1406 may be provided to a band pass filter (BPF) 1408, which outputs an estimate of breath signal.

[00100] The outputs of FIFO queues 1402 and 1404 may be sent to a fast Fourier transform (FFT) unit 1410, which perform fast Fourier transformation. At 1412, the frequency having peak output may be identified based on the output of the FFT unit 1410. At 1416, the estimate of moving speed may be calculated based on Equation (31).

[00101] At 1420, the waveforms  $F(N, \widehat{p}_1^1, i)$  may be calculated according to  $\widehat{p}_1^1$ . At 1422, the observation waveforms  $F_I$  to  $F_W$  may be formed based the signal parts  $X$  and  $Y$ . At 1424, the value of  $N$  may be changed and the  $N$  that makes  $\sum_{i=1}^W \|F(N, \widehat{p}_1^1, i) - F_i\|^2$  having minimum output value may be identified. At 1430, ranging estimate may be calculated based on  $\widehat{p}_1^1$  and  $\widehat{N}$  in accordance with Equation (24).

[00102] FIG. 15 is a signal processing block diagram 1500 in accordance with another embodiment of the present disclosure. Such embodiment may be suitable for the case where the spaces between two adjacent tones are constant. As shown in FIG. 15, each of signal parts  $X$  and  $Y$  goes through a first-in-first-out (FIFO) queue 1502 and 1504, respectively. The outputs of FIFO queues 1502 and 1504 may be sent to a Cartesian-polar coordinate converter 1506, which outputs  $\widehat{p}_1^1$ . The output of the Cartesian-polar coordinate converter 1506 may be provided to a BPF 1508, which outputs an estimate of breath signal.

[00103] The outputs of FIFO queues 1502 and 1504 may be sent to a FFT unit 1510, which perform fast Fourier transformation. At 1512, the frequency having peak output may be identified based on the output of the FFT unit 1510. At 1516, the estimate of moving speed may be calculated based on Equation (31).

[00104] At 1522, the observation waveforms  $F_I$  to  $F_W$  may be formed based the signal parts  $X$  and  $Y$ . At 1524,  $\frac{1}{W-1} \sum_{i=2}^W F_i F_{i-1}^*$  may be calculated. The result of the calculation may go through a Cartesian-polar coordinate converter 1526. At 1528,  $\widehat{N}$  may be calculated based on Equation (23). At 1530, ranging estimate may be calculated based on  $\widehat{p}_1^1$  and  $\widehat{N}$  in accordance with Equation (24).

**[00105]** FIG. 16 is a flowchart 1600 of a method of ranging a target object. The method may be performed by an apparatus (e.g., apparatus 1702/1702' described below with reference to FIG. 17 or 18). In some embodiments, the apparatus may be part of a radar system. In some embodiments, the operations performed in the method may correspond to operations described above with reference to FIGS. 1-4, 10A, 10B, 11, 14, and 15.

**[00106]** At 1602, the apparatus may transmit a plurality of signals with different frequencies towards a target object. In some embodiments, the plurality of signals may have a sequence of frequencies changing along time in a period. In some embodiments, the plurality of signals may have different frequencies and may be simultaneously emitted. In some embodiments, the plurality of signals may correspond to a plurality of stages with ascending frequencies in a period. The basis carrier frequency signal may have the lowest frequency among the plurality of signals. The basis carrier frequency signal may have the same phase in each period.

**[00107]** At 1604, the apparatus may receive the plurality of signals as a result of the plurality of signals being reflected back from the target object. In some embodiments, the plurality of received signals may be a plurality of analog signals. The apparatus may further remove high frequency components from the plurality of analog signals before converting the plurality of analog signals into a plurality of digital signals for further processing. In some embodiments, the target object may be an active reflector that resends the plurality of signals back after a fixed delay subsequent to receiving the plurality of signals at the target object.

**[00108]** At 1606, the apparatus may estimate the phase of the basis carrier frequency signal of the plurality of signals and the number of periods traveled by the plurality of signals. In some embodiments, the phase of the basis carrier frequency signal and the number of periods traveled by the plurality of signals may be estimated separated.

**[00109]** At 1608, the apparatus may determine the distance to the target object based on the phase of the basis carrier frequency signal and the number of periods traveled by the plurality of signals. In some embodiments, the accuracy of the determined distance may be independent of the bandwidth of the plurality of signals and the sampling rate of the plurality of signals.

**[00110]** At 1610, the apparatus may estimate the moving speed of the target object or the vital sign frequency of the target object through monitoring the changing of the distance over

time. In some embodiments, the detection sensitivity for the changing of the distance may increase when the carrier frequency of the plurality of signals increases. The detection range for the changing of the distance may narrow when the carrier frequency of the plurality of signals increases.

**[00111]** FIG. 17 is a conceptual data flow diagram 1700 illustrating the data flow between different means/components in an exemplary apparatus 1702. In some embodiments, the apparatus 1702 may be a radar or part of a radar. The apparatus 1702 may include a reception component 1704 that receives reflected signals from a target object 1750. In one embodiment, the reception component 1704 may perform the operations described above with reference to 1604 in FIG. 16.

**[00112]** The apparatus 1702 may include a transmission component 1710 that transmits probing signals to the target object 1750. In one embodiment, the transmission component 1710 may perform the operations described above with reference to 1602 in FIG. 16. The reception component 1704 and the transmission component 1710 may collaborate to coordinate the communication of the apparatus 1702.

**[00113]** The apparatus 1702 may include a ranging component 1706 that is configured to perform ranging on the target object based on the received reflected signals. In one embodiment, the ranging component 1706 may perform the operations described above with reference to 1606 or 1608 in FIG. 16.

**[00114]** The apparatus 1702 may include a vital sign component 1708 that is configured to estimate the moving speed of the target object 1750 or the vital sign frequency of the target object 1705 via monitoring the changing of the distance provided by the ranging component 1706. In one embodiment, the vital sign component 1708 may perform the operations described above with reference to 1610 in FIG. 16.

**[00115]** The apparatus 1702 may include additional components that perform each of the blocks of the algorithm in the aforementioned flowchart of FIG. 16. As such, each block in the aforementioned flowchart of FIG. 16 may be performed by a component and the apparatus may include one or more of those components. The components may be one or more hardware components specifically configured to carry out the stated processes/algorithm, implemented by a processor configured to perform the stated processes/algorithm, stored within a computer-readable medium for implementation by a processor, or some combination thereof.

[00116] FIG. 18 is a diagram 1800 illustrating an example of a hardware implementation for an apparatus 1702' employing a processing system 1814. In one embodiment, the apparatus 1702' may be the apparatus 1702 described above with reference to FIG. 17. The processing system 1814 may be implemented with a bus architecture, represented generally by the bus 1824. The bus 1824 may include any number of interconnecting buses and bridges depending on the specific application of the processing system 1814 and the overall design constraints. The bus 1824 links together various circuits including one or more processors and/or hardware components, represented by the processor 1804, the components 1704, 1706, 1708, 1710 and the computer-readable medium / memory 1806. The bus 1824 may also link various other circuits such as timing sources, peripherals, voltage regulators, and power management circuits, which are well known in the art, and therefore, will not be described any further.

[00117] The processing system 1814 may be coupled to a transceiver 1810. The transceiver 1810 is coupled to one or more antennas 1820. The transceiver 1810 provides a means for communicating with various other apparatus over a transmission medium. The transceiver 1810 receives a signal from the one or more antennas 1820, extracts information from the received signal, and provides the extracted information to the processing system 1814, specifically the reception component 1704. In addition, the transceiver 1810 receives information from the processing system 1814, specifically the transmission component 1710, and based on the received information, generates a signal to be applied to the one or more antennas 1820.

[00118] The processing system 1814 includes a processor 1804 coupled to a computer-readable medium / memory 1806. The processor 1804 is responsible for general processing, including the analyzation of data gathered by the apparatus itself through its own sensors and the execution of software stored on the computer-readable medium / memory 1806. The software, when executed by the processor 1804, causes the processing system 1814 to perform the various functions described *supra* for any particular apparatus. The computer-readable medium / memory 1806 may also be used for storing data that is manipulated by the processor 1804 when executing software. The processing system 1814 further includes at least one of the components 1704, 1706, 1708, 1710. The components may be software components running in the processor 1804, resident/stored in the computer readable medium

/ memory 1806, one or more hardware components coupled to the processor 1804, or some combination thereof.

**[00119]** In the following, various aspects of this disclosure will be illustrated:

**[00120]** Example 1 is a method or apparatus for ranging a target object. The apparatus may transmit a plurality of signals with different frequencies towards the target object. The apparatus may receive the plurality of signals as a result of the plurality of signals being reflected back from the target object. The apparatus may estimate the phase of the basis carrier frequency signal of the plurality of signals and the number of periods traveled by the plurality of signals. The apparatus may determine the distance to the target object based on the phase of the basis carrier frequency signal and the number of periods traveled by the plurality of signals.

**[00121]** In Example 2, the subject matter of Example 1 may optionally include that the accuracy of the determined distance may be independent of the bandwidth of the plurality of signals and the sampling rate of the plurality of signals.

**[00122]** In Example 3, the subject matter of any one of Examples 1 to 2 may optionally include that the phase of the basis carrier frequency signal and the number of periods traveled by the plurality of signals may be estimated separated.

**[00123]** In Example 4, the subject matter of any one of Examples 1 or 3 may optionally include that the apparatus may further estimate the moving speed of the target object or the vital sign frequency of the target object through monitoring the changing of the distance over time.

**[00124]** In Example 5, the subject matter of Example 4 may optionally include that the detection sensitivity for the changing of the distance may increase when the carrier frequency of the plurality of signals increases, where the detection range for the changing of the distance may narrow when the carrier frequency of the plurality of signals increases.

**[00125]** In Example 6, the subject matter of any one of Examples 1 to 5 may optionally include that the plurality of received signals may be a plurality of analog signals, where the apparatus may further remove high frequency components from the plurality of analog signals before converting the plurality of analog signals into a plurality of digital signals for further processing.

[00126] In Example 7, the subject matter of any one of Examples 1 or 6 may optionally include that the plurality of signals may have a sequence of frequencies changing along time in a period.

[00127] In Example 8, the subject matter of any one of Examples 1 to 7 may optionally include that the plurality of signals may have different frequencies and are simultaneously emitted.

[00128] In Example 9, the subject matter of any one of Examples 1 or 8 may optionally include that the plurality of signals may correspond to a plurality of stages with ascending frequencies in a period, where the basis carrier frequency signal may have the lowest frequency among the plurality of signals, where the basis carrier frequency signal may have the same phase in each period.

[00129] In Example 10, the subject matter of any one of Examples 1 to 9 may optionally include that the target object may be an active reflector that resends the plurality of signals back after a fixed delay subsequent to receiving the plurality of signals at the target object.

[00130] It is understood that the specific order or hierarchy of blocks in the processes / flowcharts disclosed is an illustration of exemplary approaches. Based upon design preferences, it is understood that the specific order or hierarchy of blocks in the processes / flowcharts may be rearranged. Further, some blocks may be combined or omitted. The accompanying method claims present elements of the various blocks in a sample order, and are not meant to be limited to the specific order or hierarchy presented.

[00131] The previous description is provided to enable any person skilled in the art to practice the various aspects described herein. Various modifications to these aspects will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other aspects. Thus, the claims are not intended to be limited to the aspects shown herein, but is to be accorded the full scope consistent with the language claims, wherein reference to an element in the singular is not intended to mean “one and only one” unless specifically so stated, but rather “one or more.” The word “exemplary” is used herein to mean “serving as an example, instance, or illustration.” Any aspect described herein as “exemplary” is not necessarily to be construed as preferred or advantageous over other aspects. Unless specifically stated otherwise, the term “some” refers to one or more. Combinations such as “at least one of A, B, or C,” “one or more of A, B, or C,” “at least one of A, B, and C,” “one or more of A, B, and C,” and “A, B, C, or any combination

thereof' include any combination of A, B, and/or C, and may include multiples of A, multiples of B, or multiples of C. Specifically, combinations such as "at least one of A, B, or C," "one or more of A, B, or C," "at least one of A, B, and C," "one or more of A, B, and C," and "A, B, C, or any combination thereof" may be A only, B only, C only, A and B, A and C, B and C, or A and B and C, where any such combinations may contain one or more member or members of A, B, or C. All structural and functional equivalents to the elements of the various aspects described throughout this disclosure that are known or later come to be known to those of ordinary skill in the art are expressly incorporated herein by reference and are intended to be encompassed by the claims. Moreover, nothing disclosed herein is intended to be dedicated to the public regardless of whether such disclosure is explicitly recited in the claims. The words "module," "mechanism," "element," "device," and the like may not be a substitute for the word "means." As such, no claim element is to be construed as a means plus function unless the element is expressly recited using the phrase "means for."