F. Strombeck, Z. S. He and H. Zirath, "AMCW Radar of Micrometer Accuracy Distance Measurement and Monitoring," *2019 IEEE MTT-S International Microwave Symposium (IMS)*, Boston, MA, USA, 2019, pp. 1473-1475.
doi: 10.1109/MWSYM.2019.8701002
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8701002&isnumber=8700641

AMCW Radar of Micrometer Accuracy Distance Measurement and Monitoring

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***Abstract*— An Amplitude Modulated Continuous Wave (AMCW) radar system is proposed that uses both the phase from the envelope and carrier to achieve micrometer accuracy distance measurement. The system has the benefit of using only two frequencies instead of an entire frequency band which is the case with FMCW radars. Many radar systems can therefore be used in a small area without risking interference. An experimental radar setup at 78 GHz is measured and verified to have a measurement error magnitude of less than 10 micrometer. This system is suitable for modern manufacturing and industry.**

***Keywords*— Amplitude modulation, millimeter-wave, radar, monitoring, Industry 4.0, AMCW, distance measurement**

I. Introduction

Industry 4.0 was initially proposed by the German Government to promote the digitization of manufacturing. Now its meaning has expanded to the current trend of automation and data exchange in modern manufacturing technologies [1]. With the advancement of low latency high speed wireless communication technology such as 5G, it is possible to connect all machines in a factory by exchanging massive data in real-time. The most important link, however, is advanced sensing solution that can monitor position with excellent accuracy, yet can easily coexist with other sensors without interference. Compact radar sensors, that can measure distance to a target with high accuracy is crucial for the pick-and-place robotic arm operation in modern factories.

Traditional sensor distance measuring methods includes ultrasonic, laser and radar. Laser sensing requires a smooth surface of the object, while ultrasonic sensors may interfere with each other if many sensors are used in the same small area. Narrow band radars can operate next to each other when different RF channels are used, in addition radar can be used for target detection even in dusty environment. Traditional frequency modulated continuous wave (FMCW) radars require a certain bandwidth to achieve a high ranging accuracy [3] [4] [5]. This implies that with a limited available bandwidth, the amount of radars that can be used in the same area is also limited. A narrow bandwidth enables more radars to be used in the same area.

Interferometric radar [7] is using only one continues-wave (CW) signal, however, its ranging window equivalents to only one wavelength. In this paper, a millimeter wave amplitude modulated continuous-wave (AMCW) radar is proposed, which occupies little bandwidth, yet can measure distance to target with micrometer accuracy with a ranging window of 15 cm.

The paper is structured as following: after introduction, the principle of the proposed radar system is presented in section II; the measurement setup and results for the radar system are given in section III; section IV is the conclusion and discussion.

II. Principle of the proposed AMCW Radar

A typical operational scenario of the proposed AMCW radar is illustrated in Fig. 1. Radars are installed both on the robotic palm and around the arm. The radar installed on the robotic palm helps the machine to estimate the distance to the target with high accuracy, and the radars installed around the arm avoid the arm colliding with surrounding obstacles. In this scenario, the sensing of the distance to the nearest target is critically important and such distance should be measured at a sufficiently high refresh rate. In addition, the radar must operate free of interference from other radars installed nearby.

The working principle of the radar relies on a transmitted signal which propagates until it reaches a target where it gets reflected. Some parts of the reflected signal will get picked up by the receiver antenna, with a time delay corresponding to the time it takes for the signal to travel back and forth to the target, as can be seen in Fig. 1.

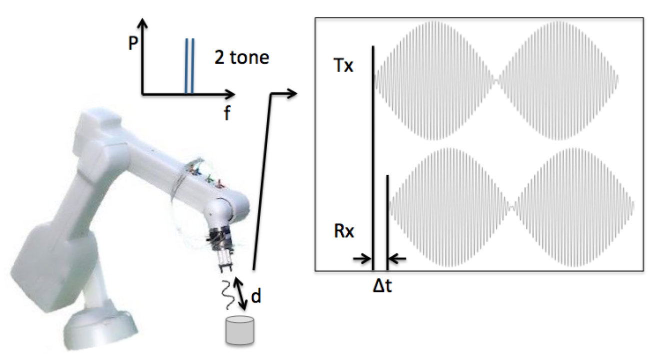

Fig. 1. Indutrial robotic equpied with AMCW radar for accurate arm control

The distance to the target is given by $2d = c\Delta t$, where c is the speed of light. The time delay of the signal will correspond to a phase delay of the received signal. The distance can be calculated by observing the received phase rotation.

$$2d = \mathrm{n}\lambda_c + \frac{\phi}{2\pi}\lambda_c \quad (1)$$

where n is an integer number and ϕ is the phase difference between the transmitted and the received signal.

The distance accuracy is limited by the estimation accuracy of the variable n and ϕ. Interferometer based radars can accurately estimate ϕ but fail to estimate n. Therefore these radars can only track a target within a narrow observation window of a distance of half a wavelength of the carrier [6] [7]. On the other hand, FMCW radars can estimate n on the expense of utilizing wide bandwidth and long sweep time, however, estimating ϕ can be only made once each frequency sweep therefore the refresh rate is limited [3].

In this paper, we propose another solution using an amplitude modulated waveform to measure the distance to the target. Using such AMCW radar can accurately estimate both n and ϕ at a high refresh rates. The transmitted amplitude modulated signal can be written as

$$s_{TX} = \sin(2\pi f_c t)\sin(2\pi f_m t) \quad (2)$$

where f_c is the carrier frequency, f_m is the modulation frequency.

The receiver shares the same local oscillator as the transmitter, therefore the received complex baseband signal can be expressed as:

$$s_{RX} = A_r e^{j\phi}\sin(2\pi f_m t + \phi_m) \quad (3)$$

where A_r is the received amplitude and ϕ is the phase rotation of the carrier. The second part $\sin(2\pi f_m t + \phi_m)$ is the envelope of the baseband signal, the phase of the envelope $\phi_m = f_m \tau$, where τ is the delay. The target distance can be estimated by:

$$2d = c\tau = \frac{\phi}{2\pi}\lambda_c = \frac{\phi_m}{2\pi}\lambda_m \quad (4)$$

This equation shows that the target can be estimated by carrier phase ϕ and/or envelop phase ϕ_m independently. As mentioned before, the estimation accuracy is different. The carrier phase can be estimated by the angle of mean value of received baseband, $\phi = \angle\overline{s_{RX}}$. To extract ϕ_m, an envelope detector should be used to obtain the envelope of the received signal. A narrow bandwidth bandpass filter can be used to suppress noise and interference from other radars. The signal is then compared with $\sin(2\pi f_m t)$, thus ϕ_m can be extracted. ϕ_m is only used for estimating n in Eq. 1, therefore, the estimation error should be less than one carrier wavelength.

III. Experimental Verification

E-band transmitter and receiver modules from Gotmic (gTSC0023 and gRSC0013) were used in the experimental verification. The transmitter and receiver used different antennas to avoid leakage of the signal directly to the receiver.

In Fig. 2 a block diagram illustrates the simplified experimental setup used during this measurement. A E8257D signal generator from Keysight was used in combination with a x6 multiplier to create the LO frequency used for the carrier and down conversion. The target was placed approximately 40 cm from the antennas. Slot array ridge gap wave antennas were used for their small volume and wide band properties

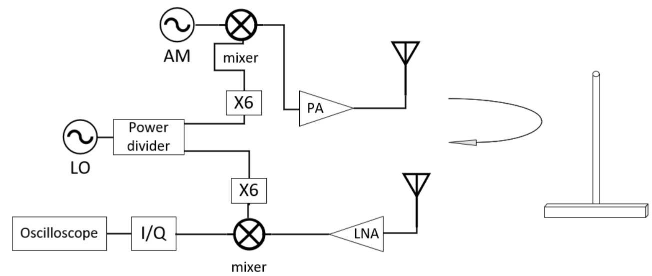

Fig. 2. The setup that was used during the measurements.

[2]. The Rx antenna height and width was 2.5 cm, while the Tx antenna height and width was 5 cm.

To modulate the amplitude an arbitrary waveform generator (AWG) M8195A from Keysight was used for this measurement to generate a sinusoidal amplitude modulation baseband waveforms.

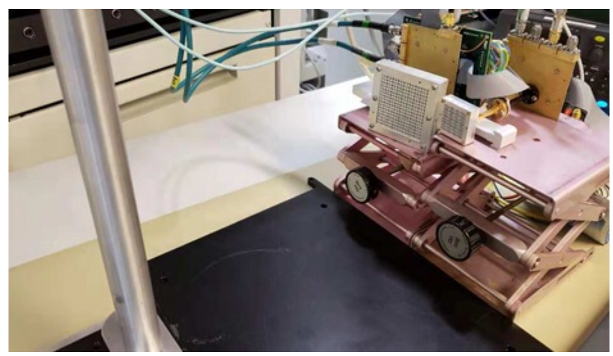

Fig. 3. A photo of the setup used during the measurements.

The carrier frequency for the measurement was set to 78.1 GHz, thus the wavelength corresponded to ∼3.841 mm. 1° accuracy of the carrier signal therefore gives ∼ 10 μm accuracy of the measurement. Using averaging over multiple periods, higher accuracy can be achieved.

The amplitude modulation rate used was 2 GHz, thus the ambiguity free window in this measurement was 15 cm. It should be noticed that the radar only occupies two sinusoidal tones of 4 GHz apart instead of the whole spectrum as FMCW does. Another radar with 2.05 GHz AM modulation, for instant, can co-exist near this radar without interference. Therefore AMCW radar can be densely installed yet without performance compromise. The received baseband signal is sampled by an oscilloscope (Lecroy Z100i) and post signal process is performed using Matlab to extract the phase of carrier and the phase of the envelope.

The distance estimation is done in two steps: firstly, the phase of received signal envelop ϕ_m is calculated and compared to the reference for coarse distance estimation; secondly, the carrier phase ϕ is calculated for fine distance measurement. In the test, the distance between the target and the antenna was changed to measure the distance accuracy using a micrometer screw. The distance was kept at least 40 cm from the target to ensure a small angle between the antennas. The received I and Q baseband signal is captured by the oscilloscope, and the envelope is tracked then pass by a band pass filter (BPF), that had a bandwidth of 10MHz for this measurement. The measurement result from coarse measurement is plotted in Fig. 4, where the target is moved 8 mm with different step sizes. The measurement error is shown which indicates an estimation error magnitude less than 3 mm. The accuracy is sufficient to estimate n in Eq. 1 with high confidence. To further improve the distance accuracy, carrier phase is used. The result shows with the help of ϕ The estimation error $< \pm 8\ \mu$m as presented in Fig. 5. Taking the reference measurement accuracy in to account the error magnitude of the system is less than 10 μm.

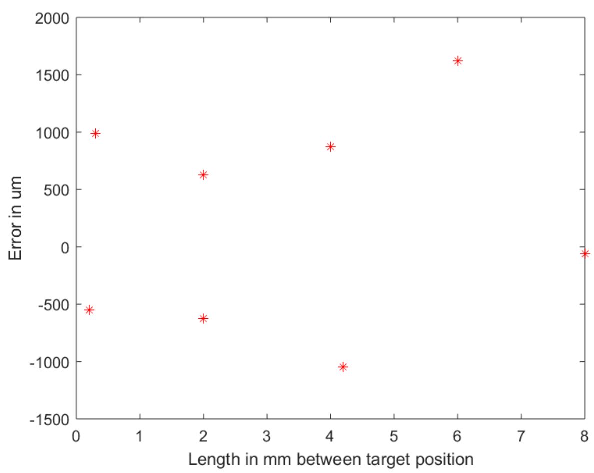

Fig. 4. Measurement error using only envelope phase (coarse estimation) at different target distance

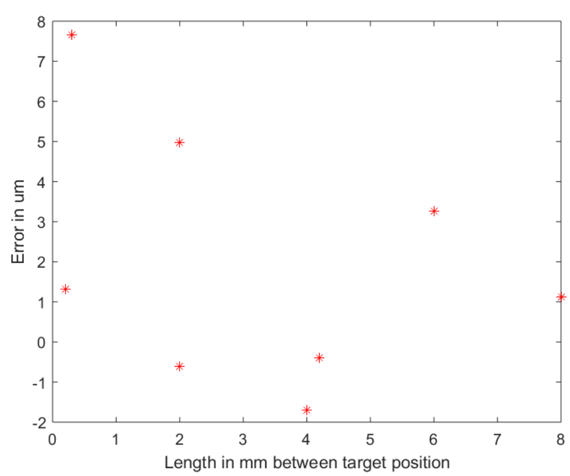

Fig. 5. The error in μm is given compared to the reference measurement. The reference measurement has an accuracy of $\pm 5 \mu$m. The target was placed at different distances from the antennas and the distance between different positions were measured in mm.

IV. Conclusion

In this work an AMCW radar operating at 78 GHz is presented, which demonstrates micrometer accuracy distance measurement with a refresh rate of 600 kHz. The radar occupies low bandwidth yet has large observation window free of ambiguity. The performance of this radar is compared with published works as shown in (Table. 1). The proposed system has the benefit of using only two frequencies instead of an entire frequency band which is the case with FMCW radars. Therefore more radars can be installed near each other without interference.

In comparison with Interferometer radar[6], AMCW radar has considerably larger ambiguity-free detection window. Dual tone Interferometer or 2-FSK radar can be used for enlarge ambiguity-free window [7], however, tones are transmitted at different time slots therefore limits the refresh rate.

Since both the carrier and the envelope are sinusoidal, shape interpolation is used for accurate phase exaction therefore micrometer-accuracy can be achieved with a limited sampling rate. Depending on the accuracy or refresh rate needed the amount of periods being averaged can be decided to meet specifications.

Table 1. Comparison with similar work

Freq. (GHz)	**BW**	**Method**	**Accuracy um**	**Meas. Rate**	**Ref.**
122.5	1 GHz	FMCW	± 2	1 kHz	[3]
124	0.6 GHz	FMCW	± 6	62.8 Hz	[4]
80	10 GHz	FMCW	± 0.5	250 Hz	[5]
24	50 kHz	6-port interf.	±35	<10 kHz	[6]
24	50 kHz	6-port interf.	±0.5	<10 kHz	[7]
78.1	2 tone	AMCW	$< \|10\|$	600 kHz	This

Acknowledgment

The authors would like to thank Gotmic for providing the transmitter and receiver modules.

The car2TERA project has received funding from the European Unions Horizon 2020 research and innovation program under grant agreement No 824962.

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