Calibration of a Six-Port-Based CW Radar Using Unknown Positions of a Target

Kamil Staszek
Institute of Electronics
AGH University of Science and Technology
Krakow, Poland
kamil.staszek@agh.edu.pl

***Abstract*—In this paper a new approach to calibrate continuous-wave radars that utilize a six-port interferometer, is proposed. The presented procedure makes use of an arbitrary number of unknown target's positions and is suitable for nearfield application. With this calibration method also a target that changes its radar cross-section along the measured distance can be used. The procedure was tested utilizing a six-port-based continuous-wave radar operating at 2.35 GHz for various number of target's positions and their spread, showing the obtainable distance measurement error not exceeding 0.012 of the wavelength. Furthermore, the obtained measurement error distribution allows for defining simple and practical guidelines for calibrating radars with the use of the proposed method.**

Keywords—continuous-wave radar, six-port network, interferometer, calibration, distance measurement

I. Introduction

Continuous-wave (CW) radars are widely used as they constitute the simplest microwave circuitry enabling remote sensing. Although the most common topology of CW radars involves frequency conversion realized with the use of mixers [1], solutions utilizing six-port (multiport) interferometers are also reported [2]. In contrast to their mixer-based counterparts, they comprise a correlator which combines the signal reflected from a target (radiated and captured by the radar) with an internally formed reference signal. An interference of these two signals is directly measured with the use of RF power detectors with no frequency conversion, what makes the circuitry simpler and improves the measurement linearity [3].

The mentioned interferometer can be realized as a passive multiport power distribution network. Its number of ports and the inner power distribution scheme together with the power detectors' measurement uncertainty define the final measurement performance [4]. In general, a higher number of power detectors (meaning also a higher number of ports of the distribution network) provides lower measurement uncertainty. The trade-off however, is a larger and more complex circuitry. Therefore, the most common interferometers are six-ports ones, as they contain the minimum number of three power detectors needed for an ambiguous measurement [5]. The remaining ports serve as excitation port, measurement port, and a port to which an additional power detector is connected, which can be used e.g., for power level monitoring.

In order to provide a reliable measurement such a radar must be beforehand calibrated. In general, methods for calibration of interferometer-based CW radars can be divided into two groups. The first one is constituted by procedures, which require to take several measurements of power measured by the mentioned power detectors for a target located in several known positions. An example of such a procedure used for calibration a six-port-based CW radar operating at 24 GHz is reported in [6]. It provides an excellent distance measurement performance at the expense of high computational effort and the need for precise knowledge of the target positions utilized for calibration. Both these aspects may be particularly difficult in low-cost applications. On the other hand, there are method utilizing the power readings for unknown, but reasonably chosen target's locations [7]. They offer lower accuracy; however, they can be implemented in systems of lower computational capacity. In majority of these calibration methods, it is required that the same target is used and it reflects microwave signal uniformly, hence the measured radar echo exhibits a regular spiral shape having a radius that exponentially decreases with increasing target's distance [8]. However, in general the target's illumination may not be identical for all positions, particularly if the target is not in farfield, but it is located close to the radar. In such a case the spiral mentioned above becomes deteriorated and such conditions affect the calibration performance, decreasing the measurement quality.

This work was supported by the Statutory Research of Institute of Electronics AGH.

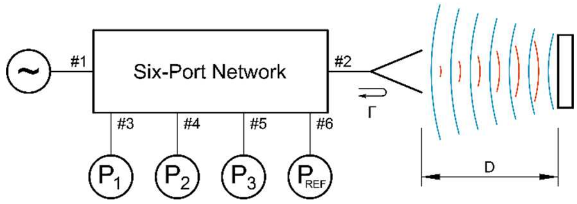


Fig. 1. A generic diagram of a six-port-based CW radar.

In this paper, a novel procedure for calibration of six-port-based CW radars is proposed. It utilizes a recently reported method [9], which was initially designated to calibrate six-port reflectometers. The presented procedure utilizes unknown target's positions, and does not require constant illumination of the target by radar, which makes it also suitable for radar calibration in a nearfield, in contrast to other reported solutions. The method is tested against the required number of the target's positions and their spread over the measured distance with the use of a six-port-based CW radar operating at 2.35 GHz. It is shown that for a large set of different target's positions used in the calibration the distance measurement error does not exceed 1.5 mm (0.012λ) over the range of 320 mm.

II. Theoretical Background

A general diagram of a six-port-based CW radar is illustrated in Fig. 1. The key element is the passive power distribution network, which is fed by RF signal from a signal source connected to port #1. This signal is distributed to port #2, to which antenna is connected and to ports #3 – #6

978-83-956020-3-0 ©2022 Warsaw University of Technology
MIKON 2022 Gdańsk, Poland

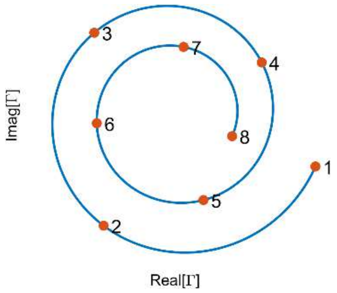


Fig. 2. Reflection coefficients of the antenna measured by an ideal six-port-based CW radar for eight target's positions equally distributed over the distance equal to wavelength.

equipped with power detectors P_1 – P_3 and P_{REF}. Next, the signal emitted by the antenna reflects from a target located at the distance D and is received by the antenna and distributed by the six-port network to power detectors P_1 – P_3. Taking the above signal propagation into account, the measured signal can be interpreted as the complex reflection coefficient Γ defined as:

$$\Gamma = \Gamma_0 + \Gamma_T e^{-2\gamma D} \quad (1)$$

where Γ_0 is the reflection coefficient of the utilized antenna in free space and Γ_T represents the reflection from target. Simultaneously, $\gamma = \alpha + j\beta$ is a complex propagation constant, which introduces exponential decrease of the magnitude and linear phase shift of the signal along with the distance D. Hence, the reflection coefficients measured subsequently for increasing distance D form a spiral on a complex plane, as shown in Fig. 2. The center of that spiral is located in Γ_0, which can be determined e.g., by taking the measurement when no target is in the antenna's field of view. After subtracting Γ_0 value, the distance D can be determined from the following expression:

$$D = \frac{\lambda}{4\pi} \arg[\Gamma - \Gamma_0] \quad (2)$$

where λ is the wavelength at the frequency of operation. It should be emphasized that for each CW radars utilizing a single frequency the range of unambiguously measured distance D is limited to λ/2.

In general, the relation between the measured power P_1-P_3 and the reflection coefficient Γ takes the following form [10]:

$$\Gamma = a_1 P_1 + a_2 P_2 + a_3 P_3 + j(b_1 P_1 + b_2 P_2 + b_3 P_3) \quad (3)$$

where a_i and b_i (i = 1, 2, 3) are system constants need to be found prior to the measurement. For an ideal six-port-based radar the value of Γ measured for a large number of target's positions form the spiral shown in Fig. 2. However, a utilization of (3) with ideal parameters a_i and b_i for a real power distribution network makes the spiral more elliptic and shifted on the complex plane. These effects are presented in Fig. 3 and Fig. 4 for different number of target's positions N and their spread L defined as a distance between the first and the last one. Such a deterioration results from magnitude- and phase-imbalance of the power distribution network and non-identical sensitivity of power detectors [10].

III. Description of the Calibration Algorithm

The algorithm utilized in the radar calibration has been recently reported in [9]. Although it was intended for reflectometers, due to close relation between the measured distance D and the reflection coefficient Γ described in the

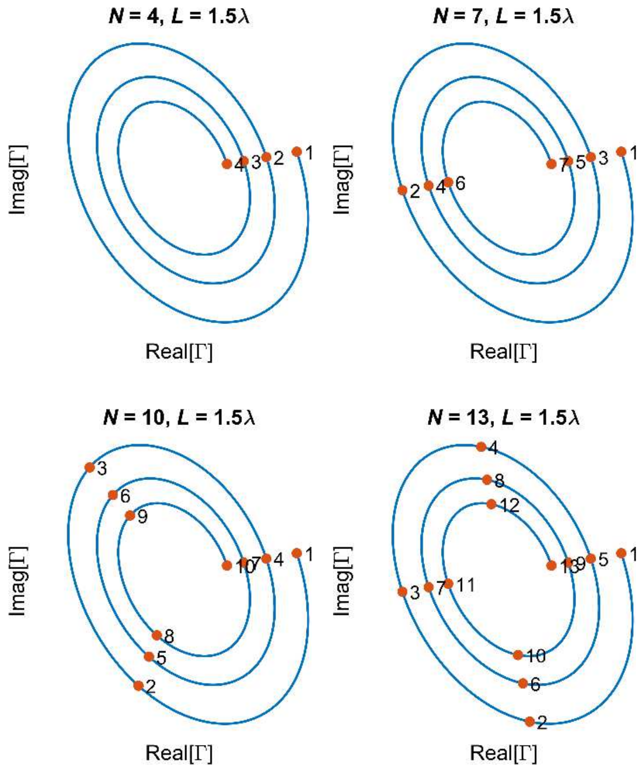


Fig. 3. Reflection coefficients of the antenna measured a real uncalibrated six-port-based CW radar for different number of target's positions N and fixed spread L = 1.5λ defined as a distance between the first and the last position.

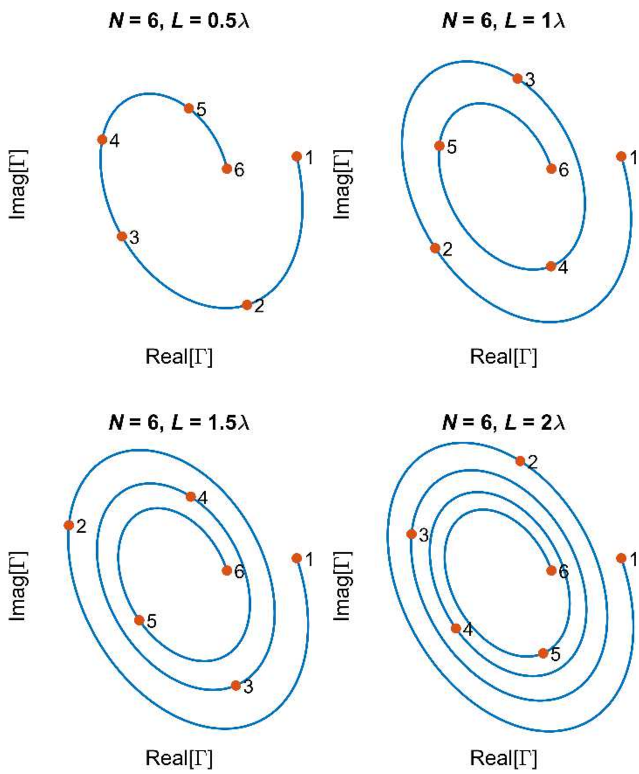


Fig. 4. Reflection coefficients of the antenna measured a real uncalibrated six-port-based CW radar for fixed number of target's positions N = 6 and different spread L defined as a distance between the first and the last position.

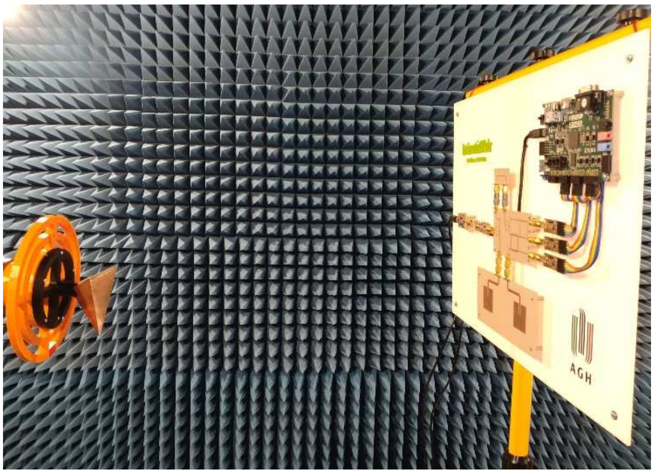
previous section, this algorithm can successfully be applied in CW radars as well. It utilizes an arbitrary number N of calibration constants having unknown reflection coefficients, which (in the considered radar application) corresponds to N unknown target's locations. Furthermore, the algorithm does not impose any particular requirements on magnitudes of the calibration constants. Therefore, the target used in calibration can be arbitrary illuminated, as the reflected signal's magnitude does not need to follow any particular trend as e.g., in [7]. This advantage makes this algorithm especially suitable for calibration in a nearfield, or for a target that changes its radar cross-section along with the distance (e.g., rotating object).

Next to the arbitrary magnitude, the phase of calibration constants utilized in the considered algorithm can also be arbitrary, which means that the target's locations used for radar calibration can also be arbitrary. There is, however, one phase-related requirement that is crucial to the calibration. To run the algorithm, it must be determined if the subsequent reflection coefficients rotate clockwise or counter-clockwise. Therefore, the subsequent target's distances must be generally increasing or decreasing and this fact must be given as an input to the algorithm. It should be underlined that particular distances between these positions do not have to be equal, and some deterioration of the assumed direction may occur. However, the overall decreasing or increasing character of the distance values must be clearly seen. This is needed to provide correct phase orientation for the algorithm. Failing this will result in inverse sign if the measured reflection coefficient's phase, which will inverse the sign of the measured distance. This is the only requirement regarding the target's positions, which in practice means that a distance between two consecutive target's positions should be not greater than $\lambda/4$ (phase difference < 180°). As seen it does not introduce any practical limitations. In Fig. 4 it is seen that for $N = 6$ and $L = 2\lambda$ the phase difference for subsequent reflection coefficients exceeds 180°, which is incorrectly interpreted by the algorithm, and in turn leads to inversed sign of the measured reflection coefficient's phase and therefore inversed distance D.

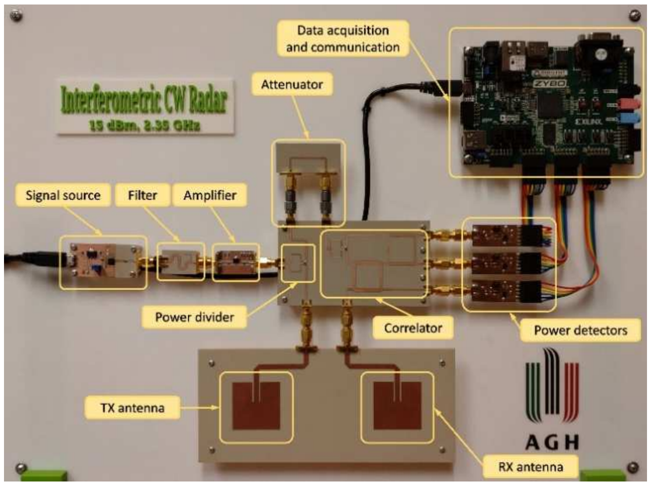
As mentioned above, the calibration algorithm uses arbitrary and unknown magnitudes and phases of the reflection coefficients. Hence, it provides a free choice of target's positions. However, as described in [9], to obtain the algorithm's convergence the measured reflection coefficients should cover possibly large range of both magnitude and phase. In the considered radar application this condition indicates that the chosen target's positions should also distinctly vary. By enlarging the spread L also the range of the measured reflection coefficients' magnitudes increases, which is crucial to the algorithm's convergence. However, for a given N, one can find the value of L for which the reflection coefficients form a straight line ($N = 4$ or $N = 7$ and $L = 1.5\lambda$ shown in Fig. 3), which obviously would not lead to calibration's convergence. Hence, the optimum number of target's positions N and their spread L need to be found.

IV. Measurement Setup

For the described search of the optimum N and L values a six-port-based CW radar presented in Fig. 5 was used. It operates at the frequency of 2.35 GHz, utilizes the interferometer described in [11], and is fed with +15 dBm of power. The power measurement was realized using three



(a)



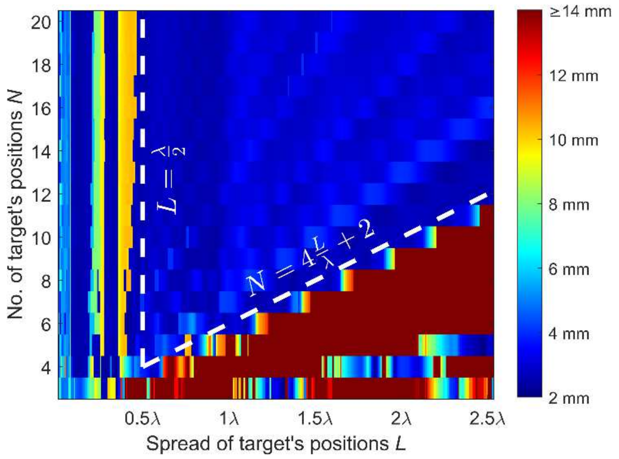
(b)

Fig. 5. The measurement setup in an anechoic chamber: (a) six-port-based CW radar and corner reflector on a robotic arm and (b) closer view of the radar.

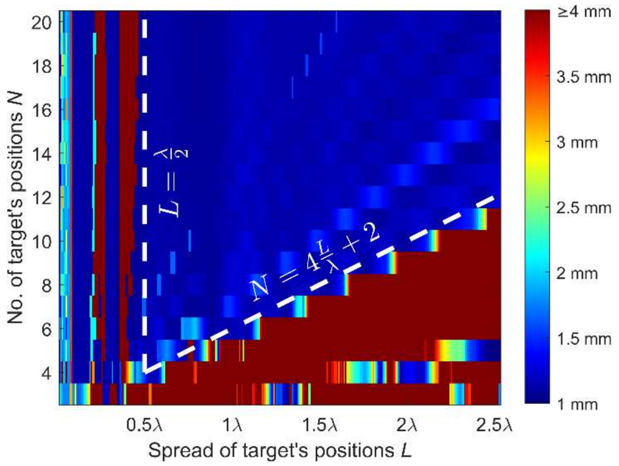
integrated power detectors LTC5587 equipped with built-in 12-bit ADCs. To suppress their nonlinear responses three dedicated Look-Up Tables were applied. The utilized radar has separate antenna for transmitting and receiving, however, the relation between the received radar echo and the power values $P_1 - P_3$ can be described by (3) as well, hence the described algorithm can be applied with no modifications. The only difference for the radar having two antennas with respect to a radar with a single antenna is that the center of the spiral Γ_0 in (1) corresponds to the isolation between these two antennas, which in practice can be lower than the reflection coefficient of a single antenna. As the target a corner reflector having the outer edges' length of 100 mm was used. To set the target at an arbitrary distance from the radar a robotic arm was utilized. A photograph of the developed measurement setup located in an anechoic chamber is shown in Fig. 5.

V. Radar's Calibration

To find the optimum N and L values the following procedure was performed. The target was placed in front if the radar's antennas at the distance D varying from 100 mm to 420 mm with the step of 0.1 mm. For each position the power readings $P_1 - P_3$ were acquired. Further, from the collected 3201 sets of power readings N sets of power readings



(a)



(b)

Fig. 6. (a) The maximum and (b) RMS distance measurement error obtained for different number of target's positions N and different spread L defined as a distance between the first and the last position. Measurements performed with the use of the six-port-based CW radar at the frequency of 2.35 GHz, for the distance range from 100 mm to 420 mm.

corresponding to the target's positions with the spread L were selected and used as the input to the calibration algorithm. The procedure was executed for each N value from 3 to 20, and for the spread L values falling between 0 and 2.5λ (320 mm). Moreover, for each tested set of positions the first position was the one of 100 mm from the radar. Having this large number of calibration results, the collected power readings for 3201 target's positions were used to calculate the target's distance using (3), in which the coefficients a_i and b_i were taken from the corresponding calibration results. Finally, the calculated distance was compared against the genuine one and the maximum and RMS values of errors were calculated for each considered set of N and L values. The obtained measurement error distributions are illustrated in Fig. 6.

Analyzing the measured distance errors' distribution a few conclusions can be formulated. First, the range of target's positions L should exceed 0.5λ to cover at least full 360°-range of the signal Γ, which is used to calculate the distance. Furthermore, for a given number of the utilized positions N the spread L cannot be too large, as it may lead to fail the phase condition described in Section III and shown as the last example in Fig. 4. As a consequence, the sign of the measured distance is incorrect and manifests itself in large errors. It is seen in the bottom right corner of the errors' distributions. The final conclusion is that the number of target's position N does not need to be high, since there is no observable improvement of the measurement error for increasing N. Simultaneously, the computational effort for the utilized algorithm significantly increases with N.

VI. Conclusions

In this paper, a procedure for calibration six-port-based CW radars was proposed. It makes use of N unknown target's positions, which do not have to be known. Moreover, the utilized algorithm is robust to the magnitude of the received radar's echo, which makes the proposed approach suitable for nearfield application and/or a calibration with the use a target that changes its radar cross-section at different positions. The proposed calibration procedure was tested with the use of the six-port-based CW radar operating at the frequency of 2.35 GHz for the target's distances between 100 mm and 420 mm. Over this range different numbers of calibration positions as well as their different spacing were tested against the obtainable distance measurement error. The distribution of the maximum and RMS error values confirms that such radars can be successfully calibrated following the proposed method and provides a simple guideline helping to select the target's positions leading to the minimum measurement errors.

References

[1] M. Reznicek, P. Bezousek, "Commercial CW Doppler radar design and application," in Prof. *27th International Conference Radioelektronika (RADIOELEKTRONIKA)*, Brno, Chech Republic, Jun. 2017, pp. 1-5.

[2] E. Moldovan, S.-O. Tatu, T. Gaman, K. Wu, "A new 94-GHz six-port collision-avoidance radar sensor," *IEEE Trans. Microw. Theory Techn.*, vol. 52, no. 3, pp. 751-759, Mar. 2004.

[3] S. O. Tatu, A. Serban, M. Helaoui, and A. Koelpin, "Multiport technology: The new rise of an old concept," *IEEE Microwave Magazine*, vol. 15, no. 7, pp. 34-44, Nov. 2014.

[4] K. Staszek, S. Gruszczynski, and K. Wincza, "Theoretical limits and accuracy improvement of reflection coefficient measurements in six-port reflectometers," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 8, pp. 2966-2974, Aug. 2013.

[5] F. M. Ghannouchi, A. Mohammadi, *The six-port technique with microwave and wireless applications*. Norwood, MA, USA: Artech House 2009.

[6] K. Staszek, S. Linz, F. Lurz, S. Mann, R. Weigel, A. Koelpin, "Improved calibration procedure for six-port based precise displacement measurements," in Proc. *IEEE Topical Conference on Wireless Sensors and Sensor Networks (WiSNet),* Austin, USA, Jan. 2016, pp. 60-63.

[7] S. Linz, G. Vinci, S. Lindner, S. Mann, F. Lurz, F. Barbon, R. Weigel, and A. Koelpin, "I/Q imbalance compensation for six-port interferometers in radar applications," in Proc. *44th European Microwave Conference*, Rome, Italy, Dec. 2014, pp. 6-9.

[8] C. Will, S. Linz, S. Mann, F. Lurz, S. Lindner, R. Weigel, and A. Koelpin, "Segmental polynomial approximation based phase error correction for precise near field displacement measurements using Six-Port microwave interferometers," in Proc. *IEEE Topical Conference on Wireless Sensors and Sensor Networks (WiSNet),* Phoenix, USA, Jan. 2017, pp. 23-25.

[9] K. Staszek, "Six-port calibration utilizing matched load and unknown calibration loads," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 10, pp. 4617-4626, Oct. 2018.

[10] R. Smolarz, K. Staszek, K. Wincza, S. Gruszczynski, "A 24 GHz microwave sensor with built-in calibration capability designed in MMIC technology," *IEEE Access*, vol. 9, no. , pp. 31513-31524, Mar. 2021.

[11] K. Staszek, S. Gruszczynski, and K. Wincza, "Six-port reflectometer providing enhanced power distribution," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 3, pp. 939-951, Mar. 2016.