

Measurement of orientation and distance change using circularly polarized UWB signals

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Abstract—The paper proposes methodology to employ circularly polarized UWB signals for simultaneous measurement of orientation and distance changes between transmitter and receiver. The proposed technique uses the rotational Doppler effect on circularly-polarized pulsed communication. The amplitude of a circularly-polarized signal is immune to polarization misalignment in the presence of rotation, however the phase is subjected to a frequency-invariant shift proportional to the rotation angle. This significantly distorts the pulse shape in the time-domain and can be used for the measurement of the rotated angle. By combining the technique with the well-known localization capability of UWB systems, one can precisely measure not only the distance, but also the orientation. This is demonstrated by both numerical and experimental studies presented in this paper.

Index Terms—Ultrawideband, UWB, Localization, Circular polarization, Remote sensing.

I. INTRODUCTION

Circularly-polarized (CP) signals are routinely used where the orientation of transmit and receive antennas is unknown or changes with time [1], since the amplitude of the CP signal is invariant to signal rotation. However, so far there are limited studies on the implications of the rotation on the phase of CP signals. Firstly, in [2] it was demonstrated for optical signals, that a CP signal rotation will produce a phase shift – a phenomenon known as *angular Doppler effect* or *rotational Doppler effect* [3].

For radio signals, it was observed in [4] that the effect can be used to monitor orientation and rotation of objects within a very large range of rotational speeds. In the experimental setup the target was fixed at a constant distance, as any distance change would have caused a phase delay and consequently an error in measurement, i.e. the system in [4] is unable to distinguish between the phase shift due to rotation and distance change.

In contrast to the classical Doppler effect, its angular counterpart produces a phase shift that is constant and frequency invariant, i.e. rotation by angle α between the transmitter and receiver results in same phase shift of α at all frequencies that

are circularly polarized. This principle was used in a dual-frequency numerical study in [5], however the measurement results were prone to a significant error due to lack of redundancy. In [6] a qualitative discussion noted that a CP UWB pulse will be distorted in the presence of rotation. While it provides no quantitative results, it suggests the possibility of simultaneous measurement of the orientation and distance using such pulses. This capability would allow robust measurements over a significantly greater distance than currently available coupling sensors [7]–[9].

Furthermore, due to the popular use of Ultra-Wide Band (UWB) signals for very precise localization [10]–[13], the localisation and orientation measurement could be combined into a single system, that provides full information about the tagged object. With the rapid development of low-cost UWB CP antenna technology, e.g. [14]–[16], such systems could be beneficial for multiple applications.

This paper investigates for the first time the practical use of UWB CP signals [17] for simultaneous measurement of the orientation and distance change between the transmit and measured antenna. It significantly extends results from [6] by demonstrating that by analyzing the UWB CP pulse phase, one can accurately determine both the orientation and distance change in the presence of noise. The presented theory validates the performance of the technique for various axial ratio, bandwidth and Signal-to-Noise ratios. The experimental verification in a semi-anechoic environment shows mean angle error of -2.7° with standard deviation 1.76° and mean distance error of -0.3 mm with standard deviation 0.3 mm. The system is intended to expand the readily-available capability of UWB localisation with orientation sensing. This is intended mainly for an integrated radio-navigation system for robotic and drone systems that are expected to form the core of Industry 4.0 manufacturing. The tag that is placed on the moving and rotating object needs to incorporate only a wideband transmitter with a circularly polarized Tx antenna, with all computation executed at the Rx side. The weight of the Tx antenna is only 16 g. The system is expected to operate up to 50 m distance without exceeding the power levels allowed by FCC UWB standard (assuming receive antenna with 12 dBic gain, i.e. similar to the one used in this study).

II. MATHEMATICAL MODEL

A. Time-domain analysis of UWB CP signals

Fig. 1 depicts the investigated scenario with two measurements: the reference measurement M1 to record the initial position/orientation and measurement M2 executed after applying a relative displacement and/or rotation to the antenna.

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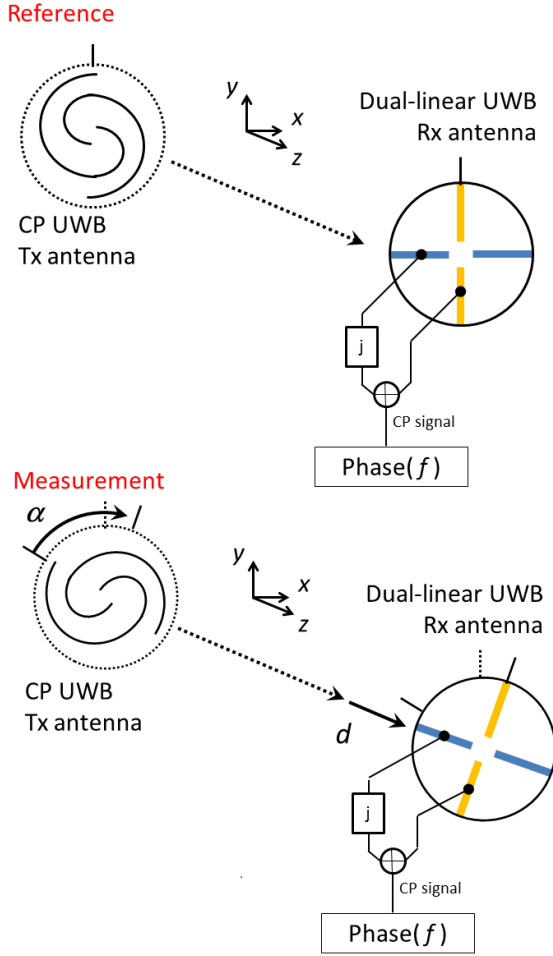


Fig. 1. Scheme of the investigated scenario, with the dual-polarized UWB receive antenna changing its orientation α and distance along z -axis Δz

The proposed technique compares the phase shift at different frequencies of the pulse, which eliminates the need for high fidelity of the radiated UWB pulse.

The transmit antenna is an UWB circularly-polarized antenna, i.e. it radiates a circularly polarized signal within the FCC UWB spectrum mask from 3.1 to 10.6 GHz. Assuming an idealised case where antenna's transfer function is negligible, the transmitted CP pulse can be depicted as a superposition of two orthogonal linearly polarized pulses: E_x and E_y [17]. The two orthogonal components have the same spectral magnitude and are phase shifted by 90° at all investigated frequencies, producing an Axial Ratio (AR) = 0 dB for every frequency involved.

The receiving (Rx) antenna is a dual linearly polarized UWB antenna, measuring two orthogonal linear components (denoted as E_p, E_q). The circular polarisation at receiver (Rx) is recovered by post-processing as in [18, Eq. (1)], i.e. the E_p signal forms imaginary part, while the E_q signal forms a real part of the right handed CP signal. This approach minimises error due to Axial Ratio (AR) variation in the receiver. For the successful calculation only the phase of the CP signal as a function of frequency f is recorded. The displacement and orientation change is calculated by comparing the phases of

the two measurements, with the calculation details outlined in subsequent sections.

B. Rotation and displacement

The receive antenna (Rx) is displaced along the z -axis by distance d and is rotated along the same axis by angle α . The effect of translation is well known and is modeled by applying a time-delay to the transmitted pulse. In the presence of rotation α , the relation of the transmitted signal E_x, E_y to the received E_p, E_q can be described by the following rotation matrix: [19, Example 7.6]

$$\begin{bmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{bmatrix} \quad (1)$$

This rotation will significantly distort the shape of the UWB pulse in time domain. Fig. 2 shows exemplary pulses of E_q - and E_p -components at the Rx antenna. It can be seen the distortion is substantially different from any distortion due to linear movement. As is subsequently demonstrated, the time delay will produce a phase shift that can be clearly distinguished from the phase shift due to rotational Doppler effect, facilitating a simultaneous measurement of d and α .

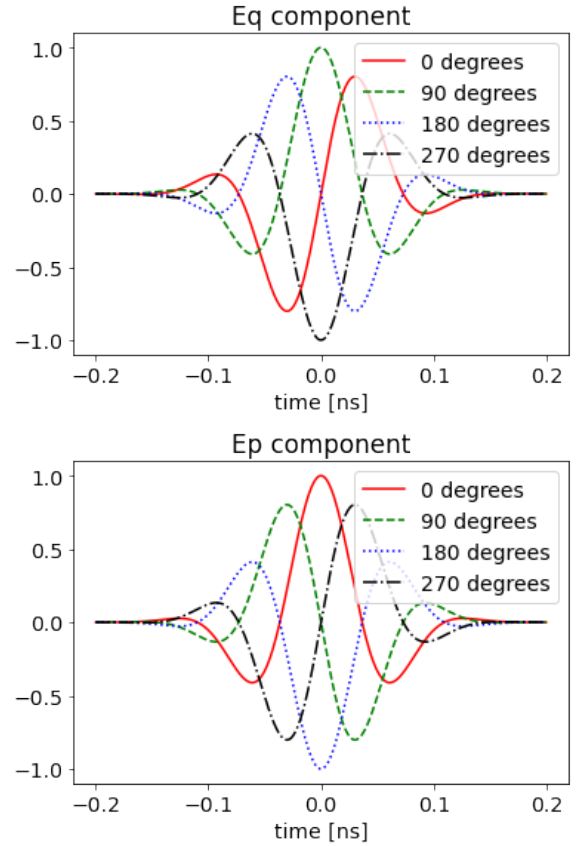


Fig. 2. Pulses received for E_q - and E_p -components different rotations α

In the numerical experiments described in Section III we compare a reference pulse corresponding to the original position and orientation of the Rx antenna with another pulse received at a new position and orientation of Rx antenna. Based on these data we estimate linear and angular displacements.

III. NUMERICAL STUDIES

The first step generates n samples for each of two Gaussian pulses, corresponding to the orthogonal electric field component E_x and E_y of the CP pulse as outlined in Section II. The pulses' bandwidth is from 3.1 GHz to 10.6 GHz, defined with respect to the Full Width at Half Maximum (FWHM) of the amplitude of the signal's spectrum. The time window of the pulses is from -0.5 ns and 0.5 ns. The number of time domain samples is $n = 1000$, if not stated otherwise.

The signal is then subjected to angular and linear displacements, as outlined in Section II. The white Gaussian noise with mean value zero and standard deviation σ is added. Since signal's power spectrum is not constant in frequency-domain, we decided to calculate Signal-to-Noise Ratio (SNR) in the time-domain. The appropriate formula is:

$$\text{SNR} = \frac{s^2}{\sigma^2}, \quad (2)$$

where s^2 is signal sample variance calculated in the time window $[-t_c, t_c]$ where $t_c = 0.19$ ns is the cutoff-time for signal's strength below -60 dB with respect to the maximum value. Note that in many full-wave simulators threshold of about -40 dB is used. Here we take lower value for better accuracy.

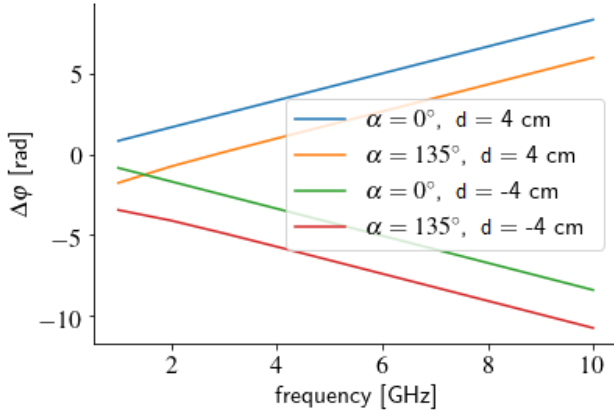


Fig. 3. Phase differences $\Delta\phi(f)$ for exemplary pulses without noise

The signal is then analysed on the receiver side to compute angular and linear displacements. This information is contained in the phase difference with respect to the reference pulse. Therefore, both pulses are transformed to the frequency domain and the phase difference between them $\Delta\phi(f)$ is calculated for each frequency.

Fig. 3 shows phase difference $\Delta\phi(f_i)$ for exemplary pulses with various rotations and displacements. As expected linear displacement results in a linear dependence between $\Delta\phi$ and frequency f while angular displacement is related to a constant dependence.

In the presence of noise, one should not expect $\Delta\phi$ to be a linear function of the frequency. Therefore the least squares method is used to fit a straight line to the set of data points $(f_i, \Delta\phi(f_i))$, where f_i 's are frequency points belonging to the bandwidth of the transmitted Gaussian pulse.

TABLE I
MEAN ABSOLUTE ERROR ESTIMATED WITH THE LINEAR-REGRESSION ALGORITHM

SNR	angular displacement error	linear displacement error
3 dB	7°	0.59 mm
6 dB	6°	0.44 mm
9 dB	5°	0.3 mm

Let c denote the speed of light in vacuum. Since the signal's time delay due to displacement d is equal d/c , its phase shift is proportional to frequency f and equals

$$\Delta\phi = 2\pi f \frac{d}{c}. \quad (3)$$

From that we see that the slope a of the regression of $\Delta\phi$ with respect to variable f is equal $2\pi d/c$. Therefore we can estimate d with the following formula

$$d = \frac{a}{2\pi} c. \quad (4)$$

On the other hand, the rotation matrix (1) is frequency invariant. Therefore when applied to CP signals, the rotation introduces constant phase shift that allows to estimate the angular displacement α by the intercept point (i.e. constant bias) of the regression line.

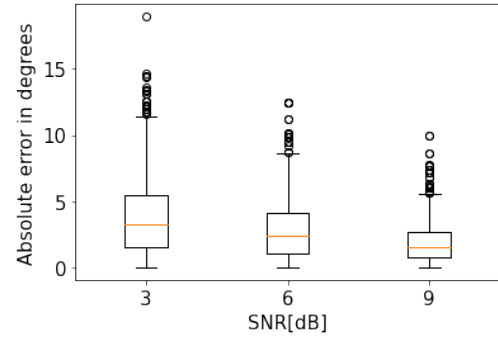


Fig. 4. Absolute error of the measured angular displacement

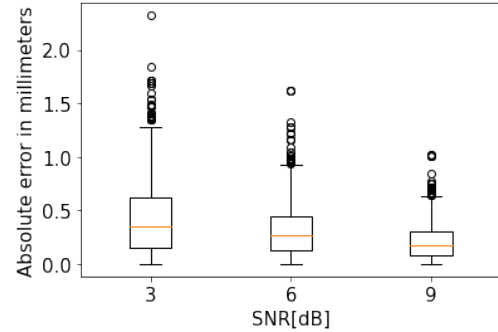


Fig. 5. Absolute error of the measured linear displacement

To validate the proposed technique 3 equally-spaced values of the linear displacement in the range from 0 mm up to 15 mm are selected. The angular displacement is varied from 0° up to 45° with step equal 5°. For each of these settings both parameters are estimated using the proposed linear regression

method. Table I shows the absolute errors of the estimated parameters averaged over selected values of linear and angular displacements. Additionally, in Fig. 4 and Fig. 5 we show descriptive statistics of calculated absolute errors. The method was evaluated for three different SNR values: 3, 6 and 9 dB which represent high-noise scenarios.

It can be seen that for all investigated SNR values the system allows good resolution in both angle and distance. For the most noisy case of SNR = 3 dB the mean angular error is 7° with 75 % of samples exhibiting error of 5° or less. For SNR = 9 dB the respective errors are 5° and below 4° for 75 % of samples. This is considered sufficient for most applications.

The mean errors for distance change are below 1 mm. It should be noted here, that this accuracy refers only to the distance change with respect to single antenna. The localization accuracy - as reported in [11] - will exhibit significantly larger errors due to the required distance measurement from at least three different antennas ('anchors'). The exact localization accuracy also strongly depends on the processing algorithm itself and is therefore beyond the scope of this paper.

To verify the sensitivity of the proposed technique, the effects of axial ratio, bandwidth and frequency offset were studied. Fig. 6 demonstrates the error of rotation measurement as a function of varying AR. The AR was adjusted by modifying the amplitude of the E_x component of the transmitted signal. The increase in error for values up to AR = 10 dB is very small, demonstrating good robustness even for a class of elliptical polarization, with stable AR within the investigated bandwidth. This is most likely because the AR impacts mainly amplitudes of the rotating signals, but not the phase differences produced by the angular displacement. Therefore sufficiently low AR is required to ensure sufficient link budget for all angles throughout the rotation. As long as this is satisfied, further improvements of the AR have limited impact on increased accuracy.

For the error in distance change shown in Fig. 7 the AR has no impact.

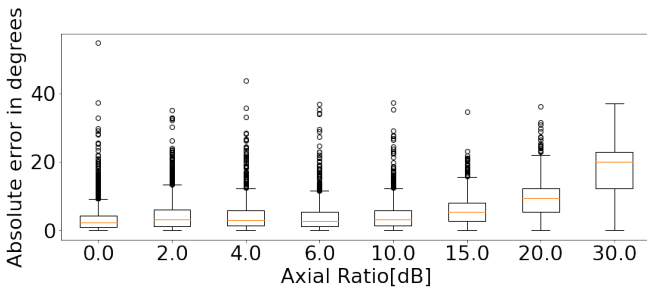


Fig. 6. Absolute error of the estimated angle displacement as a function of AR

The bandwidth reduction was simulated by reducing the number of frequency-points for the linear regression. Figs. 8 and 9 show the effect of bandwidth on the orientation and linear displacement respectively. As expected from linear displacement theory, the decrease of bandwidth resulted in greater displacement measurement inaccuracy. A similar trend is seen in Fig. 8 for the rotation measurement. For the bandwidth of 2.5 GHz the errors are 6.5° and 0.48 mm for

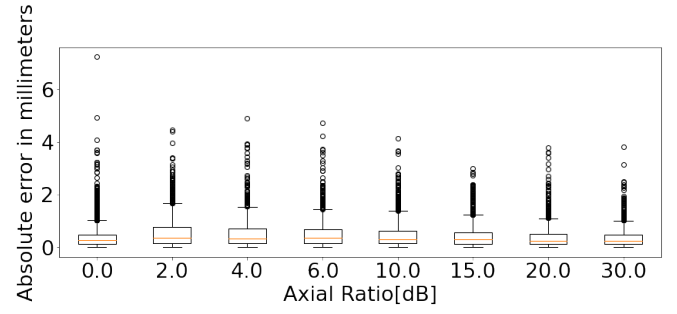


Fig. 7. Absolute error of the estimated shift displacement as a function of AR

the α and d respectively.

Lastly, the impact of the center frequency was investigated by shifting the whole spectrum by up to 200 MHz (i.e. without altering the absolute bandwidth). The study did not revealed any substantial changes in the performance. This is expected, as the phase shift produced by rotation is frequency invariant [20].

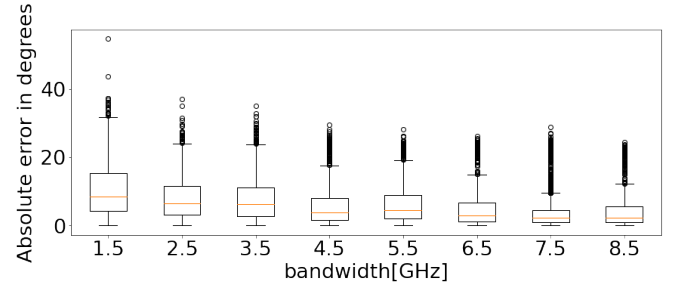


Fig. 8. Absolute error of the estimated angle displacement vs absolute bandwidth

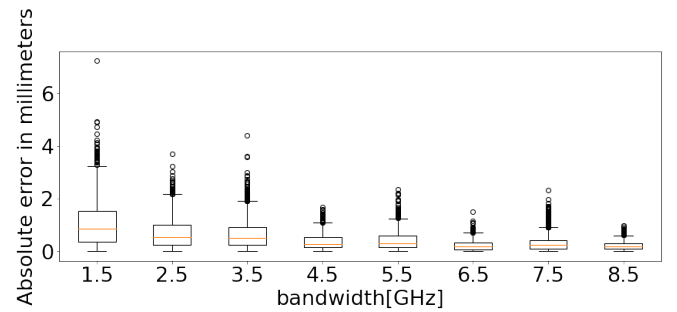


Fig. 9. Absolute error of the estimated linear displacement vs absolute bandwidth

IV. EXPERIMENTAL RESULTS

The experimental set-up is shown in Fig. 10. The transmit antenna is compact UWB planar slot antenna [14], with two orthogonal wideband slots fed through an UWB phase shifter. The antenna generates elliptical polarization, with measured boresight AR in Fig. 12. As can be seen, the $AR < 3$ dB requirement for circular polarization is not satisfied within the full bandwidth: although two circularly polarized minima are visible at 3.5 GHz and 6.6 GHz, there is an increase of up to 8 dB at 5 GHz. Also, for higher frequencies above 9 GHz there exist ripples in AR up to 25 dB. However, as shown

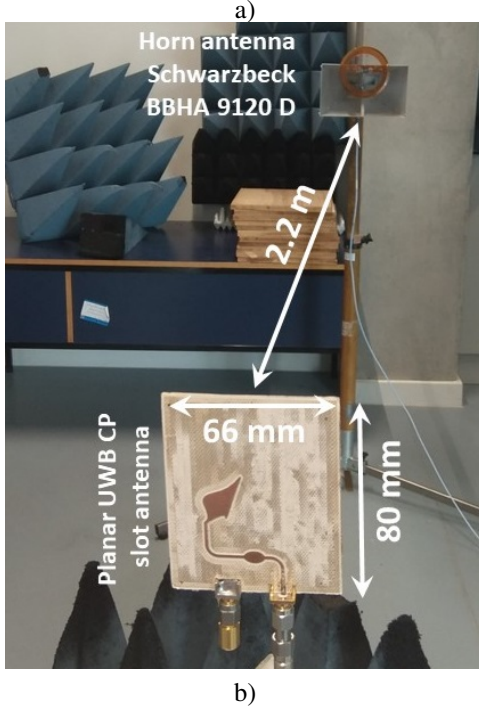
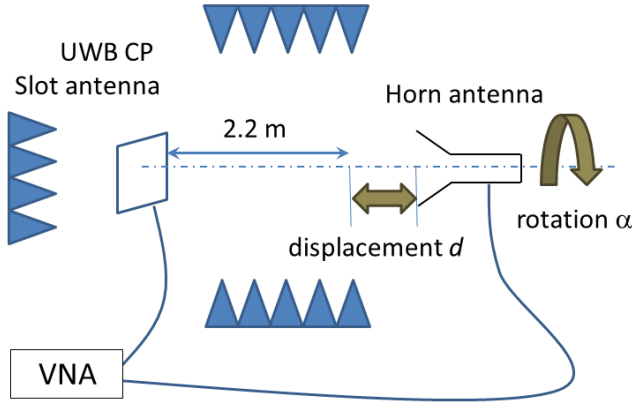


Fig. 10. Experimental setup of the proposed technique: a) schematic view; b) picture of the setup with dimensions

in Fig. 6, the proposed technique can operate within $AR < 10$ dB with negligible increase in error.

The receive antenna is an UWB ridged horn antenna Schwarzbeck BBHA 9120 D, typically used as a probe for antenna measurements. As it supports single linear polarization, two different measurements are taken for each sample, i.e. for horizontal and vertical polarization. The experiment is conducted in a concrete-walled open-laboratory space of TU Dublin Grangegorman Campus, with limited number of absorbers located at first order reflection points. The distance over which the measurement is performed is 2.2 m, with realized gains of both antennas shown in Fig.12b). The gain of the planar UWB CP slot antenna was measured using the three-antenna methodology, while the gain of the horn is given by manufacturer's data. The size of the UWB CP slot antenna is 66 by 80 cm. Its operating principles and design procedure are described in details in [14]. It exhibits relatively low gain, which a consequence of relatively small

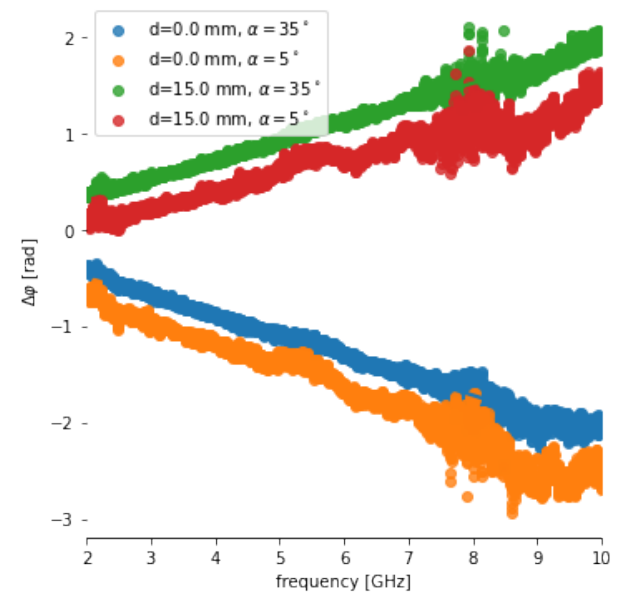


Fig. 11. Measured phase shifts $\Delta\varphi$ for different configurations of the Rx antenna and corresponding linear regression lines.

d (mm)	α ($^\circ$)	Estimate of d (mm)	Estimate of α ($^\circ$)
0.0	0.0	-0.02	359.33
0.0	5.0	0.37	10.67
0.0	10.0	0.43	15.77
0.0	15.0	0.49	20.41
0.0	20.0	0.41	25.09
0.0	25.0	0.38	28.78
0.0	30.0	0.28	33.25
0.0	35.0	0.19	37.39
0.0	40.0	0.05	41.06
0.0	45.0	0.00	45.00
5.0	0.0	5.35	1.89
5.0	5.0	5.65	8.23
5.0	10.0	5.70	13.49
5.0	15.0	5.77	18.53
5.0	20.0	5.75	23.72
5.0	25.0	5.67	28.68
5.0	30.0	5.60	33.27
5.0	35.0	5.63	37.56
5.0	40.0	5.53	42.15
5.0	45.0	5.45	46.70
10.0	0.0	9.67	357.89
10.0	5.0	9.96	5.97
10.0	10.0	10.10	12.39
10.0	15.0	10.19	17.96
10.0	20.0	10.19	23.20
10.0	25.0	10.15	28.18
10.0	30.0	10.00	37.74
10.0	35.0	10.09	33.17
10.0	40.0	9.96	42.26
10.0	45.0	9.83	46.11

TABLE II
ANGLES AND DISPLACEMENTS CALCULATED IN THE EXPERIMENT

structure with wide beamwidth. Although a larger CP antenna with a more selective beam could improve the link budget, for practical application the antenna's size and weight are also a valid concern.

The results are measured as a complex transmission coefficient S_{21} using Rohde & Schwarz ZVA Vector Network Analyser (VNA). To cover 2 - 10 GHz bandwidth with

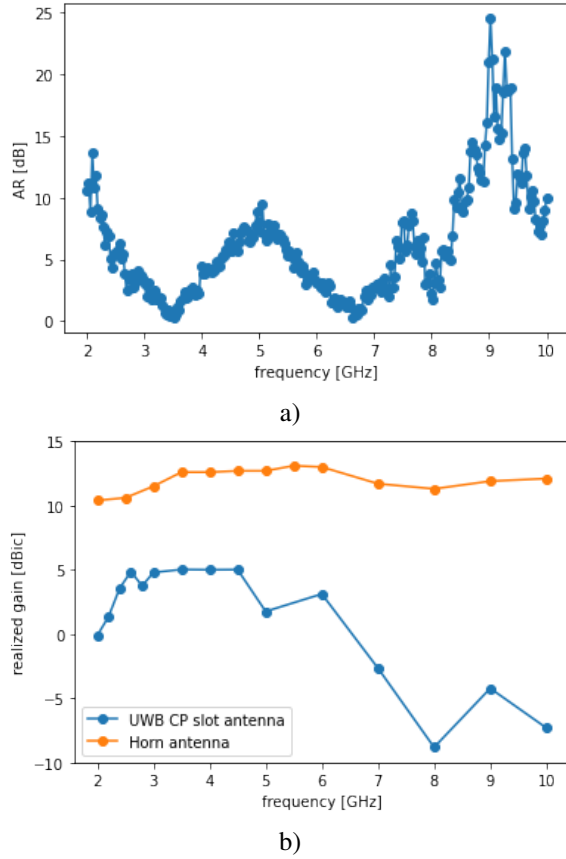


Fig. 12. Measured antenna parameters: a) axial ratio of the transmit antenna; b) realized gains of both Tx and Rx antennas.

4001 frequency samples. The Rx antenna was subjected to rotation α and displacement d with respect to the initial location and orientation. The experiment combined 3 values of displacement d varying from 0 mm to 10 mm with a step of 5 mm and 10 values of rotation α from 0° to 45° with step of 5° . This yields a total of 30 combinations shown in Table II.

Contrary to the numerical studies in Section III the regression was applied in two steps. The rationale behind this was to improve quality of the method which was impaired by imperfections of the real measurements. In the first step frequency points with amplitude of the received signal below -50 dBm were removed before fitting of the regression line. This was because weak signals produce random phase variation due to division by zero. The goal of the second step was to counteract the influence of outlying points. Here another regression line was fitted after excluding 10% of the data with the largest absolute values of residuals. The accuracy of the proposed method is evaluated by mean error, i.e. an arithmetic average of differences between true values and respective estimates. The precision of the algorithm is evaluated by standard deviation of these differences. Mean angle error is about -2.7° with standard deviation 1.76° , whereas mean distance error is -0.3 mm with standard deviation 0.3 mm. The mean errors for angle and distance indicates a slight bias in the measurements, when simultaneously estimating the displacement and rotation angle. However, this bias can be compensated by appropriate calibration. Note that precision is better than the numerical

Work	Rotation meas.	Distance meas.	Range	Reported Angle	precision Distance
[7]	Yes	No	< 1 cm	–	–
[9]	< 90°	Yes	< 1 cm	–	–
[21]	< 180°	No	0.4 m	< 5°	N/A
[4]	Yes	No	0.75 m	1.5°	N/A
[10]	No	Yes	3.5 m	N/A	1 cm
[11]	No	Yes	5 m	N/A	13 cm
			20 m	N/A	23 cm
[13]	No	Yes	8 m	N/A	4.1 cm
This work	Yes	Yes	2.5 m	1.76°	0.3 mm

TABLE III
COMPARISON OF THE PROPOSED WORK WITH STATE-OF-THE-ART RF ROTATION SENSORS

results presented in Table I, which is due to much larger signal-to-noise ratio when using VNA. The relative error for distance measurement is 6.7%. This calculation excluded values with $d = 0$ mm, as those would result in division by zero.

Table III compares the proposed technique with other works that reported various rotation or distance change measurements. In [10], [11], [13] the precision is reported as the standard deviation, whereas the resolution declared by authors is quoted in [4], [21]. The 'range' column denotes the maximum distance over which the measurement was performed, as reported in respective publications. Overall, most rotation sensors use proximity coupling and are designed to operate over small distances. The UWB displacement measurements offer good accuracy and long range, but so far they are not able to integrate rotation sensing.

V. CONCLUSION

The paper proposes a new measurement technique that employs UWB CP signals for simultaneous measurement of distance and rotation. The technique is demonstrated numerically and experimentally using respectively 120 and 35 different scenarios with varying distances and orientation angles. The results show very high accuracy of the proposed technique even with distorted AR of the antenna.

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