Promise of a Better Position

Gabor Vinci, Stefan Lindner, Francesco Barbon, Robert Weigel, and Alexander Koelpin

Industrial automation today is an essential technology underlying our modern society. Advanced positioning and sensor feedback tasks in automation processes often require distance displacement detection, e.g., to measure and track the movement of robots. Furthermore, the detection of mechanical stress in complex industrial machinery through an accurate vibration analysis is often a task of major interest. Therefore, high-resolution distance measurements with short- and long-range positioning are important for a large number of sensing applications and can also be used as a precondition for vibrometer applications. Several automation technologies rely on high precision positioning sensors to track linear as well as rotational movements of various machinery. The tracked positioning information provided by the sensor interface determines the accuracy of the positioning system, thus the quality

Gabor Vinci, Stefan Lindner, Francesco Barbon, Robert Weigel, and Alexander Koelpin are with the Institute for Electronics Engineering, University of Erlangen-Nuremberg, Cauerstr. 9, 91058 Erlangen, Germany.

Digital Object Identifier 10.1109/MMM.2012.2216710
Date of publication: 14 November 2012

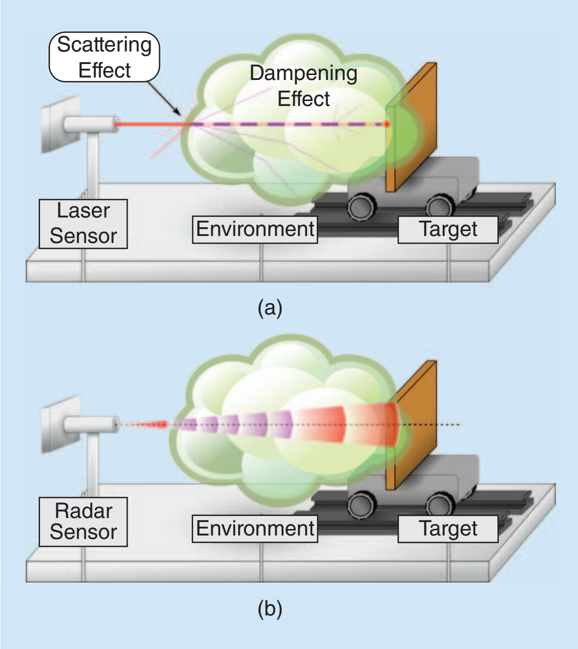

Figure 1. *Target detection in a dusty/foggy environment with (a) laser and (b) radar.*

of the overall industrial automation process. Moreover, the positioning sensor serves the control systems and algorithms as an interface to the physical world, being therefore directly involved in the physical properties of the environment and of the observed target. Several approaches have been implemented so far, making use of different physical principles such as optical techniques [1] as well as radar technology [2], showing

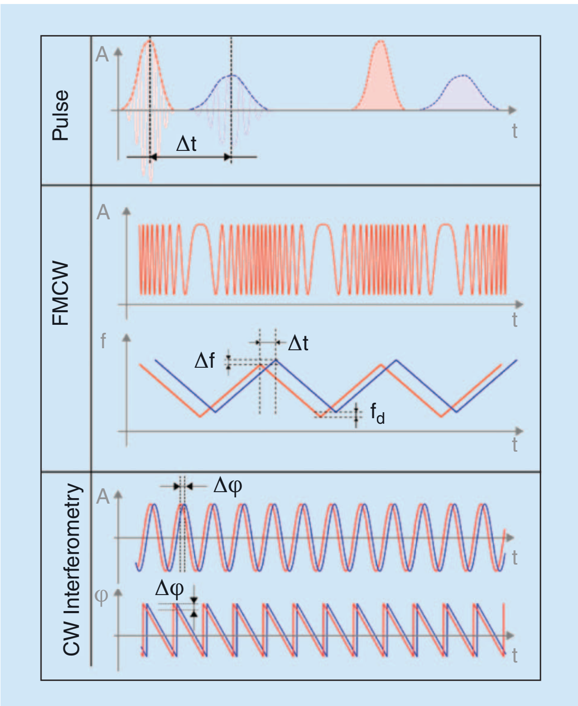

Figure 2. *A comparison of different radar techniques.*

different advantages and disadvantages. Nevertheless, the tough requirements imposed by industrial environments often impose great challenges to traditional positioning sensors. An innovative measurement technique based on the six-port interferometer radar principle [3] provides excellent measurement properties, proving to be immune to several undesired effects influencing common distance and rotation measurements. Although well known since the early 1960s, the six-port technique gained recent relevance in radar measurements [4], [5]. Mainly due to the progress in material technology and cost reduction in the production of high-frequency planar electronic circuits, six-port technology (being mainly based on passive microstrip structures on high-frequency laminate boards) has lately found several implementation possibilities. Latest research results in this field show promising effects for the implementation of this technique in industrial positioning sensor technology.

Optical-Based Measurement Techniques

Laser interferometry [6] and laser pulse time-difference measurements are the most common optical high-resolution, contactless distance measurement techniques [7]. Laser techniques feature high accuracy, high resolution, as well as a wide dynamic range and excellent frequency response. Concerning these parameters, optical systems are superior compared to all other common techniques. The drawback of optical techniques is the difficulty to penetrate dust and fog with the laser in harsh environments [Figure 1(a)]. The optical diffusion in a nonclear propagation media introduces measurement errors [8]. With increasing suspended particle density in the propagation environment, dampening and scattering effects increase, so the laser cannot reach the surface of the object under investigation. Even optical lenses and mirrors can get dirty. These inconveniences of laser-based systems are the cause of an increasing interest in alternative nonoptical measurement techniques that are robust against such industrial environment conditions.

Radar-Based Sensors

One of the main noncontact-based alternatives to laser is the radar technique. The main advantage of radar versus optical-based systems is that the measurement concept is based on the propagation of microwave signals that interact in a different way with the environment. Radar-based measurement techniques also work when a direct optical line of sight to the object under investigation is not guaranteed since radar waves can propagate much better through foggy or dusty air [Figure 1(b)].

Furthermore, even bulky and optically nontransparent dielectric slabs or nonmetallic shields can be penetrated by the radar signal. Another advantage of radar based systems is that, due to the technical advances in high-frequency printed circuit board and monolithic microwave integrated circuits (MMICs) production, the manufacturing costs of microwave circuits dropped relevantly in the last decade. Therefore, radar is cheaper today than an equivalent optical measurement system.

State of the Art

Many radar techniques such as pulse and frequency modulated continuous wave (FMCW) radars have been in use for decades for almost all possible industrial sensing applications where optical systems cannot be used [9].

Pulse radars emit a short microwave impulse signal that hits the target and gets reflected back to the transmitter. The received signal is delayed with respect to the transmitted one depending on the round-trip time of flight (RToF) of the signal to the target and back to the sensor. In Figure 2, the first image presents the transmitted signal (in red) and the received signal (in blue) delayed of a time Δt. By measuring the flight time of the signal, the distance to the target can be derived. However, since the measurement principle is based on time detection, such a technique cannot be used for short-rage measurements or high-precision distance detection due to the relatively low accuracy in very-short-time interval measurements.

FMCW radars, on the other hand, feature as transceiver output a continuous microwave signal that is frequency-modulated, typically with a triangle-shaped signal that drives the voltage controlled oscillator (VCO) generating this output frequency [10] [11] (Figure 2). This internal reference signal (red) is then mixed with the signal reflected from a target (blue), resulting in a baseband signal called the "beat signal." Different modulation signals such as sine or sawtooth can also be implemented. Nevertheless, the triangle modulation is preferred since both distance and velocity of the target can be measured, taking advantage of the Doppler frequency shift effect caused by the movement of the target itself [12]. Due to the frequency modulation, the time delay can be measured as a frequency difference between the reference and the received frequency ramp (horizontal shift in time of the received signal frequency ramp in Figure 2). Additionally, the speed of the moving target causes a shift in frequency of the received signal due to the Doppler effect [13], [14]. The baseband down-converted signal provides this information that can be analyzed with the use of signal processing.

Issues of Radar

Nevertheless, such traditional radar techniques, being based either on a time difference or frequency offset evaluation in baseband, do suffer from undesired

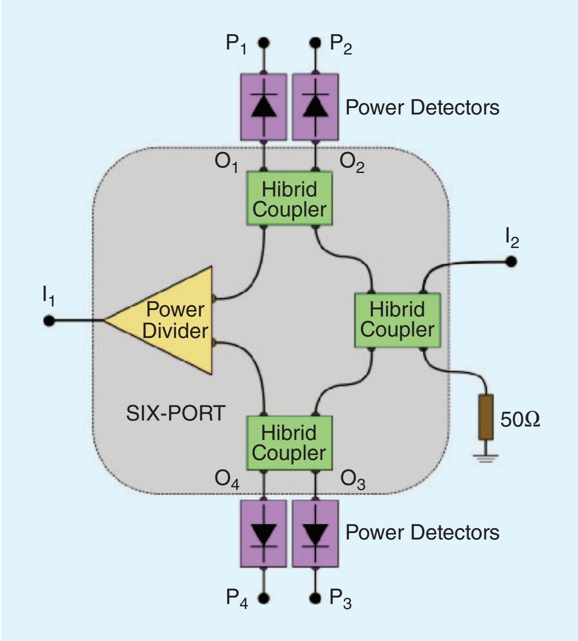

Figure 3. *The fundamental structure of the six-port receiver.*

effects. For instance, in the FMCW technique, in order to reach a high spatial resolution on short distances, very steep frequency ramps are generated [15]. This allows the system to generate a larger frequency shift between the reference signal and the reflected signal, even for very small distance detection. That's why the sweep bandwidth determines the spatial resolution of FMCW radars. VCOs are either optimized for a continuous wave (CW) output at a stable resonant frequency with a long time constant of the resonating circuit to guarantee a precise carrier frequency generation or for fast tuning through the control voltage [16]. For a very precise distance measurement with FMCW radars, a trade-off between these two design strategies has to be reached, leading therefore to a nonstable output

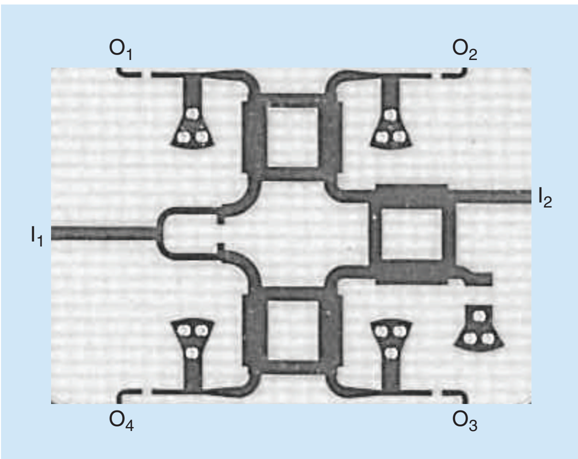

Figure 4. *A photo of the passive six-port receiver network.*

Due to its peculiar characteristics, the six-port receiver has recently found interesting applications in distance and displacement measurements.

frequency and evidencing the output nonlinearity of the oscillator source [16]. A static calibration of the VCO nonlinearity can be performed to compensate these effects, but this method cannot correct for dynamic nonlinearities of the VCO (i.e., phase noise) [17] [18]. These dynamic processes can influence the performance of FMCW radar dramatically.

An additional phase evaluation has been proposed as an additional measurement technique for FMCW radars in order to increase the measurement accuracy [19] [20]. Being able to detect a phase shift of the backscattered signal with respect to an internal reference can increase the spatial resolution of the radar device. A coarse evaluation is performed with the standard FMCW technique by means of a frequency shift measurement and, consequently, through the frequency ramp steepness. An additional phase shift evaluation allows a higher resolution measurement within the period of the wavelength used for the phase shift measurement. Up to now, for common radar devices, a subwavelength resolution has been realized by phase measurements in the baseband (at low frequencies) leading to tolerances stimulated by noise, nonlinear effects of the mixing components, and digitizing errors, like the quantization error. Additionally, the resolution of such radars is correlated to the used bandwidth being limited by the standardization of the frequency spectrum [10]. Alternatively, to the phase evaluation, the centroid of the target peak in time domain can also enhance the radar's resolution to subwavelength accuracy.

Six-Port Based Positioning Sensors

Due to its peculiar characteristics, the six-port receiver (see Figures 3 and 4) has recently found interesting applications in distance and displacement measurements [5], [21]. The six-port interferometer can easily discriminate a phase difference of two signals directly at the microwave frequency presenting therefore excellent spatial detection accuracy. This is due to the CW interferometry technique of the six-port receiver in the microwave domain versus the signal analysis in baseband of the homodyne or superheterodyne receivers used in traditional radar architectures [3] (Figure 2).

As opposed to other radar techniques, instead of evaluating the time difference of the backscattered signal or a frequency offset of an FMCW ramp, only the microwave phase difference between the reference (I_1) and the backscattered signal (I_2) from the target is measured with the six-port interferometer, which performs multiple phase shifted superpositions of these signals [22]

$$O_1 = 0.5(I_1 + jI_2), \quad (1)$$

$$O_1 = 0.5(jI_1 + I_2), \quad (2)$$

$$O_1 = 0.5(jI_1 + jI_2), \quad (3)$$

$$O_1 = 0.5(I_1 - I_2). \quad (4)$$

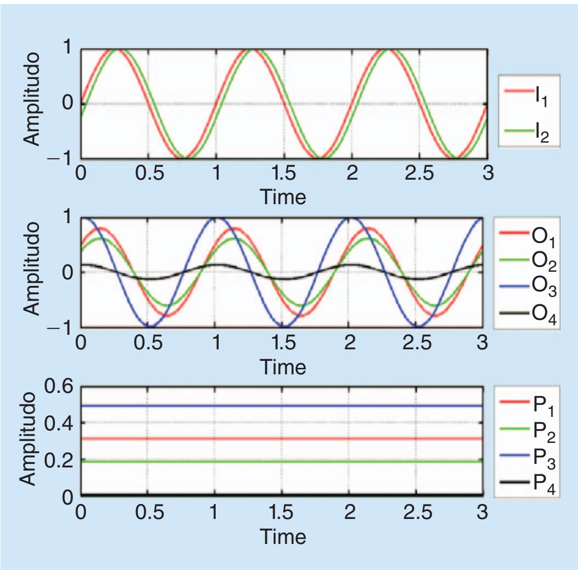

Figure 5. *Input and output signal relationship of the six-port receiver.*

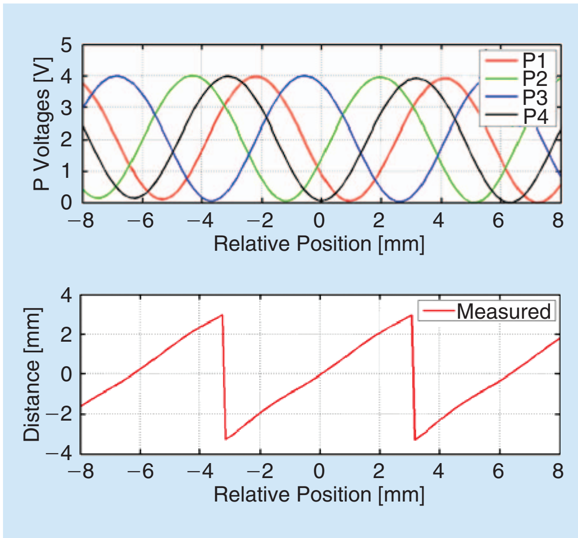

Figure 6. *Noncalibrated measured voltage signals at the output of the six-port with respect to detected relative distance.*

Four different power signals are generated, resulting from the quadrature phase shifts between the reference and the backscattered signals (1)–(4) and consequently down converted to baseband by diode-based power detectors delivering voltages P_1, P_2, P_3, and P_4 directly related to the relative phase shift between the input signals (Figure 3). Due to the quadrature relationship of the baseband outputs, a complex number is formed in a differential form. The argument of this number is equivalent to the phase shift $\Delta\varphi$ between I_1 and I_2 (5). As can be seen in Figure 5, a phase shift between the two input signals I_1 and I_2 generates certain differences in the output signals O_1, O_2, O_3, and O_4. According to (1)–(4), if the two input signals would be in phase, O_4 would be equal to zero (counter-phase superposition of the two input signals I_1 and I_2), whereas O_3 would present maximum amplitude (in-phase superposition of I_1 and I_2), while O_1 and O_2 would be identical (input signals superimposed with a positive and negative quadrature phase shift). Diode-based power detectors generate from these high-frequency outputs the baseband voltages P_1, P_2, P_3, and P_4 that are directly proportional to the power of the high-frequency output signals. Using these baseband voltage values as described in (5), it is possible to calculate the phase difference $\Delta\varphi$ between the two input signals I_1 and I_2. As illustrated in (6), the relative distance displacement L can be therefore calculated relatively to the microwave signal wavelength λ (Figures 5 and 6)

$$\Delta\varphi = \tan^{-1}\left(\frac{P_1 - P_2}{P_3 - P_4}\right), \tag{5}$$

$$L = \frac{\Delta\varphi \cdot \lambda}{2\pi}. \tag{6}$$

Particularly interesting is the analysis of small displacements of an observed target, for instance, vibration monitoring. Since the six-port-based distance measurement technology provides very-high-accuracy distance detection down to the micrometer scale (Figure 7), even the smallest vibrations (i.e., distance variations of the target surface with respect to the sensor) can be accurately detected (Figure 7). Performing a frequency domain analysis (for instance with a fast Fourier transform), a spectrogram of the mechanical vibrations of the observed target can be obtained. This leads to precious information about the working conditions of diverse industrial machinery.

By observing, for instance, a rotating turbine, thus illuminating the complete machine with the six-port distance measurement radar sensor, the main mechanical resonances can be recorded and monitored. In case of a mechanical malfunction or degradation, e.g., a wearing of the axis bearings, minor changes in the mechanical resonances will occur. Such effects can be therefore monitored without even applying sensors directly on the machine. In other words, a contactless vibration analysis for diverse industrial machines can be easily performed with six-port-technology-based sensors. As the reconstruction algorithms feature low complexity and can be calculated very fast, the maximum

Since the six-port-based distance measurement technology provides very-high-accuracy distance detection down to the micrometer scale, even the smallest vibrations can be accurately detected.

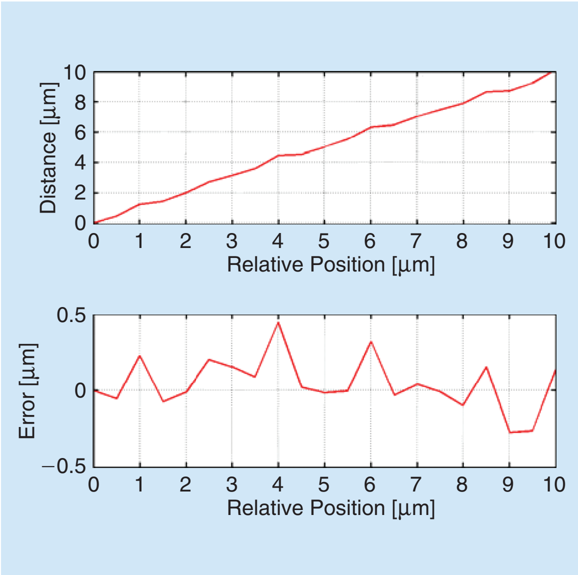

Figure 7. *High-resolution distance measurement with a six-port based sensor and the relative detection error.*

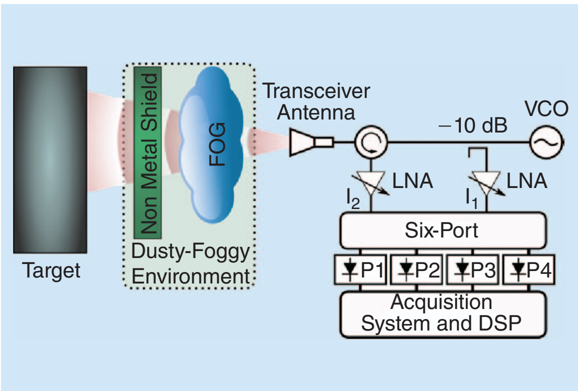

Figure 8. *Six-port interferometer based displacement and vibration measurement radar.*

Submillimeter accuracy can be reached over a measurement range of a few meters.

detectable vibration frequency is only limited by the sampling frequency of the system.

The Ambiguity Problem

The presented interferometry six-port technique increases the measurement accuracy by a phase analysis in the microwave frequency domain and offers high resolution for narrow-band signals [23]. The total dynamic range of the output signal is mapped to the relative phase relations of the two input signals within one wavelength. Since distance measurements with the six-port receiver are based on a phase-difference evaluation, an ambiguity issue occurs if the measured distance is larger than a single wavelength [5], [4] (Figure 8). In this case, the phase evaluation delivers an ambiguous result with a periodical repetition over the distance variation, depending on the wavelength of the used microwave signal. The system is not able to distinguish different distances whenever the corresponding phase difference exceeds one wavelength. In other words, the distance to the target can only be measured with no ambiguity when the target moves within a range of a wavelength of the signal used to perform the measurement (Figure 8). Therefore, making use of a single receiver, a single signal source or a single signal frequency does not natively allow an absolute measurement of the target distance but only a relative measurement within a limited range.

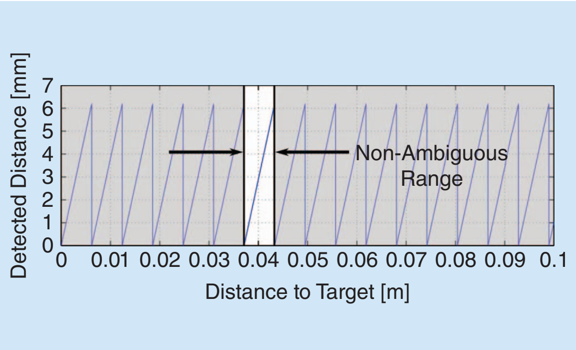

Figure 9. *The ambiguity issue in the distance measurement when using simple six-port based sensors.*

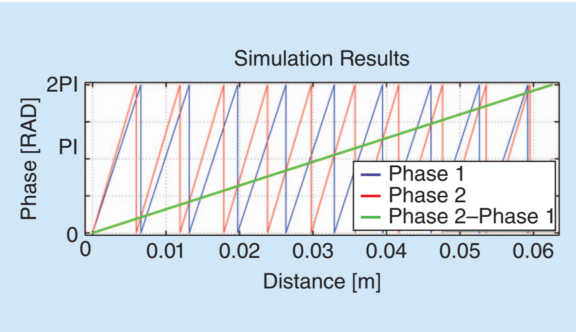

Figure 10. *Simulated phase measurement results at two different frequencies (red and blue) and the calculated linear nonambiguous phase difference (green).*

Absolute Distance Measurement for Six-Port Interferometers

There are possibilities of performing an absolute distance measurement within a wide range. The simplest approach is to count the discontinuities in phase wraps between the periods and add an appropriate offset to the measured value. This approach is similar to the phase-unwrap function known from electronic measurement instruments like vector network analyzers. Unfortunately, this approach has some limitations. First, an initial position has to be known as reference from where the periods can be counted. Furthermore, the movements of the target in the measurement system have to be slow and continuous.

Another approach is to use not only a single frequency but at least two different frequencies with a spacing of f_{Spacing} between them. The measurement is then done by calculating the phase difference between the reference signal and the backscattered signal at both frequencies. Because of the different wavelengths this leads to two different phases with a similar ambiguity. By subtracting these two phase-values, the phase of the beat frequency can be calculated. This beat frequency is the same as f_{Spacing} and can be in the range of a few MHz up to the bandwidth of the six-port receiver at approximately a few gigahertz. A distance calculation can be also performed with this phase difference and therefore based on the beat frequency. The phase from zero to 2π is mapped to the wavelength of the beat frequency leading to an unambiguous region of $c/(2 \cdot f_{\text{Spacing}})$ being c the speed of light, as can be seen in Figures 9 and 10. Nevertheless, this procedure does not influence the subwavelength accuracy of the system since the phase difference detection is still done at the microwave frequency. In other words, submillimeter accuracy can be reached over a measurement range of a few meters.

Figure 10 illustrates the system simulation of the described procedure. The mean microwave frequency of the system is for instance 24 GHz, and the ambiguities as well as the resulting discontinuities in the phase are clearly visible. To eliminate these ambiguities, a second frequency is used on the same measurement channel with a spacing of 2.4 GHz with respect to the first one. The second frequency

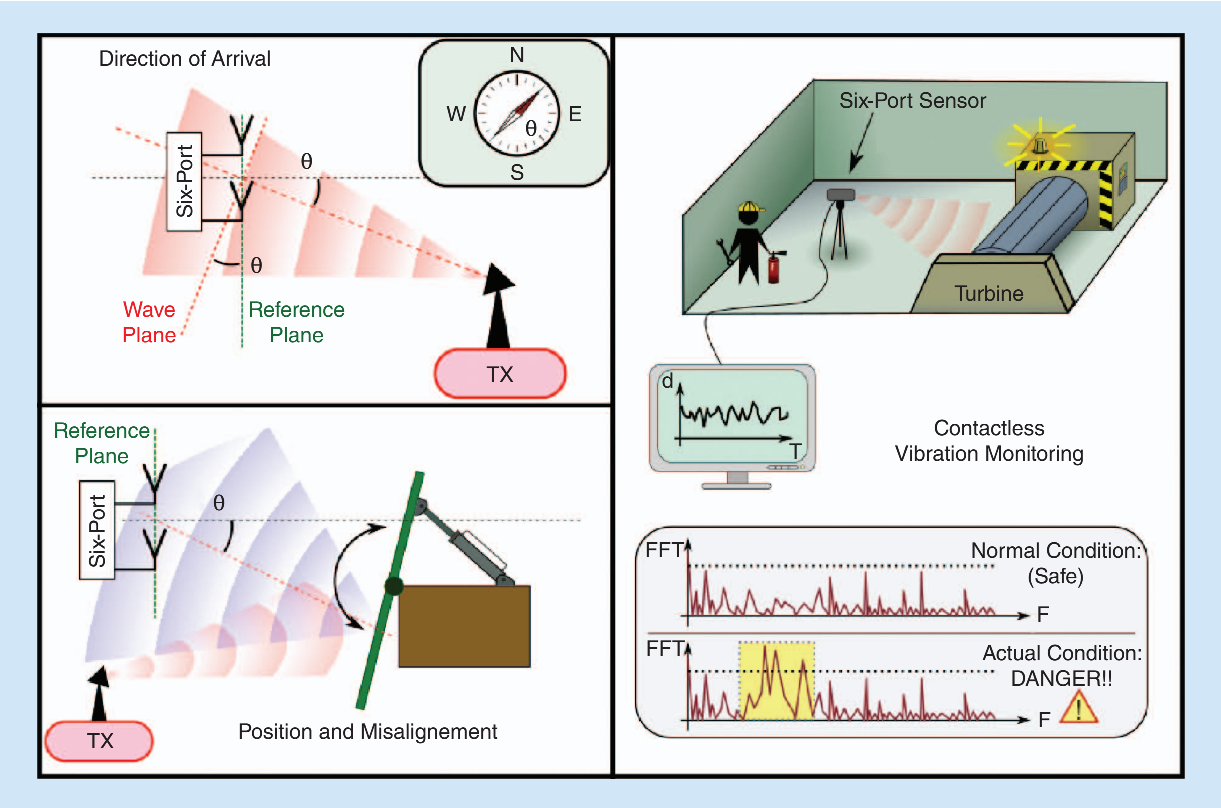

Figure 11. *Different application scenarios for six-port based sensors.*

has a similar ambiguity range, but by building the difference of these two measured phases, a linear relationship being equivalent to the phase of 2π of f_{Spacing} can be observed [24].

However, it has to be mentioned that this method has a problem with fast moving targets, because the oscillator generating the two frequencies needs a settling time between the two measurements and, in the meanwhile, the observed object should not move. Furthermore, for very-long-range measurements, the calibration of the power detectors is essential since the received backscattered signal power may change heavily over the measurement range. This has to be taken into account, and the power detectors have to be characterized over a wide dynamic range as well as over at least two frequencies.

Direction Finding and Angle Measurement

Direction finding is also of major interest for several industrial applications [25], [27]. In this case, angle measurements can be performed. Even for these measurements, the six-port microwave interferometer concept is a valid alternative to classic superheterodyne-receiver-based approaches. The six-port technique deals with the fact that the direction of arrival (DOA) angle can be evaluated by measuring the phase difference of the incoming signal between two receiving antennas aligned along a reference axis. These two signals are superimposed in the six-port structure, thus leading to constructive or destructive interference, depending on their relative phase difference directly at the microwave frequency of the incoming signal. Common mixer-based approaches do perform a phase-difference analysis, but after a preliminary down-conversion through a mixer at intermediate frequencies or directly in baseband.

The six-port receiver recently gained relevance for several DOA sensor applications (Figure 11). It

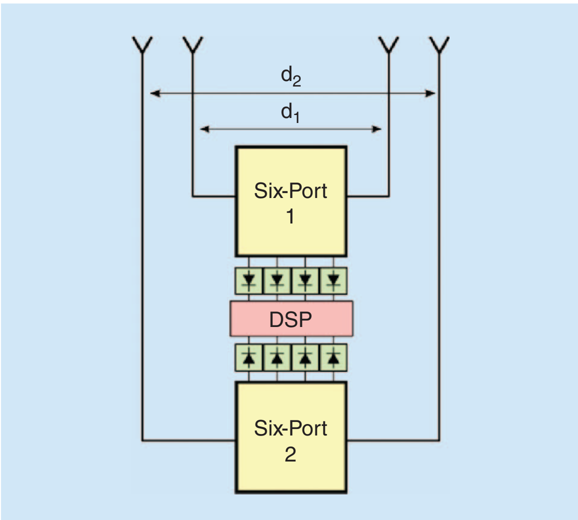

Figure 12. *A dual six-port setup.*

The six-port receiver proves to be a promising technology for diverse industrial positioning sensors for both ranging or angle measurements.

proved to be a valid technology to perform accurate misalignment angle detection of highly focused automotive radars [22], [26]. The six-port DOA detector has opened a whole new set of possibilities for novel industrial sensors and radar applications. High accuracy, low complexity, and low cost are the main advantages of this approach.

Six-port-based DOA detectors can be used to track the relative position of radio frequency sources, regardless if CW, FMCW, or pulse modulation is used. For instance, an active radar beacon positioned on a target can be tracked to monitor the targets position.

Furthermore, even reflected signals can be analyzed with such a DOA detector. For instance, the accurate angular orientation of a machine surface can be monitored through a secondary radar concept. A CW microwave signal is emitted from an antenna towards the target's surface. The reflected signal is then received by the DOA detector that performs an incoming angle detection of the reflected signal. The change in the orientation of the reflecting surface leads to a different angle of incidence of the signal at the DOA detector (Figure 11). In this way, it is easily possible to monitor the rotation of industrial mechanical constructions such as planar moving platforms or any mechanical reference plane position. Nevertheless, this simple DOA detection system does have ambiguity issues. Depending on the ratio between the wavelength of the microwave signal and the distance between the two receiving antennas at which the phase difference is measured, a periodical repetition of the detected angle is present. The system is not able to distinguish different angles of arrival whenever the corresponding phase difference exceeds 2π.

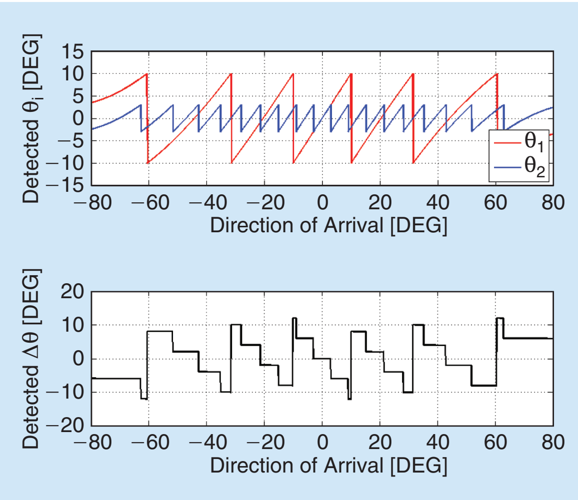

Figure 13. *A dual six-port principle for ambiguity free DOA detection.*

Solution to Ambiguity in Direction Finding

A solution to this issue has been recently proposed, making use of a dual-six-port concept [25]. Two parallel six-port systems, Six-Port$_1$ and Six-Port$_2$, with two input antenna pairs having different relative distance d_1 and d_2 are connected to one central signal processing unit that analyzes the detected angles θ_1 and θ_2 received by Six-Port$_1$ and Six-Port$_2$, respectively (Figure 12). For every incident angle, the system calculates the difference $\Delta\theta = \theta_2 - \theta_1$ between the two detected angles. $\Delta\theta$ is a function with a period that depends on the ratio between the antenna pair distances d_1 and d_2. By choosing an appropriate ratio, $\Delta\theta$ can be used to map the desired angle of incidence range that needs to be monitored with no ambiguity (Figure 13).

As can be seen in Figure 13, within the desired angle of incidence range, $\Delta\theta$ defines unique steps with a constant value. These steps offer the possibility of uniquely identifying a subsection of the observation range within which a known offset can be added to the detected angle of arrival $\theta_{1,2}$ to determine the actual DOA angle. In other words, analyzing $\Delta\theta$ leads to the cancelation of the ambiguity in phase by a compensating offset. The offset can be mapped in the system during a calibration procedure.

Outlook and Limitations

The six-port receiver proves to be a promising technology for diverse industrial positioning sensors for both ranging or angle measurements. Several applications can benefit from the positive aspects of the six-port concept (Figure 11). Different commercial approaches and implementations of the six-port receiver are currently under development, therefore, the deployment of such a technology for a large market can be predicted in the future. Microwave circuit integration such as MMIC technology is also contributing to a larger-scale distribution and to a shift of this technology to higher frequencies [26]. This can lead to even cheaper, more accurate, and more compact sensor systems for diverse industrial as well as consumer implementations throughout different application scenarios.

However, it must be noted that there are limitations to this concept. Multipath propagation can interfere with both distance as well as with angle measurements. The most noticeable effect of strong multipath interference (due to undesired reflections on surfaces other than the target itself) is a measurement inaccuracy [4]. To avoid this undesired effect, a strongly focused beam for the radiating antenna has to be used in order to force the system to only illuminate the target and observe only the object of interest ignoring influences coming from the environment.

Another limitation of this technology is the low dynamic range offered by the six-port receiver [4]. The poor performance of the passive diode-based power detectors in the six-port structure as well as the nonlinear power-voltage transfer characteristic of the Schottky diodes introduce limitations for the detection performance. For most of the industrial sensing applications, this is not an issue, but for some low-power applications, this could be an important limitation. For instance, a long-distance measurement of a monitored target (for vibration or position detection) could be critical due to attenuation in the propagation channel when the power level of the reflected signal is lower than the noise floor of the power detectors used in the six-port receiver.

Conclusions

Six-port technology is a promising new approach for high-accuracy positioning sensors focused on industrial applications. The main advantage is high-accuracy distance detection with relatively low production costs. The complexity of the circuit is relaxed if compared to traditional radar-based systems, and when compared to state-of-the-art radar sensor technology, the six-port proved to be very tolerant to many environmental effects or undesired phenomena such as Doppler frequency shift and local oscillator phase noise. Currently, a lot of research is being conducted on this topic and special measurement applications have already found in the six-port positioning technology the right solution to reach the desired performance specifications with distance accuracy in the submillimeter and angle accuracy in the millidegree range.

References

[1] L. Ruan, G. Tian, J. Wan, H. Li, and H. Huo, "Development of high-speed non-contact vibration measurement system," in *Proc. Electronic Measurement Instruments, 10th Int. Conf.*, vol. 2, Aug. 2011, pp. 244–247.

[2] A. Stelzer, C. G. Diskus, K. Lubke, and H. W. Thim, "A microwave position sensor with submillimeter accuracy," *IEEE Trans. Microwave Theory Tech.*, vol. 47, no. 12, pp. 2621–2624, Dec. 1999.

[3] G. F. Engen, "The six-port reflectometer: An alternative network analyzer," in *1977 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 44–46.

[4] M. G. Fadhel and A. Mohammadi, *The Six-Port Technique*, Boston: Artech House, 2009.

[5] F. Barbon, G. Vinci, S. Lindner, R. Weigel, and A. Koelpin, "A six-port interferometer based micrometer-accuracy displacement and vibration measurement radar," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Jun. 2012, pp. 1–3.

[6] G. E. Moss, L. R. Miller, and R. L. Forward, "Photon-noise-limited laser transducer for gravitational antenna," *Applied Optics*, vol. 10, no. 11, Nov. 1971, pp. 2495–2498.

[7] M. Zeitouny, M. Cui, N. Bhattacharya, P. Urbach, S. van den Berg, and A. Janssen, "Long distance measurement with sub-micrometer accuracy using a frequency comb laser," in *CLEO/Europe EQEC 2011 Conf. Dig.*, 2011, p. CH5_1.

[8] R. Yang, X. Han, and D. Jian ,"Distortion and delay of laser pulse propagation in sand and dust storm," in *Proc. Antennas, Propagation EM Theory, 7th Int. Symp.*, Oct. 2006, pp. 1–4.

[9] A. A. Kostenko, A. I. Nosich, and I. A. Tishchenko, "Radar prehistory, soviet side: Development of the three-coordinate L-band pulse radar in Ukraine in the late 1930's," in *IEEE APS Int. Symp. Dig.*, Boston, vol. 4, 2001, pp. 44–47.

[10] G. M. Brooker, "Understanding millimeter wave FMCW radars," in *Proc. 1st Int. Conf. Sensing Technology*, Palmerston North, NZ, Nov. 2005, pp. 152–157.

[11] J. D. Taylor, *Introduction to Ultra-Wideband Radar Systems*, Boca Raton, FL: CRC Press, 1994.

[12] L. Reynolds and Y. Ayasli, "Single chip FMCW radar for target velocity and range sensing applications," in *11th Annual Gallium Arsenide Integrated Circuit Symp. Technical Dig.,* 1989, pp. 243–249.

[13] S.-R. Huang, M. L. Robert, and J. P. Kevin, "On estimating the amplitude of harmonic vibration from the Doppler spectrum of reflected signals," *J. Acoustical Society America*, vol. 88, no. 6, pp. 2702–2712, 1990.

[14] M. Pichler, C. Seisenberger, A. Ziroff, and A. Stelzer, "Ambiguity resolution with multiple FMCW range-doppler radar sensors," in *Proc. ICECom, 2010 Conf.*, pp. 1–4.

[15] H.-H. Ko, K.-W. Cheng, and H.-J. Su, "Range resolution improvement for FMCW radars," in *Proc. European Radar Conf.*, Oct. 2008, pp. 352–355.

[16] T. Musch, Broadband suppression of phase-noise with cascaded phase-locked-loops for the generation of frequency ramps, *Adv. Radio Sci.*, vol. 1, pp. 37–41, DOI: 10.5194/ars-1-37-2003, 2003.

[17] C. K. Winter, G. E. C. Capps, and D. J. Daniels, "*A High Linearity FMCW Sweep Generator*," Milton Hill House: ARMMS, 2010.

[18] W. Wu, J. R. Long, R. B. Staszewski, "A digital ultra-fast acquisition linear frequency modulated PLL for mm-wave FMCW radars," in *Proc. IEEE Int. Radio-Frequency Integration Technology, Symp.*, Dec. 2009, pp. 32–35.

[19] S. Ayhan, M. Pauli, T. Kayser, S. Scherr, and T. Zwick, "FMCW radar system with additional phase evaluation for high accuracy range detection," in *Proc. European Radar Conf*. 2011, pp. 117–120.

[20] S. Ayhan, P. Pahl, T. Kayser, M. Pauli, and T. Zwick, "Frequency estimation algorithm for an extended FMCW radar system with additional phase evaluation," in *Proc. Microwave Conf.*, Mar. 2011, pp. 1–4.

[21] G. Vinci, F. Barbon, B. Laemmle, R. Weigel, and A. Koelpin, "A wide-range 77 GHz direction of arrival detector with integrated dual six-port receiver," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Jun. 2012, pp. 1–3.

22] G. Vinci, A. Koelpin, and R. Weigel, "Employing six-port technology for phase-measurement-based calibration of automotive radar," in *Proc. Microwave Conf., 2009*, Asia Pacific , pp. 329–332.

[23] G. Vinci, F. Barbon, R. Weigel, and A. Koelpin, "A high accuracy Direction-Of-Arrival and Misalignment Angle Detector," in *Proc. Microwave Conf.*, Mar. 2011, pp. 1–3.

[24] H. Zhang, L. Li, and K. Wu, "Software-defined six-port radar technique for precision range measurements," *Sensors IEEE J.*, vol. 8, no. 10, pp. 1745–1751, Oct. 2008.

[25] G. Vinci, F. Barbon, B. Laemmle, R. Weigel, and A. Koelpin, "Wide-range, dual six-port based Direction-Of-Arrival detector," in *Proc. 7th German Microwave Conf.*, Mar. 2012, pp. 1–4.

[26] G. Vinci, B. Laemmle, F. Barbon, R. Weigel, and A. Koelpin, "A 77 GHz direction of arrival detector system with SiGe integrated six-port receiver," in *Proc. IEEE Radio Wireless Symp.,* Jan. 2012, pp. 247–250.

[27] T. Yakabe, X. Fengchao, K. Iwamoto, F. M. Ghannouchi, K. Fujii, and H. Yabe, "Six-port based wave-correlator with application to beam direction finding," *IEEE Trans. Inst. Measurement*, vol. 50, no. 2, pp. 377–380, Apr. 2001.