Imaging radar systems for non-destructive material testing An overview of the state of the art, the limitations and the opportunities of radar technology.

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Abstract Radar systems have been used for over 100 years to measure distances and angular positions accurately. Radar systems benefit from relatively long wavelengths, which means that most absorption and scattering mechanisms do not have a relevant influence on the propagation conditions of the emitted electromagnetic waves. As a result, radar systems were and are used primarily for measurements under poor environmental conditions. Today, we usually find applications that work with waves in the meter to millimeter wave range. Especially in the millimeter wave range, the influence of the atmosphere can no longer be neglected. Communication systems, in particular, with their need for large bandwidths, are driving the development of components in the millimeter wave range, thus opening up further fields of application. In this context, imaging radar systems are increasingly important in various application areas. This paper will look at the possible applications in industrial process monitoring [1] [2] [3] [4] [5]. The monitoring of production processes benefits from the phenomenon's importance that many non-conductive materials are partially transparent to an electromagnetic wave. Radar systems thus allow a view below the surface and can therefore measure the material thickness of, e.g. plastics in extruders. This paper will investigate the advantages and disadvantages of radar technologies and procedures and their suitability for use in production lines.

Keywords Non-destructive-testing, industrial, application, inline, radar, imaging, synthetic-aperture-radar, MIMO, coherent, portal-scanner, high-frequency, conveyor belt

1 Distance measurement

Before we look at imaging systems, however, let us first consider how a radar system measures the distance to an object in the first place. Usually, explanations use the concept of pulsed radar systems. In the transceiver path, pulses are generated and emitted. The pulse propagates until it reflects off an object, and the signal is beamed back to the radar. The time between the transmission of the pulse and the reception of the reflected pulse is twice the distance between the radar and the target. If there are several targets in the direction of propagation, the radar system measures the different echoes, provided the pulse is short enough. This approach, still used in many air surveillance systems, is unsuitable for industrial applications. System concepts which can create extremely short pulses to generate a sufficiently high-range resolution are expensive. While resolutions in the centimeter or meter range are sufficient for long distances, industrial applications usually require resolutions in the centimeter to the millimeter-wave range, sometimes even down to the micrometer range. However, the generation of extremely short pulses with simultaneously high energy and the necessary back-end structures with high sampling rates are uneconomical for industrial applications.

For this reason, the basis of almost all low-cost systems are approaches based on frequency-modulation. Here, a frequency ramp is emitted. As with the pulsed concept, the transmitted signal is reflected at the target and radiated back to the radar. The received signal is mixed with the currently transmitted signal at the receiver. Since the frequency modulation is continuous, the signal's transit time to the target and back means that the currently transmitted frequency no longer corresponds to the received frequency (Fig. 1). A constant ramp slope results in constant frequency ω_a of the output signal s_a:

$$s_a \approx A \cdot \cos(\underbrace{\dot{\omega}\tau t}_{\omega_a}), \text{ with } \dot{\omega} = 2\pi \frac{B}{T}$$

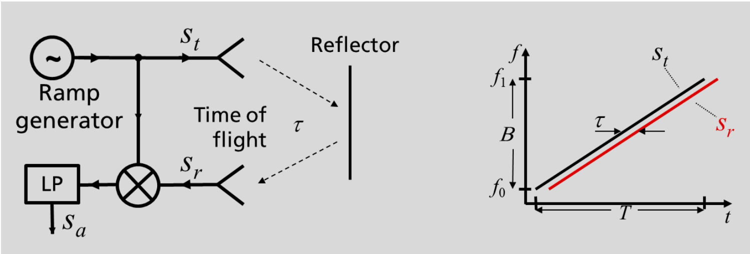

Figure 1: FMCW Principle.

The IF frequency ω_a is directly proportional to distance. In contrast to a pulsed system, the system does not measure time but the frequency shift. This concept allows more precise measurements than a comparable pulsed system. Another advantage is that the transmitter emits continuously, so the total transmission power is not bundled into one short pulse. As a result, a much lower maximum transmission power is required to achieve the same system dynamics than a single pulse.

2 Mechanical scanners

Close-range applications usually use focusing optics with the object to be viewed in the focal point. If the object is moved in the focal point, it can be imaged two-dimensionally. The wavelength of the measuring frequency used determines the achievable lateral resolution. For a system at 300 GHz, focussing to below 500 µm can theoretically be achieved with a short focal length. Since radar systems allow phase and time-of-flight measurement, objects can be reconstructed two- and three-dimensional. Here, a distinction must be made between resolution and measurement accuracy. The resolution determines the ability of a radar to separate two neighbouring objects from each other. The bandwidth of the radar system determines the minimum distance between two objects to be divided. It is usually a maximum of 10% to 30% of the centre frequency of the radar system. For the sake of simplicity, a distance resolution of 2 mm is assumed. If there is only one scattering center in this range cell, e.g. a flat surface, the range to this surface can be determined much more precisely via the phase information in

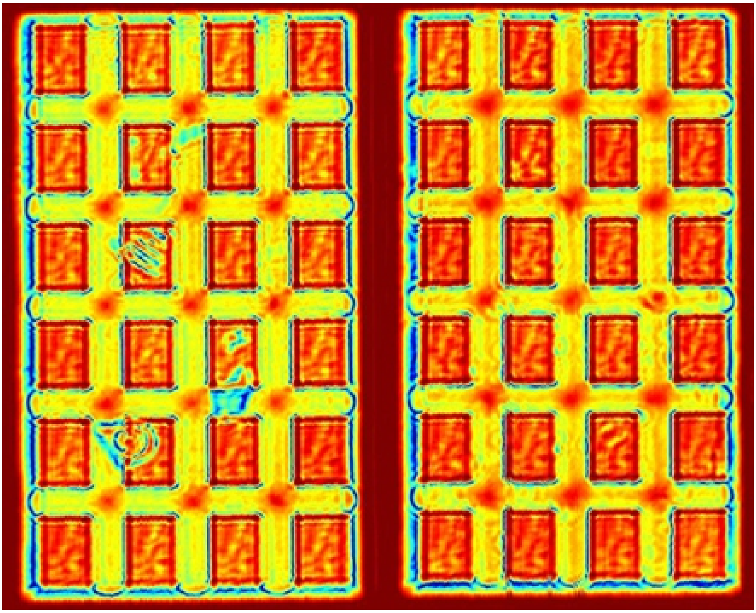

Figure 2: Transmission image of a bar of chocolate with (left) and without (right) impurities.

a coherent radar. Usually, the longitudinal measurement accuracy is higher by a factor of 100 than the lateral resolution of a corresponding system. Theoretically, packaged products can be inspected in this way (Fig. 2), but the measuring time could be faster for use in a conveyor line, so the technology is more suitable for single-piece inspection. This is especially true for moulded plastic parts where the composition and structure of internal layers need to be imaged. A fast imaging system with a single channel requires a quick mechanical scanning process and a high measuring speed of the sensor. High-frequency systems typically do not use detector concepts that allow continuous wave measurements with update rates between several thousand and hundred thousand measurements per second. Most scanning methods are based on a linear motorised XY scanner. The most significant disadvantage of 2D scanner systems is the low scanning speed, so a scan of an area of a DIN A4 sheet can take up to one hour. Faster motor

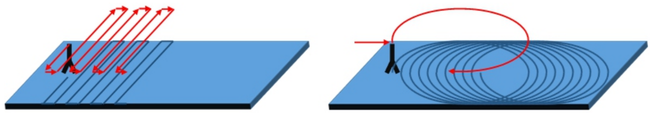

Figure 3: Comparison of the scan paths for a classic XY scanner (left) and a rotating scanner approach (right).

concepts with a lower positioning accuracy can realise such a measurement in one to two minutes. But even with this speed improvement, the mechanical 2D scanner concepts are far from the measurement time needed for inline quality control systems in production lines. The time loss is mainly caused by braking and acceleration of the linear motor stages. The change in direction causes a time gap that slows down the entire measuring system. A promising approach to speed up the measurement is to change from a linear motor concept to a rotating scanner concept (Fig. 3, right). A transmission measurement is carried out with these systems, such as the T-Sense. The device under test (DUT) passes between the two rotating probes. In the current generation of devices, 30,000 measuring points are scanned per second with this fast scanning method. This concept makes it possible, for example, to check a DIN A4 envelope within a few seconds.

3 Illustration with SAR method

However, these measurement methods are unsuitable for larger structures such as window frames or wind turbine blades. For more complex 3D structures, synthetic aperture techniques (SAR) are often used. With these, the object to be examined is scanned at a greater distance with a coherent radar, and a synthetic aperture is created. In this case, no strongly bundling antenna concepts are used, as in the case of close-range scanning, but rather antennas with a particularly wide antenna lobe. A SAR radar processor stores all amplitudes and the corresponding phase position of the echo signals of all pulse repetition periods over a time T from all positions where the section to be observed is located in the antenna's footprint. During scanning, the individual reflection points of the object to be measured are detected at different

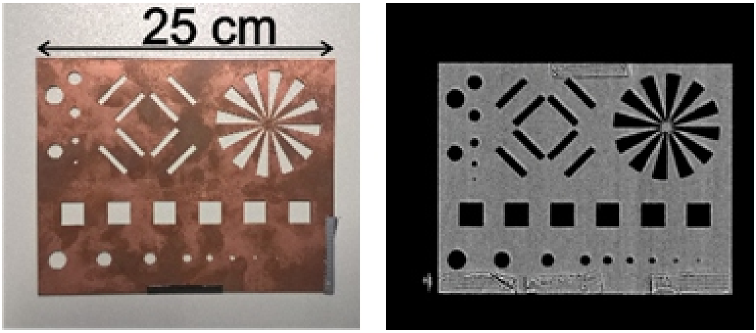

Figure 4: Test sample and the corresponding SAR image at 120 GHz.

angles, and a focussed image is generated by mathematical methods such as the "back projection" algorithm. When using a synthetic aperture in an endless motion, the numerical aperture of the image is determined only by the aperture angle of the antenna. As the distance from the target increases, the size of the synthetic aperture also increases so that the spatial resolution is independent of distance. For this reason, satellite-based radar systems often use SAR methods for Earth observation. However, they are also excellently suited for close-range applications and are used today, particularly for security scanners (Fig. 4). If you want to use a 3D SAR approach in an inline measurement configuration, you can use a TX/RX line and the conveyor belt's movement to span the virtual aperture. A fully populated array is technologically complex due to the high number of channels required. In this context, MIMO lines with reduced TX/RX channels have recently been investigated. However, hybrid approaches can also be used that combine mechanical scanner concepts with the assembly line configuration. There is also the possibility of moving a single-channel system for slow belt speeds. Here again, a rotating scanning approach is a reasonable alternative [6]. In the implementation presented, the antenna rotates at a frequency of 10 Hz, so the duration per cycle (360°) is 100 ms. For a SAR configuration, the band movement should ideally be orthogonal to the direction of movement of the antenna. Unfortunately, this is no longer guaranteed in the side ranges, as the direction of movement of the antenna corresponds to the direction of movement of the conveyor

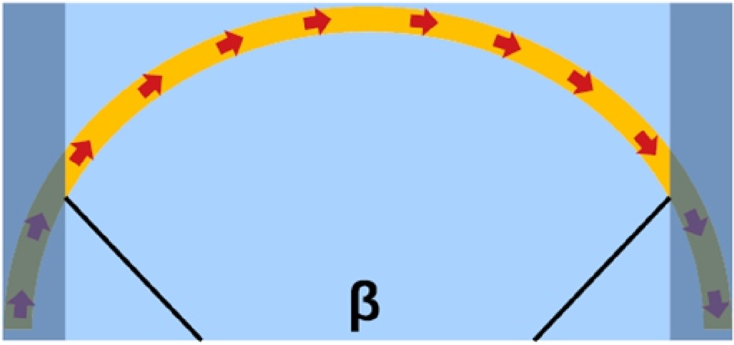

Figure 5: The path of movement of the antenna (yellow), the measuring range of the semicircle (β) and the side edges of the semicircle where no measurements are recorded (dark blue area).

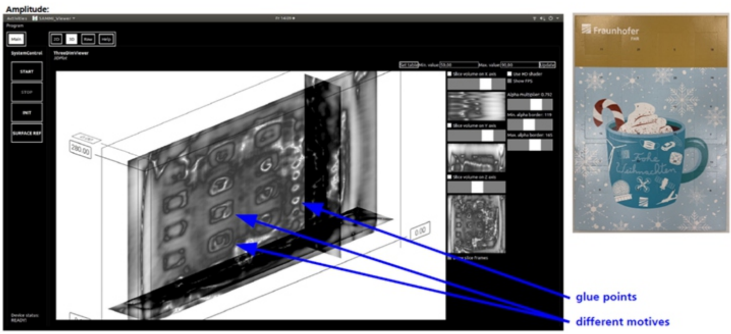

Figure 6: Visualisation of the 3D point cloud using the example of an advent calendar.

belt. Therefore, the measuring range is limited to the middle (Fig. 5, measuring range marked in light blue). Any sectional planes can now be placed in the resulting 3D point cloud to precise search for product defects (Fig. 6).

4 Imaging through MIMO radar systems

However, SAR methods require the movement of either the sensor or the object to be examined. Therefore, research is currently focusing on the development of radar-based camera systems. Since fully occupied antenna arrays are still too costly, MIMO systems are used. MIMO stands for Multiple-Input Multiple-Output. It is a system consisting of several transmitting and receiving antennas. MIMO systems can be developed for different operating modes, the most common being the design in which each transmitting antenna transmits a time-delayed transmission signal independently of the other transmitting antennas. The basic idea of this concept is to use an array of transmitters (TX array) to illuminate the object under test and an array of receivers (RX array) to detect the backscattered radiation coherently. This concept creates a virtual far-field antenna between the transmitter and each receiver antenna. The thinning of the array is achieved by design. By folding the TX and RX arrays, a fully occupied antenna array can thus be simulated. To simulate a fully occupied array with 100 elements, one needs ten transmitters and ten receivers in the best case and ten times the measurement time since all transmitters must be switched through one after the other. The virtual antenna elements' arrangement is usually made so that the resulting virtual array corresponds to the geometry of a fully occupied antenna array. The best-known application for this technology is the body scanner, which is now installed at numerous airports worldwide [7] [8]. The illustration (Fig. 7) shows a typical MIMO image of a person as created with comparable security scanners. When set up in one location, the MIMO radar system resembles a phased array antenna with a thinned-out antenna array. Each radiator has its transmit-receive module and A/D converter. But in a phased array antenna, each radiator transmits only one (possibly time-delayed) copy of a transmit signal generated in a central waveform generator. In a MIMO system with sequential control of the system, the measurement time increases according to the number of transmission channels. For this reason, MIMO systems are often used in which each radiator has its own waveform generator with which an individual signal form can be emitted. This unique waveform forms the basis for assigning the echo signals to their source. For more effective radar signal processing, each individual transmit signal can then be specif-

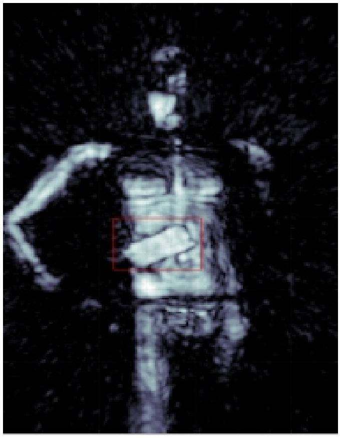

Figure 7: Radar image of a person taken with a MIMO system at 15 GHz.

ically modified (”adaptive waveform”) to improve the signal-to-noise ratio (SNR) for each target in the subsequent sampling. Furthermore, suppose the generation of the respective waveform in the transmitters is synchronous with each other, i.e. based on a synchronising clock from a central ”mother generator”. In that case, this is referred to as coherent MIMO. By increasing the frequency of such systems and combining them with low-cost silicon technology, highly integrated radar cameras can be developed. The first compact prototypes already exist [9], but this development is still in its infancy and requires further steps, especially with regard to integration and the evolution towards higher frequencies. In the long term, however, 300 GHz radar cameras could be used in a wide range of industrial areas.

5 Conclusion

In recent years, radar systems have developed into indispensable sensor systems in the industrial environment. Their application area focuses on measurement environments with very harsh environmental conditions. At the moment, however, other advantages of radar systems are coming to the fore. In addition to the high measurement speed, research focuses on imaging processes with high spatial resolution. 3D-SAR concepts are a promising approach. These future works apply in particular to real-time capability with simultaneous high assembly line speeds.

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