Millimeter-Wave Radar for Civil Applications

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***Abstract*— This contribution gives an overview of civil state-of-the-art and also some novel applications of radar sensors in the millimeter-wave frequency range, together with some general principles and a number of examples of such radar systems.**

I. Introduction

In the recent 10 or 20 years, the application of millimeter-wave radar sensors in civil areas has grown significantly; maybe the most noticeable application being in the automotive area where the first commercial radar for adaptive cruise control (ACC) has been introduced by Mercedes in 1999. While military developments had started much earlier, even based on metal waveguide circuits together with Gunn elements and IMPATT diodes, and later on with hybrid planar circuits, it took a much longer time for civil systems, although many researchers were convinced about system maturity much earlier [1], [2]. The main reason for such a delay has been the immense cost pressure for most of the civil applications, so critical development steps had to be achieved first, including

– transistors with sufficiently high cut-off frequencies
– planar circuits with surface mounted devices (including automatic assembly)
– reliable millimeter-wave MMICs at reasonable cost
– novel multilayer, multifunctional circuits.

MMICs firstly were based on GaAs, but SiGe and CMOS circuits are developed with potentially reduced cost. Quite complex circuits are also possible today combining printed circuit boards for DC supply, IF, baseband and digital circuits with microwave substrates hosting the mm-wave MMICs, passives, transmission lines, and partly even antennas [3].

Simple CW sensors in the 24 GHz ISM band have found already widespread consumer applications, e.g. [4], [5], but today, much more advanced mm-wave radar systems are under development or already in use including scanning/ imaging functions, operating partly at much higher frequencies and bandwidths with range resolutions in the centimeter range.

II. Application Overview

A tabular overview of typical civil mm-wave radar applications, certainly not complete, is given in Table I. The frequency range considered here starts with the 24 GHz ISM band for many of the consumer/commercial applications, includes the bands of 76 – 77 GHz for long range (ca. 200 m) and the two bands 21.65 – 26.65 GHz and 77 - 81 GHz for short range automotive applications (up to about 50 m), [9], [10], and partly goes up to the lower THz range for concealed weapon detection [22] or research applications [23]. Typical radar principles are CW for motion detection or speed measurement, FMCW or frequency-stepped CW, and pulsed systems, often with correlation receivers which operate in an equivalent time sampling mode to reduce final evaluation frequency and bandwidth.

Concerning obstacle detection, an interesting application is emerging due to the Concorde accident in 2000 which was probably caused by a piece of metal lost by another plane on the runway. Millimeter-wave radar could be a tool to detect such debris immediately [7], [8].

In the automotive area, Mercedes just equipped their E-class cars with four broadband 24 GHz sensors and the advanced medium/long range 77 GHz ARS 300 radar fabricated by Conti [24] which is able to scan over a wide angle and can fine-adjust the elevation angle. This radar also is offered for a range of other applications, e.g. area surveillance or different industrial applications. The latter also shows a general trend – with the increasing availability of automotive radar sensors, these are finding more and more potential applications in other areas as well [20].

Already in the 1980s, efforts had been done to improve the safety of helicopters by radar detecting high voltage lines or cable car ropes [11]; this topic has been addressed again recently [12]. Another problem for helicopters, both in the military as well as in the civil area, is loss of visibility during landing on dusty or snowy ground (brown- or white-out), this also has gained increasing interest [13], [14].

TABLE I
Application Overview

Consumer appl.	Door opener, sanitary applications (water faucets, flushing), …	[4], [5]
Traffic (general)	Speed over ground, speed surveillance, traffic statistics, debris detection on airport runways, …	[6] – [8]
Automotive	Adaptive cruise control, parking aid, blind angle control, or assistance systems for stop-and-go, breaking, lane keeping, lane changing , ...	[9], [10], [24], [25]
Helicopters	Obstacle detection (e.g. high voltage transmission lines), landing aid (brown-out/white-out)	[11] – [14]
Industrial	Level measurement, contour mapping, autonomously guided vehicles, vibration detection, ...	[15] – [21], [26]
Security	Intrusion detection, body scanners (weapon detection), …	[4], [5], [22]
Research	Vulcaneological surveillance, space missions (docking, landing), …	[23]

Since a long time, level measurements in industry are performed by radar, originally operating at microwave frequencies. Today, many systems operate in the 24 GHz or 26 GHz frequency range, but also higher frequency systems with increased bandwidth are under consideration [15]. For container loading stations, radar systems have been developed for collision avoidance of autonomous transport vehicles [21], and in (surface) mining, imaging radars help to detect surfaces and contours of troughs or mines [16] – [19].

Recent terrorists' attacks also have increased again the interest in millimeter-wave or terahertz imaging sensors for the detection of hidden weapons and explosives, e.g. [22].

III. Application Examples

A. Automotive Radars

Since the first introduction of (long range – up to 200 m) automotive radars in 1999, today the third generation of sensors has been introduced by a variety of companies [27]. Two examples with very special features, both in the 76 GHz to 77 GHz frequency range, will be shortly described in the following.

The first sensor is the ARS300 sensor by Continental [24], supplied, for example, for Mercedes. Its speciality is the scanning antenna (Fig. 1) based on a dielectric waveguide close to a constantly rotating drum with a special grating structure [28]. The grating structure varies with rotation angle and allows different antenna beam directions and properties of the radiated beam in azimuth. Focussing in elevation is done by a folded reflectarray structure [29] consisting of a polarizing grid (polarization filter) at the front side and a planar reflectarray which, in addition, can be tilted to some extent to adjust the beam direction in elevation.

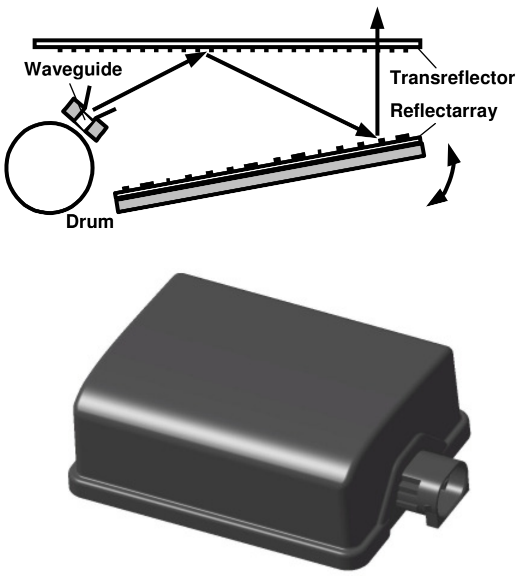

Fig. 1 Cross section and photograph of the Continental ARS300 automotive sensor with mechanical scanning [24]. (Drawing and photography by Continental)

Due to two different sections of gratings on the drum, the field of view of this sensor is ± 9° and ± 28° for “long-range” and “mid-range” operation, respectively.

The second sensor is the LRR3 radar by Bosch ([25], Fig. 2). In this sensor, for the first time, the complete mm-wave electronic for **four** radar channels is realized on a single SiGe MMIC, fabricated by Infineon. Four patch antennas, integrated on an RF substrate together with the MMIC, act as feeds for a lens antenna [30]. In this way, four antenna beams are generated, and a common evaluation of all beams together result in an excellent lateral resolution.

Fig. 2 Exploded view on the LRR3 automotive radar of Bosch [25] (photography by Bosch).

For short and medium range automotive applications (up to 50 m), additional sensors are used, partly operating in the 21.65 GHz – 26.65 GHz. As the licence for this band in Europe is limited until 2013, great efforts are undertaken to develop systems in the new 77 GHz – 81 GHz band, research, for example, is presented in [31].

B. 2D Level Measurement

Industrial level measurement increasingly requires not only simple distance monitoring, but also 2D imaging [15 - 20], [26]. For example, in surface mining of brown coal in Germany, the coal is transported via conveyor belts to a loading station, and then by cargo trains to electric power stations. In a preliminary investigation, the loading status of the wagons has been monitored by a 24 GHz FMCW radar with a switched antenna with synthetic aperture [32]. Measurement distance was 3 m, range and angular resolution about 20 cm and 3°, respectively. The radar data result from a single shot of 5 ms duration. Both wagon edges and the top surface of the load can be recognized clearly (Fig. 3), this is true also for the transition between two wagons. In this way, the overall load of coal can be determined integrating the measured contour while the train is passing the measurement station.

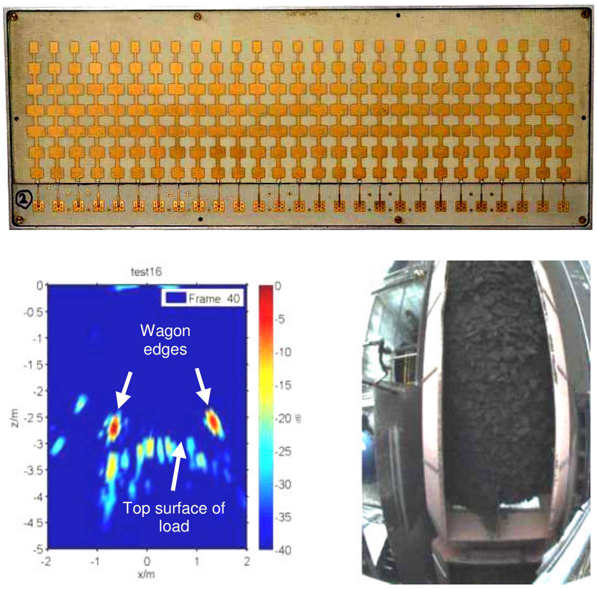

Fig. 3 24 GHz sensor (top), radar image of the loading status of a wagon transporting brown coal (bottom left) and view on the loaded wagon (right).

C. Helicopter Radar

A major cause for accidents involving helicopters are collisions with high voltage transmissions lines and cable car ropes. This has been investigated already using radar [11 – 14] as well as lidar [33]; the first is expected to provide major advantages in severe weather situations. A recent research activity is conducted by the Japanese Electronic Navigation Research Institute (ENRI), [12], exploiting 77 GHz technology from automotive applications. Without radar support, high voltage transmission lines remain invisible in the (snowy) mountain area; only radar information overlaid to the optical picture gives the necessary information including distance (Fig. 4). An open challenge still is a system with fast and efficient 2D scan.

D. Detection of Debris on Airport Runways

Driven by the crash of a Concorde plane in 2000, new efforts have been undertaken to detect debris, or "foreign objects of debris" (FOD) on airport runways. One possibility is to use mm-wave radars at the side of the runway. At a low angle of incidence, the runway itself reflects away most of the incident wave, but obstacles lying on the ground show a reasonable reflection. Using a wide-band sensor – in the tests reported here 73 GHz - 80 GHz – range cells of a few centimeters further reduce the effect of some remaining clutter.

In first tests [8] performed in cooperation between the University of Nice/Sophia Antipolis (LEAT), France, and the University of Ulm (Inst. of Microwave Techniques), Germany, with support by the French Civil Aviation Authority, a number of test measurements have been performed at the airport in Aix les Mille in southern France using several small parts of debris, e.g. a piece of bent metal, different tools, or an M10 nut (Fig. 5, top). Only very few reflections can be seen from the 15 m wide runway itself; strong clutter, however, appears from the grassy ground at both sides. With a transmit power of about 1 mW and an antenna gain of 35 dB, even the M10 nut could be recognized at a distance of up to 25 m (Fig. 5, bottom). Improved results with a larger cosec antenna and improved signal processing are presented in [34].

IV. Conclusion

Although this overview is by far not complete, it demonstrates an increased interest and a growing implementation of mm-wave radar sensors for civil applications. Besides quite simple consumer systems, driving applications are in the automotive and security area. An enormous progress in technology – mm-wave MMICs, planar integration and packaging techniques, as well as advanced signal processing circuits – enables a lower-cost fabrication and the development of more complex radar sensors, for example including imaging facilities as shown in some of the examples above.

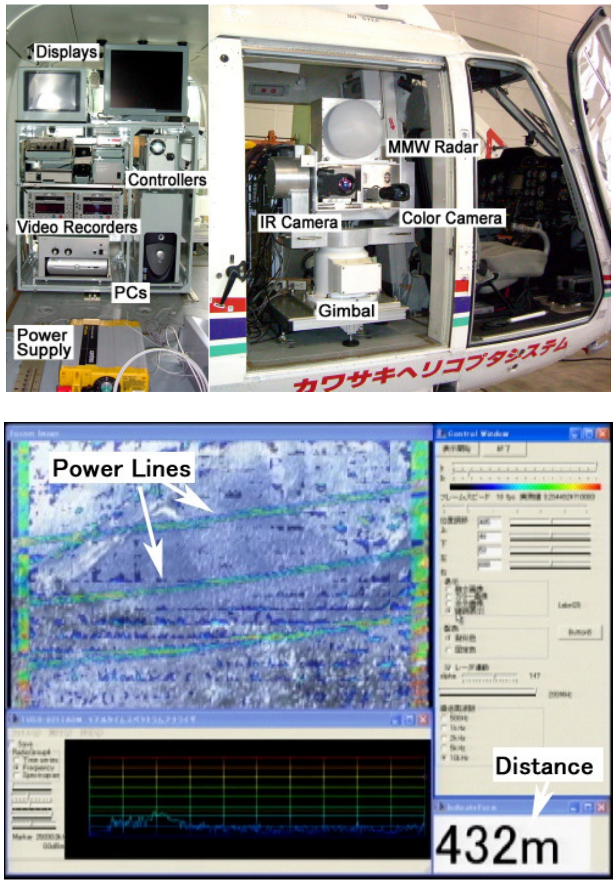

Fig. 4 Test system and display of optical view and overlaid radar information of a 77 GHz helicopter radar (courtesy of ENRI, Japan).

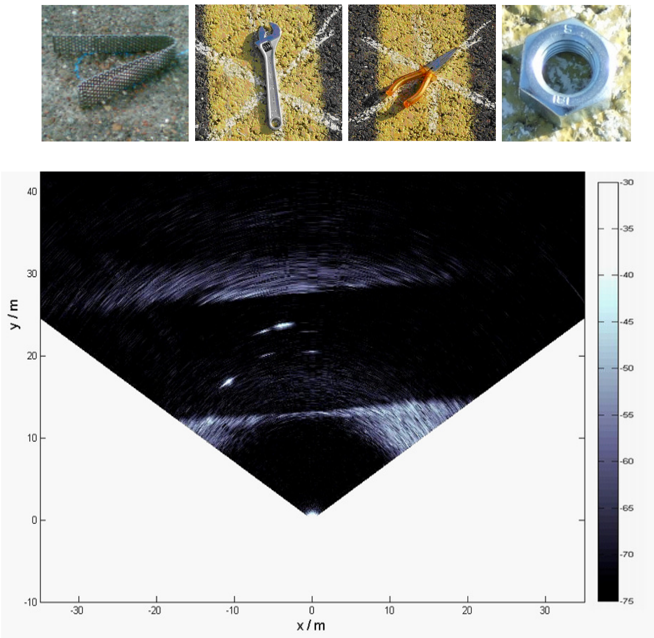

Fig. 5 Some parts of debris (top) and first test measurement results.

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