Last advances in freehand sensing for mmWave imaging

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***Abstract*—This contribution presents the last developments of freehand systems for electromagnetic sensing, focusing on millimeter-wave (mmWave) freehand imaging systems. In particular, the impact of positioning errors in the quality of the obtained electromagnetic images is discussed, emphasizing the importance of using tracking systems that can be embedded in the freehand device. In addition, several challenges faced by freehand systems to achieve a higher scanning speed and a reduced computational burden towards fully autonomous portable systems are summarized.**

I. INTRODUCTION

In recent years, the use of freehand systems have been proposed. These systems revolve around the use of a compact sensing device which is moved by hand, conferring them great flexibility. This is the more distinctive feature of freehand systems, as they enable their operator to accomodate the sensing device to each specific measurement scenario and application, avoiding the use of heavy mechanical positioners or platforms. In addition, usually freehand systems comprise a positioning system to track the movement of the sensing device. As a consequence, it is possible to increase the field of view of the freehand scanners, to map the acquired data, and to enable the use of processing techniques that require the combination of measurements from different positions. Some examples of this type of systems are freehand ultrasound scanners for medical applications [1], [2], probing systems to directly map the electric or the magnetic field radiated by a device under test in the context of electromagnetic interference measurements [3], freehand systems for antenna diagnosis and characterization [4], [5], and freehand millimeter-wave (mmWave) imaging systems [6]–[8]. In the following sections, the last advances, challenges, and potential applications of freehand systems for electromagnetic sensing, focusing on mmWave imaging, will be discussed.

II. FREEHAND MMWAVE IMAGING

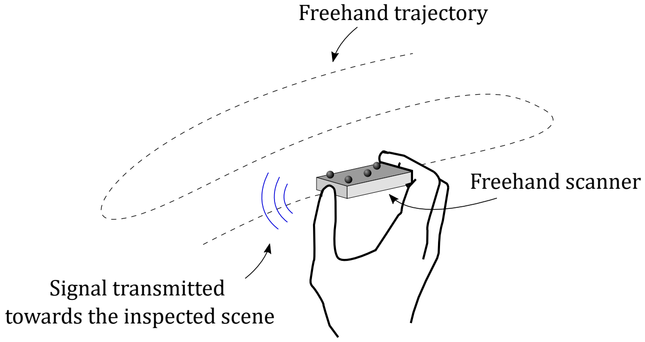


Fig. 1. Scheme of a mmWave freehand imaging system.

The advances of mmWave technology have enabled the development of compact radar-on-chip modules which are employed in a wide range of fields such as gesture recognition or automotive applications. The concept of freehand mmWave imaging, illustrated in Fig. 2, was introduced in [6]. In that work, a frequency-modulated continuous-wave (FMCW) radar-on-chip module comprising 2 transmitters (TXs) and 4 receivers (RXs) was used to take measurements of the area under scan while its position was tracked by an optical tracking system. The tracking was external and it consisted of four infrared cameras deployed in the surroundings of the area under scan, and four reflective markers attached to the radar module, enabling the accurate estimation of the position and orientation of the radar module during the scan. In order to obtain high-resolution images, a high tracking accuracy must be achieved to enable the use of synthetic aperture radar (SAR) techniques, as the standalone resolution of the radar module is significantly low due to its reduced size. In particular, a delay-and-sum algorithm was used to process the non-uniformly acquired measurements due to the freehand nature of the system, and to enable real-time updates of the results as more data is acquired. In addition, a technique to ensure an adequate sampling of the area under scan, avoiding oversampled areas, was implemented. The optical tracking system was replaced in [8] by a tracking camera based on stereoscopic vision and an inertial measurement unit (IMU), avoiding the use of an external positioning system. Although freehand scanners cannot achieve the same accuracy as conventional imaging approaches based on booth-size systems or raster scanning, these systems have demonstrated that high-resolution images can be retrieved with compact handheld scanners. This paves the way to the adoption of radar technology in different applications, such as non-destructive evaluation, in which the use conventional radar imaging systems was not feasible in terms of cost, flexibility and size. Moreover, mmWave imagers could be embedded in general purpose devices, such as smartphones, either including a dedicated radar module or reusing a mmWave communications radiofrequency front-end [9]. Some of the last contributions have exploited multiple-input multiple-output (MIMO) topologies [7], resulting in faster and less noisy images, as well as novel algorithms [10] to speed-up image calculations on large 3D volumes.

In addition, the main challenges to be faced towards improved freehand mmWave imaging systems are:

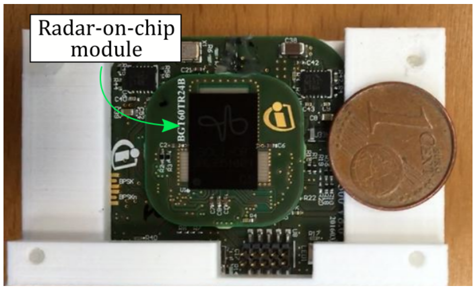
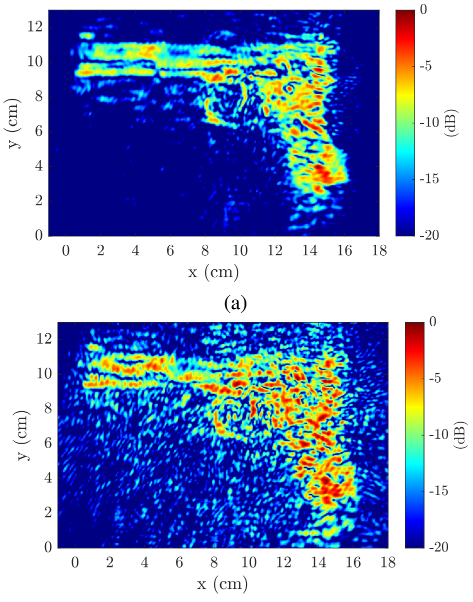


Fig. 2. Radar-on-chip module of the freehand system presented in [6].

- Development of higher accuracy tracking systems which can be embedded within the scanner. The current trend towards the use of higher frequencies imposes even more challenging tracking accuracy requirements. An example of the degradation produced in electromagnetic images due to positioning errors can be observed comparing Fig. 3a, obtained with the freehand system presented in [6], and 3b, retrieved after adding random positioning errors to the original measurements according to a normal distribution o mean $\mu = 0$ and standard deviation $\sigma = 0.5\,\mathrm{mm}$.
- Use of radar modules comprising a higher number of TXs and RXs independent channels to increase the scanning speed of the system, while keeping a reduced imager size.
- Derivation and implementation of processing algorithms capable of reducing the computational burden of processing the data acquired by the scanner. It is desirable to reduce the computational resources required to retrieve the images so all the computations can be performed in the portable scanner. Moreover, this challenge is intimately link with the higher data throughput that would result as the number of TX/RX channels is increased, which should be processed in real-time. In addition, the algorithms, as the one proposed in [10], should be able to deal with non-uniformly acquired samples.
- Development of techniques enabling the use of signals from general purpose radiofrequency front-ends (i.e., not dedicated radar modules) to facilitate embedding mmWave imagers in general purpose devices.

III. CONCLUSION

Freehand systems provide high flexibility and portable solutions for multiple applications. In particular, mmWave freehand imaging systems enable the retrieval of high-resolution images with a portable scanner moved by hand, avoiding the need of mechanical positioners. Moreover, the operator of the scanner can interactively decide where to move the imager based on the feedback from the results computed with previous measurements, which are updated in real-time. Thus, freehand systems have the potential to open the use of mmWave imaging for a wide number of applications, including the possibility of embedding them in general purpose devices (e.g., cell phones). For that purpose, several challenges, discussed in this paper, have to be addressed. Results from different freehand mmWave scanners will be presented at the conference and their performance will be compared.



(a)

(b)

Fig. 3. (a) Electromagnetic image obtained employing a freehand system, and (b) resulting image after introducing positioning errors according to a normal distribution of $\mu = 0$ and $\sigma = 0.5\,\mathrm{mm}$.

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