2021 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (APS/URSI) | 978-1-7281-4670-6/21/$31.00 ©2021 IEEE | DOI: 10.1109/APS/URSI47566.2021.9704178

A Dynamic Antenna Array for Imageless Contraband Detection

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***Abstract*—We present and experimentally demonstrate a novel approach to contraband detection using sparse Fourier domain sampling with a dynamic antenna array. A 38-GHz two-element antenna array is dynamically rotated to generate a ring-shaped filter in the Fourier transform domain of a scene, or the spatial frequency domain, where unique responses from contraband are identified, without image reconstruction. Objects with sharp edges generate sharp yet broadband spatial frequency responses that can be identified with only a subset of the spatial frequency information. In contrast to other millimeter-wave contraband detection approaches, the presented system does not depend on a fully reconstructed image nor has the ability to form one. In the presented technique, only a subset of all available spatial frequency samples are measured by the two-element dynamic antenna array with the objective to identify the strong broadband spatial frequency responses associated with sharp edges. Conducted measurements include a fabricated knife prop as contraband concealed under clothing, along with a control scenario. Measurement results demonstrate the ability to recognize a metal object, and furthermore indicate the ability to identify the shape of the target based on the responses from the knife edge as well as the angled tip that are visible in both simulation and measurement.**

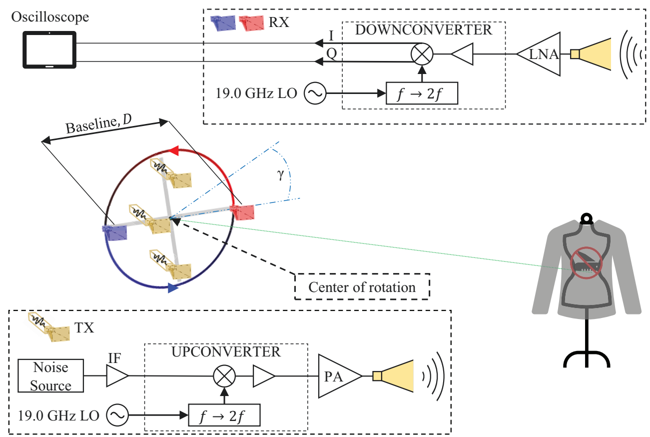

Fig. 1. Dynamic 38-GHz antenna array comprising two receiving antennas and three noise transmitters all on a rotating structure to ensure copolarization. The angular separation of the antennas and the rotation angle define a sample in the spatial frequency domain. As the antenna rotates, a ring-shaped filter is formed, from which unique features of geometric objects can be detected.

I. Introduction

Accurate identification of contraband and concealed objects is paramount for safety screening at airports, large facilities, and large events. Imaging systems have been of increasing interest due to the benefit of detecting contraband at standoff distances. Several imaging methods have been explored, including optical [1], X-ray [2] and millimeter-wave [3]. Millimeter-wave is especially promising due to its non-ionizing radiation, its high frequency yielding improved resolution, and the ability to propagate without appreciable loss through smoke, fog, clothing and other materials [4]. However, imaging systems can require complex signal processing to classify objects [5], and also have privacy concerns since most imaging systems also capture images of the person's body.

Recently, we introduced a new method for scene classification based on collecting a small subset of the scene information in the Fourier transform domain, or spatial frequency domain, using a dynamic antenna array [6]. Objects with sharp edges produce response that are sharp in angle but broadband in spatial frequency. By implementing a ring-shaped filter with a dynamic antenna array, these features can be measured and used to classify objects in the scene, without ever reconstructing the image itself. The processing requires only a cross-correlation of the signals received by the two antennas in the dynamic array, and a thresholding operation, thereby providing a computationally efficient mechanism for object detection. In addition, the approach does not have the privacy concerns of full imaging systems: not only does the approach not require an image, the collected subset of samples is far less than that needed for full image reconstruction, thus an image cannot be formed from the sampled data.

In this work, we design and implement a 38-GHz two-element dynamic antenna array for detecting contraband hidden beneath clothing. The imaging system is based on a correlation interferometric receiver paired with a set of noise transmitters. The array is dynamically rotated over a 180° angle, producing a ring-shaped filter in the spatial frequency domain. We demonstrate the ability to capture strong spatial frequency responses from a hidden knife-shaped reflecting object.

II. Spatial Frequency Sampling with a Dynamic Antenna Array

The concept is shown in Fig. 1. The dynamic antenna array uses only two receiving antennas separated by a baseline D, the outputs from which are cross-correlated. At a given orientation, the cross-correlation between the antennas produces a sample of the spatial frequency domain information of the scene. The dynamic array is rotated around the centroid of

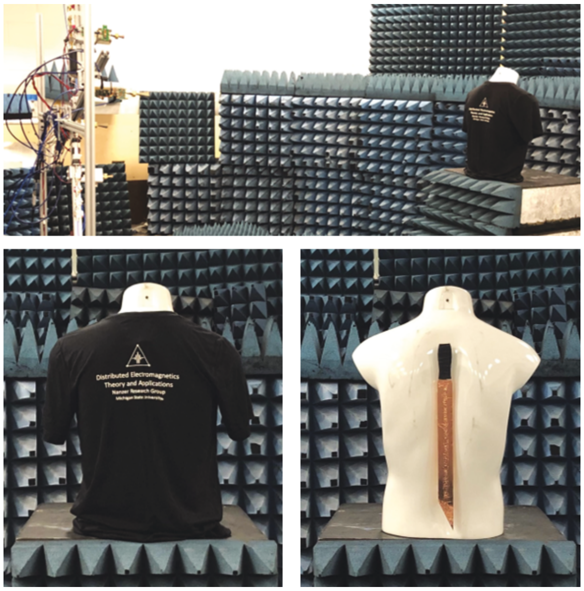

Fig. 2. Top: Measurement setup. Bottom Left: Clothed mannequin torso with knife prop as concealed contraband. Bottom Right: Unclothed mannequin torso showing the position and orientation of the knife prop.

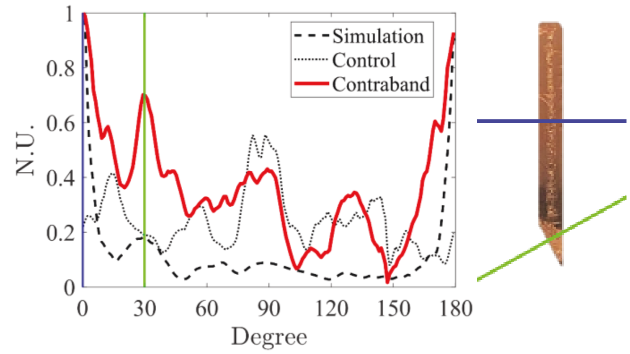

Fig. 3. Experimental results of the spatial frequency samples collected by the rotating dynamic antenna array over a 180° angular span in 1° increments. The strongest responses manifest orthogonally to the largest edges of the object (blue line). The smaller angled knife edge is also visible (green line).

the two antennas, forming a ring-shaped filter in the spatial frequency domain. The sampling function synthesized by the dynamic antenna array's motion can be expressed as

$$S(u,v)=\sum_{k=0}^{K-1}\delta(u-u(k))\delta(v-v(k)), \tag{1}$$

where K is the total number of spatial frequency samples and $u(k)$ and $v(k)$ are the spatial frequency samples acquired at discrete instances of time over an integration time τ such that the total observation time of the dynamic array is $T=\tau K$. The samples are dependent on both the baseline and the angular position, γ, of the dynamic antenna array. Accurate sampling in the spatial frequency domain requires the received signals to be incoherent across space and time [7]. We meet this requirement by transmitting uncorrelated noise from three different transmitters, providing a scattered signal that is spatio-temporally incoherent, but also strong in reflected power, enabling detection with commercial hardware.

III. Experimental Result

The imageless contraband detection system was built with a center frequency of 38 GHz, supporting the use of commercially available hardware and antenna baselines that are electrically large but physically small. Two measurements were conducted in a 7.6 m semi-enclosed arch range (Fig. 2): a control scenario with a mannequin torso wearing a shirt, and the mannequin with a knife prop hidden underneath the shirt. The fabricated knife prop has a physical length of 45 cm from base to tip, width of 3.81 cm, and a tip that has an physically measured angle of 27°. The dynamic antenna array was configured to form a baseline of 76 λ between the two receiving antennas with a total angular span of 180° rotated in 1° increments. The result is shown in Fig. 3 with the control scene scenario in dotted-black and the observation of evident strong responses due to the knife prop of contraband scenario in red. The blue line indicates the location of the response from the knife edge, which manifests orthogonally to the largest physical edge, and which is clearly apparent in both simulation and measurement at 0° or 180°, matching the expected locations of the responses. These are absent in the control measurement, providing a strong feature for detection. Furthermore, the angular position of the two strongest responses form an angle of $\approx$ 29° that matches closely to the angle of the fabricated knife prop's tip (27°). The similarity between the angles of actual sharp edges of the knife prop and the dynamic antenna array measured spatial frequency responses provides additional information to predict the object's possible geometry.

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