Concealed Object Contrast Enhancement Using Radar Methods in a Submillimeter-Wave Active Imager

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***Abstract*—A single-pixel, active, heterodyne submillimeter-wave imager has been developed to detect concealed weapons on persons at standoff ranges of many meters. A major imaging challenge is that a target's reflected power often yields poor contrast of concealed objects because of specular scattering. To address this problem we have adapted high-resolution radar techniques to a 600 GHz active imager and generated three-dimensional through-clothes images of concealed objects with cm-scale resolution.**

I. INTRODUCTION AND BACKGROUND

THE detection of concealed person-borne weapons, explosives, or contraband at long standoff range remains a high priority of the national security community. Submillimeter-wave imaging offers a solution to this problem because low-THz frequencies penetrate clothing and because recent advances in THz technology are enabling the construction of compact high-resolution imagers.

The most mature standoff millimeter- and submillimeter-wave imaging technologies, including those offered commercially [1], rely on passive detection of thermal radiation contrasts over a person's body arising from emissivity differences between skin, clothing, and a hidden object. While often effective, two potential drawbacks of this approach are that the imaging frame-rate for a given SNR is limited by the sensor's fundamental noise floor, and that in some situations the thermal contrast of a hidden object is too small to detect.

Active submillimeter-wave imagers might overcome these challenges because high source powers permit high-SNR detection even for very short integration times, and because a concealed object exhibits different levels of contrast with its surroundings when under active illumination. In this paper we address the issue of contrast and show that active, coherent target illumination can fail to detect concealed objects because of interference from strong specular scattering effects. Instead, we explain how incorporating ultra-high resolution radar capabilities into an active THz imager can eliminate this clutter to reveal hidden objects with high reliability.

II. RESULTS AND DISCUSSION

A detailed description of the Jet Propulsion Laboratory's THz imaging radar has been published elsewhere [2-4]. Briefly, the system employs the frequency-modulated continuous-wave (FMCW) radar technique, transmitting a chirped signal from about 576 to 605 GHz. Digital FFT-based range compression is then done to yield both the magnitude of the target's reflected power and its range. Images are acquired by scanning the focused beam over a target, typically requiring several minutes to capture a torso-sized field of view. Owing to the radar's ultra-broad bandwidth of 29 GHz, as well as its antenna diameter of 40 cm, sub-cm resolution is achieved in three dimensions at 4 m standoff ranges.

Figure 1 shows a THz image of a person with a concealed metallic gun replica held underneath his shirt at 4 m standoff. Although this image was acquired with the JPL THz radar, only the total power received for each pixel is shown – no range information is utilized in the image generation other than a broadband range filter covering about ±1 m in front of and behind the target. The gun is unrecognizable without prior knowledge of its location because there is very little contrast of its backscattering strength compared to its surroundings. In fact, at certain locations on the target (arm, hair, and shoulder), the received signal intensity is much brighter than that from most of the gun. Clutter from the laboratory wall also complicates the image interpretation.

This lack of contrast between a hidden metallic object and clothing or skin might be surprising because THz energy reflects much more strongly from metal than nonconducting materials. For example, Appleby and Wallace [5] report measurements showing that at 600 GHz the reflectivity of skin is slightly under 10%, an order of magnitude (10 dB) smaller than the virtually perfect reflection of THz energy from metal. Yet this is only a fraction of the image's full intensity scale (Figure 1). In fact, the detected signal intensity in Figure 1 varies by more than 40 dB over the person. This huge power diversity swamps any intrinsic contrast in the reflectivity of the target's body, clothing, and the hidden gun, and it is largely a consequence of specular reflection, i.e. variations in the angle of incidence between the beam and target.

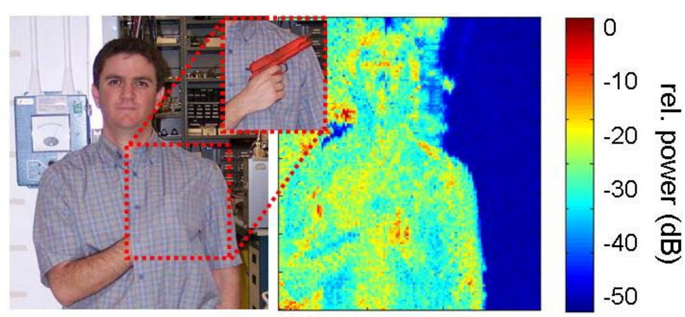

Figure 1: Power-only active THz image of a person with a concealed metallic gun replica.

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Depending on an object's roughness and material, the THz reflectivity measured by a single-pixel transceiver can be extremely sensitive to the beam's angle of incidence with the object. The values cited in [5] were obtained at normal incidence, and to assess the importance of specular effects, we used the 600 GHz radar to quantify the relative reflectivity of some common materials as a function of the angle of incidence. Three materials we measured were a block of unpolished aluminum, a crumpled sheet of aluminum foil, and a leather jacket (to mimic skin). Each of these items exhibits large variations in reflectivity as a function of incidence angle. For example, the signal from aluminum block drops by more than six orders of magnitude within only a few degrees of rotation, reaching levels more than 20 dB below the strongest reflection of the leather surface. The crumpled foil does not have the same sharp dependence at normal incidence, but with a reflectivity variation exceeding 30 dB over 20° of rotation, it can appear either brighter or darker than the leather surface (which itself varies by 20 dB over ±10 degrees) depending on the angle of incidence.

The impact of specular reflection can also be seen in Figure 2, which shows two 600 GHz radar images of a mannequin with a metallic gun replica concealed by a T-shirt. As in Figure 1, these images were obtained at 4 m standoff and represent power only, and for clarity the clutter signals from the laboratory wall and the near-range optics and leakage were filtered out by range gating. In Figure 2a, the gun was carefully positioned for near-normal beam incidence, and it can be clearly identified in the THz image. However, Figure 2b shows an image of the *same target* after it had been rotated by about 20 degrees. With the gun no longer at a normal angle of incidence, it essentially disappears. Any active, coherent THz imager that relies only on power detection must contend with this difficulty of identifying objects whose intrinsic reflectivity contrast may be overwhelmed by the effects of specular reflection.

We have addressed this problem by using the ultra-high range resolution of the THz imaging radar to enhance the contrast of concealed objects on persons. Figure 3 shows three-dimensional scene reconstructions based on the *identical* raw data obtained in the scan of Figure 1. These reconstructions were obtained by selecting, for each pixel of the image, the range-compressed signals corresponding to the "front" and the "back" target surface encountered by the beam. This was done using an adaptive algorithm based on the range returns meeting certain threshold and surface continuity criteria [4]. The result is that the "front" surface in Figure 3a shows a faithful reconstruction of the target's exposed skin and his shirt, while the "back" surface in Figure 3b shows an image clearly revealing the hidden hand and gun.

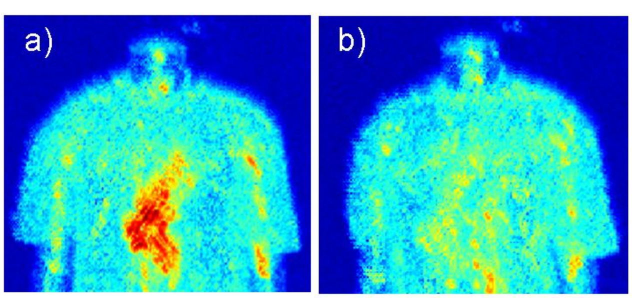

Figure 2. Power-only THz image of a mannequin with a metallic gun replica concealed by a T-shirt. a) Near-normal beam-gun angle of incidence. b) Mannequin rotated ~20° away from normal incidence.

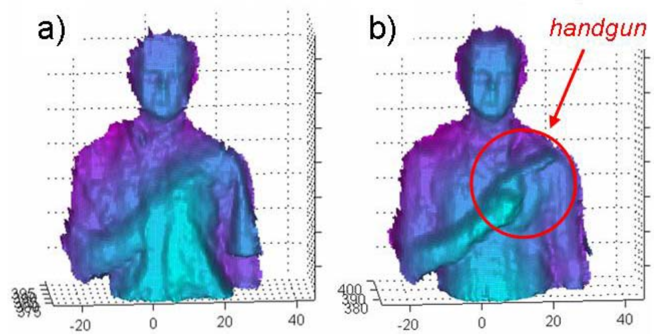

Figure 4: Front-surface (a) and back-surface (b) three-dimensional reconstructions of the scene in Figure 1, obtained by utilizing the ultra-high range resolution THz radar.

Compared to the power-only THz image of Figure 1, the advantage of using ultra-high resolution radar is clear from Figure 4: significant enhancement of concealed objects can be achieved by measuring their three-dimensional shape rather than simply the reflected power. Also, because the radar resolution is inversely proportional to its bandwidth and independent of the standoff range, extending the system's capabilities to tens of meters standoff is feasible as long as the antenna size increases commensurately, and we have made successful through-clothes radar images at 25 m standoff [4]. Besides long range operation, a more serious challenge to the active THz radar for real-world security applications is its slow imaging time. To achieve near-video frame rates for this system, a more complex and costly multi-pixel active scanning array will likely be needed.

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