Applications of superconducting bolometers in security imaging

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Abstract. Millimeter-wave (MMW) imaging systems are currently undergoing deployment World-wide for airport security screening applications. Security screening through MMW imaging is facilitated by the relatively good transmission of these wavelengths through common clothing materials. Given the long wavelength of operation (frequencies between 20 GHz to \(~100\) GHz, corresponding to wavelengths between 1.5 cm and 3 mm), existing systems are suited for close-range imaging only due to substantial diffraction effects associated with practical aperture diameters. The present and arising security challenges call for systems that are capable of imaging concealed threat items at stand-off ranges beyond 5 meters at near video frame rates, requiring substantial increase in operating frequency in order to achieve useful spatial resolution. The construction of such imaging systems operating at several hundred GHz has been hindered by the lack of submm-wave low-noise amplifiers. In this paper we summarize our efforts in developing a submm-wave video camera which utilizes cryogenic antenna-coupled microbolometers as detectors. Whilst superconducting detectors impose the use of a cryogenic system, we argue that the resulting back-end complexity increase is a favorable trade-off compared to complex and expensive room temperature submm-wave LNAs both in performance and system cost.

1. Introduction

1.1. Contrast mechanism for concealed object imaging

Electromagnetic radiation in the frequency range from 30 GHz to 300 GHz is commonly referred as millimetre-wave radiation (1 mm \(\leq \lambda \leq 10\) mm), and is followed in frequency by the submillimetre-wave region, commonly defined to span the frequencies from 300 GHz to 3 THz. In addition, the overlapping region up to 30 THz has been termed as the "Terahertz" frequency range. Leaving the naming conventions aside, the frequency range between 300 GHz to 3 THz represents a cross-over from "electronics" to "photonics": Many common simplifications and approximations used by both communities often break down at this wavelength range. It can also be considered as one of the least exploited regions of the EM spectrum, primarily due to i) lack of affordable detectors ii) limited atmospheric transmission due to water vapour attenuation and iii) relative immaturity of engineering design tools.

The applications of passive MMW imaging to security screening applications has been well known for a long time \([1, 2, 3, 4, 5]\). The principle of the application is simple: common clothing
materials are rather transmissive up to about $\sim 1$ THz; In passive imaging the contrast is formed between the background (the human body) and the object through the radiometrically different brightness temperature of the object. The brightness temperature of the object, $T_{\text{obj}}$, is a function of its emissivity $e$, physical temperature $T_{\text{obj},p}$ and radiometric temperature of the surroundings $T_S$ through $T_{\text{obj}} = T_S(1-e) + T_{\text{obj},p}$. In the most extreme case of a perfect reflector (a case for most metals up to $\sim 500$ GHz), $e = 0$ and $T_{\text{obj}} = T_S$. Thus, the radiometric contrast in this case is the difference of the radiometric temperature of the human body $T_H$(close to 290 K at frequencies above 300 GHz) and that of the surroundings, $\Delta T = T_S - T_H$. The associated signal power over a pre-detection bandwidth of $\Delta \nu_{RF}$, the associated signal power is $P_{\text{sig}} = M k_B \Delta \nu_{RF}$ where $M$ is the number of modes detected (typically associated with the polarization modes of $M = 1$ for single polarization and $M = 2$ for dual polarization; Larger number of modes are possible, but only for non-diffraction limited imaging systems).

1.2. Figures of Merit
The principal figures of merit for a passive imaging system are

- Radiometric resolution, defined by the Noise-equivalent Temperature Difference (NETD)
- Spatial or angular resolution
- Temporal resolution
- [spectral resolution]

1.2.1. Radiometric resolution (NETD) The Noise Equivalent Power (NEP) of a detector relates to post-detection signal-to-noise ratio as $\text{SNR} = P_{\text{sig}} \left(\frac{\text{NEP}_{\text{sys}} \Delta f_{\text{ENBW}}}{\text{ENBW}}\right)^{-1}$, where $\Delta f_{\text{ENBW}}$ is the post-detection effective noise bandwidth for data collection in a single pixel in the image.

The Noise Equivalent Temperature Difference (NETD) of a passive MMW imaging system is given by the radiometer equation Eq. 1, where $T_A$ is the antenna temperature (the radiation temperature of the pixel being viewed), $T_R$ is the receiver noise temperature, and $\Delta \nu_{RF}$ is the radiometric bandwidth [6]. Often mechanical scanning of $N_i$ image pixels with $N_{\text{rec}}$ receivers is utilized which reduces the per-pixel dwell time and increases $\Delta f_{\text{ENBW}} \propto N_i/N_{\text{rec}}$. This leads to trade offs in systems designs between the number of receiver channels in the focal plane array, the field of view (FOV), the noise and the image update frame rate.

$$\text{NETD}_{\text{sys}} = (T_A + T_R) \sqrt{\frac{\Delta f_{\text{ENBW}}}{\Delta \nu_{RF}}} = \frac{\text{NEP}_{\text{sys}} \sqrt{\Delta f_{\text{ENBW}}}}{k_B \Delta \nu_{RF}}$$

(1)

1.2.2. Angular (or spatial) resolution The angular resolution $\Delta \theta$, in a passive MMW image is set by the diffraction limit associated with the size of the primary optics aperture $D$, this being given by $\Delta \theta \sim \lambda/D$ where $\lambda$ is the radiation wavelength. The corresponding spatial resolution at the object space, located at a distance $R_o$ from the entrance aperture is $d = 2 R_o \tan \Delta \theta/2 \sim R_o \Delta \theta = \lambda R_o / D$. Since the volume of an imaging optic is typically $\propto D^3$ (due to image forming optical system design considerations), it is clear that decreasing the wavelength improves angular resolution (for a given maximum aperture diameter).

1.2.3. Temporal resolution The temporal resolution of a camera is given by the maximum frame rate attainable with the system. In most cases, the temporal resolution is limited by two factors

i) The required dwell-time per pixel for a required SNR; better NEP enables lower dwell time; and
ii) Optomechanical considerations associated with the fact that most MMW and SMMW imaging systems employ optomechanical scanning. The wavelength (which is $\sim 1000$ times larger than that corresponding to optical wavelengths often leads to relatively large scanning apparatus.

For stand-off imaging applications, a frame rate in excess of 10 frames/second is required.
2. Overview of the superconducting imager

2.1. Systems engineering challenge

The relatively novel cryogenic approach to the stand-off security screening challenge is subject to common prejudices: People generally do not want to mess with cryogenics, unless there isn't a room-temperature option available. Obviously, this should be clear to anyone attempting to design demonstrators for any application. Nevertheless, the successful application of our technology is very much connected with the unglorious job of good cryogenics system design. It is worthwhile to note that this challenge is common to any other groups developing cryogenic devices for wide-spread use (not including e.g. astrophysical instrumentation, which are typically one-off instruments). As examples of pioneering deployment one could mention such systems as the Elekta-Neuromag Magnetoencephalography systems [7], the D-Wave Systems Inc.'s Quantum Computing Systems [8] and Hypres Inc.'s Primary Voltage Standard Systems [9].

Closed-cycle cryocooler technology is in many ways the most important application enabler. Unfortunately most commercially available 4 K cryocoolers fall within the realm of general-purpose laboratory instruments that are not application specifically fine-tuned. This is understandable given the economics of undertaking such optimization tasks.

The overarching goals of our cryogenics systems design have been the following:

- low power consumption
- > 1 year maintenance interval
- field-serviceability
- low cost of operation
- automation
- robustness to environmental conditions

Superconducting sensor physics aside, we emphasize that the successful demonstration of a system such as ours is a complex undertaking, requiring good understanding of multiple disciplines, including cryogenics, low noise electronics, optical systems, mechanical engineering, signal conditioning, user interface, microfabrication and reliability analysis.

To date, we have built, tested and demonstrated one system, based on a linear array of 64 antenna-coupled microbolometers. At the time of writing, an optimized high-resolution system is undergoing trials, while a third one, designed for multi-frequency ("colour") imaging is being designed. For brevity, we shall address these systems as "1st generation", "2nd generation" and "3rd generation systems" in the following text. The overall architecture of all three is similar, but the evolutionary step from the 1st generation system to the 2nd one has been a substantial one. In the following, we will first describe the various components of the systems, highlighting the differences between each one where relevant, show measured performance and finally some images from videos acquired with the 1st generation system. We also refer the reader to numerous prior articles regarding the system [10, 11, 12, 13].

2.2. Antenna-coupled superconducting microbolometers

2.2.1. Theory The bolometers used in our systems are closely related to other antenna-coupled bolometers, such as superconducting HEB mixers [14, 15] as well as earlier room-temperature antenna-coupled microbolometers [16, 17]. The operation of our detectors can be accurately modeled using same methodology employed in the aforementioned devices by first writing the 1-D heat equation which describes the (one-dimensional) heat-flow across the suspended bridge which is thermally shunted at its ends which are connected to the antenna terminals:
dielectric links, \( n \) close to 15 K, our goal is to have high-resistivity NbN with a 

\[ \kappa \frac{dT}{dx^2} + \frac{P_{\text{sig}}}{A l_n} + \frac{V^2}{\rho l_n^2} = 0, |x| < l_n \]

\[ \kappa \frac{dT}{dx^2} = 0, l_n < |x| \leq l, \]

where \( \kappa \) and \( \rho \) are the thermal conductivity and electrical resistivity of the bridge, \( A \) its cross-sectional area, \( l \) its total length and \( l_n \) the length of the normal state hotspot at its centre. Enforcing the boundary conditions that \( dT/dx |_{x=0} = 0 \) and \( T(x = l/2) = T_0 \) yields a solution for the bridge electrical current, assuming an infinitesimally small width of the superconductor-normal state transition

\[ I = \frac{V}{R_n} \left\{ 1 + \frac{2}{(p_o + p_e - 1) + \sqrt{(p_o + p_e + 1)^2 - 4p_o}} \right\} \]

where \( R_n = R_{n0} (1 + \alpha V^2 / R_{n0} G) \) is the normal-state resistance which includes a small positive temperature coefficient of resistance \( \alpha \) in the normal state, \( p_o = P_{\text{sig}} / P_{\text{sat}} \) is the normalized optical power with \( P_{\text{sig}} \) the incident THz power and \( P_{\text{sat}} = G(T_c - T_{\text{bath}}) \) the saturation power. The normalized electrical power is \( p_e = V^2 / (R_n P_{\text{sat}}) \). In the limit \( p_o \ll 1 \) the expression for the I-V reduces to the form in ref. [18] \( I = V/R_n + P_{\text{sat}}/V \). A set of \( I-V \) curves are shown in Fig. 1.

The noise of bolometers arises from several different sources. Of these, the so-called thermal fluctuation noise (or phonon noise) which arises from spontaneous energy fluctuations between the thermally isolated element and the heat bath (somewhat analoguously to Johnson noise generated in a resistor) gives the fundamental limit to performance. To first order, the NEP of a bolometer is given by

\[ \text{NEP}_{\text{tot}} = \text{NEP}_{\text{TFN}}^2 + \text{NEP}_{\text{amp}}^2 + \text{NEP}_{\text{excess}}^2, \]

where thermal fluctuation noise \( \text{NEP}_{\text{TFN}} \approx \sqrt{4k_B T^2 G_{th}} \). The other noise terms, Johnson noise present in a resistive thermometer, \( \text{NEP}_{\text{J}} \), read-out preamplifier, \( \text{NEP}_{\text{amp}} \) and excess noise due to EMI pick-up, heat bath temperature fluctuation etc., \( \text{NEP}_{\text{excess}} \) are often of significance, but can be made small with good bolometer design. Thus, the TFN of the bolometer becomes the limiting noise term. The \( \text{NEP}_{\text{TFN}} \) of a bolometer is a strong function of the bolometer temperature: Thermal conductivity (and thus thermal conductance \( G_{th} \)) is proportional to \( T^n \), with \( 1 < n < 3 \), depending on the material system. In metallic thermal links \( n \approx 1 \) whereas for dielectric links, \( n \approx 3 \). Thus, the \( \text{NEP}_{\text{TFN}} \) of a bolometer scales with temperature as \( T^{3/2} \) to \( T^{5/2} \).

The strong temperature dependence implies that bolometers gain in performance enormously from refrigeration.

2.2.2. Device fabrication

Niobium nitride (NbN) has been used as our bolometer material at VTT. Unlike in the HEB mixers, where it is desirable to fabricate good quality films with a \( T_c \) close to 15 K, our goal is to have high-resistivity NbN with a \( T_c \) not much above that of Nb (9 K). High resistivity is desirable from the standpoint of impedance matching the bridge to the lithographic antenna, and it also helps improving the thermal resistance between the bridge and the heat sink. Furthermore, the use of NbN allows for the tuning of the critical temperature, given that the \( \text{NEP} \propto T_c^{3/2} \), and thus a higher critical temperature would possibly erase any performance gained by improved matching. Fortunately, growing poor quality NbN is not a problem!
The bolometers have been fabricated at VTT’s microfabrication facility in Espoo, Finland. The goal has been to develop a fabrication process that provides excellent detector yield and device parameter uniformity. A reliable release step of the NbN bridge from the Si substrate that does not destroy the superconductivity properties of the NbN has been developed. The NbN film is deposited cold by reactive RF sputtering on an PECVD grown SiO$_2$ layer (thickness $\sim$ 100 nm) atop a 100 mm diameter (and more recently, 150 mm diameter) 500 microns thick high resistivity Si wafer, followed by the antenna metal layer (Al) with a thickness of $\sim$ 250 nm.

The Al layer is patterned first by wet etching which removes the overlaying Al from the bridge region, followed by the patterning of the NbN to form the antenna and the bolometer bridge. The final patterning step opens etch windows to the SiO$_2$ adjacent to the bridge. While the NbN is protected by the photoresist from the top (and by the SiO$_2$ from the bottom), an SF$_6$ plasma etch at high pressure (for maximizing the etch isotropy) is performed on the now exposed Si. Undercutting of the Si releases the thin NbN bridge from the substrate. Finally, a RIE plasma etch in an O$_2$ atmosphere is done to remove the photoresist. An optical micrograph of a fabricated device is shown in the inset of Fig. 1.

Our 1st generation system employed a modular approach where the detectors were diced to 8-pixel chips measuring $\sim$ 24 mm by $\sim$ 5 mm, and placed in to machined copper modules that provided electrical connections to each pixel and also accurately centered 2 mm diameter hr-Si substrate lenses to the back-side of each detector.

The 2nd generation system will incorporate practically identical detectors as were used in the 1st generation system. The only major change is the doubling of total pixel count: As is discussed below, we needed to increase the sampling of the FOV in the 2nd generation system. This will be effectively accomplished by a) doubling our detector channel count from 64 to 128, and b) decreasing the FOV of the system by half, to about 7.5° (H) $\times$ 3.75° (V). The overall size of the FPA will remain essentially unchanged from the 1st generation system, with an FPA length of about 20 cm. Doubling the channel count is (contrary to many room temperature technologies) a relatively straightforward task, given the low cost of our detector technology.

2.3. Readout electronics

Interrogating small current signals from low-impedance cryogenic detectors without adding noise in the process is not a trivial task. To achieve this, we utilize a previously reported room temperature readout (Thermo-Electrical Readout Amplifier, TERA) whose principle and operating characteristics are summarised in prior article [19]. The readout can be used to amplify signals for bolometers operating above 1 K. Due to the electro-thermal feedback within the bolometer [20, 21], the dynamic impedance of a bolometer can be noise matched to a room temperature readout amplifier with noise temperature of few Kelvins. To achieve stable operation at the bias point, external negative feedback is utilized to provide voltage biasing at large bandwidth above the thermal bandwidth of the bolometer. The readout circuit is shown in

Figure 1. A set of eight I-V curves from a 1st generation system chip. The dashed line indicates a fit with the theoretical curve, given by Eq. 3. In operation, the detectors are biased at the "bottom" of the I−V curve. Inset shows a micrograph of a single detector.
The bolometer, depicted by the admittance $Y$ in Fig. 2, is connected to a bias circuit consisting of a cryogenic high frequency shunt (with a shunt resistance $R_x$ and a shunt capacitance $C_x$, total impedance $Z_x$) which stabilizes the feedback circuit at high frequencies through dominant pole compensation. In our 1st generation system, the amplifier with an open loop gain $A(\omega)$ was an Interfet IF3602 whose noise temperature $T_A = 4.7$ K and an optimum source impedance of $R_{\text{opt}} = 3.3$ k$\Omega$, which is close to the dynamic impedance $Z_d = dV/dI$ of the bolometer at the current minimum point of the $I$-$V$ curve. In the subsequent 2nd and 3rd generation systems the FET has been replaced with a regular operational amplifier. The primary drivers for this replacement was the cost of the highly specialized FET, and also its inherent temperature instability.

A feedback resistor with a conductance $G_{\text{fb}}$ is located at 4 K. The amplifier noise is characterized by $S_{i,A} = 2k_B T_A / R_{\text{opt}}$ current noise and $S_{u,A} = 2k_B T_A R_{\text{opt}} (1 + f_c/f)$ voltage noise where $f_c$ is the $1/f$ noise corner frequency. In addition, the high frequency shunt and the feedback resistor add current noise contributions $S_{i,x} = 4k_B T_0 / Z_x$ and $S_{i,fb} = 4k_B T_0 / R_{\text{fb}}$, but these terms are small. Thus, the amplifier adds a noise current given by $S_{u,A} Y_{\text{tot}}^2$, where $Y_{\text{tot}} = (dI/dV + Z_x^{-1} + R_{\text{fb}}^{-1})$ is the total admittance of the circuit. At post-detection frequencies above the $1/f$ noise knee and at the current minimum point of the bolometer $I$-$V$ curve, the noise of the amplifier is smaller than the noise intrinsic to the bolometer.

Apart from reverting from the use of the FETs to Op-amps, another improvement is related to our data-acquisition subsystem. The 1st generation imager used a separate stack of National Instruments 6259-series 16bit multichannel ADC’s (2 x 32 channels). The addition of another 64 channels for the 2nd generation system would have required another set of two cards, furthermore increasing the electronics cost, and more importantly, requiring a dedicated PC for running the cards. The new system has incorporated 16-channel ADC and DAC converters integrated on the same PCB housing the read-out electronics for 16 channels (see Fig. 3. The AD conversion takes place at sample rates up to 5 MS/s. The converters in turn communicate with an on-board ARM microprocessor which handles the commands from higher system level, and carries out some basic signal processing tasks. Each of the total of 8 boards then communicate via an USB driver with a "house-keeping" computer, where tasks such as synchronization, systems monitoring and data formatting takes place. A special feature of the system is that it provides an IP camera video stream that is AES-256 encrypted, thus providing a highly secure data communications for client systems.
2.4. Cryogenic subsystem

The cryogenic vessel of the system reported in [12] consisted of a co-axial cryostat with a stainless-steel vacuum can, housing two concentric sets of heat-exchangers and radiation shields surrounding a commercial pulse tube cryocooler. A set of 8-pixel antenna-coupled microbolometer modules (8 in total) were mounted on the 2nd stage heat-exchanger of the cryocooler.

The initial choice for a pulse tube was based primarily on a) their long maintenance-free life time (in excess of 15 000 hours) and b) the availability of an external valve unit for the cooler head, which simplifies the ground isolation of the cryocooler from the rest of the system. However, the wall-plug efficiency of pulse tubes is worse than that of many other types of cryocoolers, necessitating the use of a larger compressor. The type of pulse tube used in the 1st generation system is coupled to a single-phase 2.3 kW compressor. This requires the use of mains lines (240 V) with 32 A fusing which is not as common place as the regular 16 A fusing used for regular house-hold appliances (for 240 V mains, i.e. European standard).

Figure 4. A schematic of the 2nd generation camera data-aquisition subsystem

The 2nd generation system design started thus from our baseline goal to develop a system that can be run off 16 A mains lines, with sufficiently long maintenance-free lifetime. The best option proved to be the Sumitomo RDK-101-series, which is one of the smallest 4K cryocooler units available commercially. This cooler operates with a slightly different principle (so called "Gifford-McMahon" architecture), and involves moving mechanical parts at the cold-head that need more frequent servicing that the pulse tube which does not have any moving parts at the cold head. However, even the RDK-101 can be field-serviced.

The other major difference between the PT and the GM cooler is the available cooling capacity: The Cryomech PT403-series is certified for approximately 10 W and 0.25 W cooling power at the 1st (@ 65 K) and 2nd stages (4 K), respectively. The numbers in comparison for the GM are 2 W and 0.1 W, i.e. considerably smaller cooling power is available. Despite this, the smaller cooling capacity of the GM is sufficient, while leaving

Figure 5. The 2nd generation imager cryogenic front-end.
Another topic that has been carefully designed is the overall vacuum compatibility of the components that go into the cryostat: our aim is to end up with a system that is virtually maintenance-free (with the exception of the cryocooler) and which does not require constant vacuum-pumping in order to avoid slow cryopumping of contaminants on the cold surfaces of the cryocooler.

Recently completed tests on the 2nd generation cryocooler show that the system is performing better than anticipated: The 2nd stage base temperature is 4.0 K, while the 1st stage heat exchanger reaches a base temperature of $\sim$ 60 K. This performance can be considered rather satisfactory, given that the system incorporates in excess of 400 wires from room temperature to base temperature and houses a sizeable ($\sim$ 20 cm long) cold finger, and a large window, while the cryocooler provides only an estimated heat lift of 70-80 mW of cooling power at 4 K.

2.5. Optics subsystem

The primary parameters specifying the design of the optical subsystem are i) Stand-off distance ii) Field-of-View (FOV) iii) Angular resolution and iv) system footprint.

Given that we desire to operate over a multi-octave THz bandwidth, the 2nd generation system will employ reflective optics which are essentially frequency-independent in their operation. A detailed description of the optics of the 1st generation system can be found in [13]. Since we use a linear array of detectors, scanning is required in order to build a 2-dimensional image. Our choice has been conical scanning, in which each detector beam is scanned in a circular pattern across the field of view. This results to $N$ overlapping circles with $N$ the number of channels in the linear array. A software interpolation algorithm is used to map a 2-dimensional image.

A key issue we wanted to change from the 1st generation camera was the fact that the wide field of view (15° (H) 7.5° (V)) was conically scanned with a relatively small number of detector channels (64). This caused rather severe undersampling of the FOV,
resulting (after image interpolation) to a spatial resolution of $\sim 4$ cm at a distance of 5 meters, far more than the diffraction limit of optics with aperture diameter of about 50 cm. Another issue that was deemed desirable was to revert to an off-axis telescope design, as the 1st generation optics incorporated a relatively large bending mirror which resulted to an estimated loss of efficiency by $\sim 30\%$ through vignetting [22]. Lastly, a desire to decrease the overall optics footprint was present, in order to reduce the overall system volume. A similar periscopic conical scanner as was employed in the 1st generation system will be used also in the new camera [13].

The optics has been designed and optimized using Zemax with comparisons of the Zemax physical optics package with a vector field simulator, GRASP8. The primary and secondary mirrors are both aspherics to control off-axis aberrations. The primary has a diameter of $\sim 530$ mm.

As mentioned before the FOV of the system will be $3.75^\circ \times (H) 7.5^\circ$ (V), (corresponding to a FOV of $2\,\text{m} \times 1\,\text{m}$ at the target distance of 5 meters) with a magnification of 5:1. The simulated diameter of the system point spread function (PSF) is $13\,\text{mm}$ at 400 GHz. This can be compared with recent measurements shown in Fig. 7, which indicates a closely matched focus distance of $\sim 5\,\text{m}$, but a PSF width that is about twice the simulated one. The cause behind the discrepancy between the simulated and measured results is currently under investigation, and could be due to alignment errors of the mirrors.

The overall efficiency of the optics (neglecting the scanner efficiency) is predicted to be $> 85\%$.

3. Imagery
To date, we have acquired near real-time videos with the 1st generation system. Some examples of these are shown in Fig. 8. The 2nd generation system will improve the spatial resolution of the imagery by at least twofold.

4. Conclusions
In this paper we have reported on our results on two passive SMMW imaging systems, both of which employ superconducting detector arrays. The importance of building easy-to-use, automated cryogenic systems should be emphasized. Cryogenic detectors outperform the current state-of-the-art in room temperature SMMW radiometers for this application. Our future efforts are focused on testing all of the various subsystems of the 2nd generation system, and also in starting the construction of the 3rd generation "colour" imager, which may improve discrimination between threat objects and innocuous items.

Acknowledgments
The authors acknowledge the support of EU FP7 security research project "Integrated Mobile Security Kit", TEKES, the Finnish Funding Agency for Technology and Innovation (funding decision 40246/10), and the European Space Agency (Contract No. 22905/09/NL/JD).

Figure 8. Three frames from a passive THz video with a concealed metal hand gun. (Top) Gun underneath jacket; (middle) jacket opened; (bottom) Backside, with a wallet in jeans’ back pocket. Distance to target is 5 meters at 6 fps.
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