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Construction and evaluation of the terahertz human phantom

***Abstract**. We report on construction and evaluation of a moving wirelessly-controlled thermal phantom for testing cameras working in the terahertz range (0.1-3.0THz). A terahertz camera operating at 0.25 THz and a standard thermal camera were used for tests. We compared the images taken for the phantom and a man and we obtained satisfactory similarities both for naked as well as dressed objects with hidden items (guns, knives, bombs). The temperature stability of the phantom is also sufficient for evaluation of the cameras.*

***Streszczenie.** Przedstawiono konstrukcję i badania ruchomego zdalnie sterowanego fantomu termalnego człowieka opracowanego do testów kamer terahercowych (0,1-3,0THz). Do testów użyto kamery terahercowej pracującej w zakresie 0,25THz i kamery termalnej. Uzyskano bardzo dobre podobieństwo pomiędzy obrazami w zakresie THz dla człowieka oraz fantomu oraz satysfakcjonującą stabilność termalną fantomu. (**Konstrukcja i badania fantomu w zakresie teraherzowym**)*

Keywords: terahertz radiation, terahertz camera, terahertz phantom, thermal camera.
Słowa kluczowe: promieniowanie terahercowe, kamera terahercowa, fantom termalny, kamera termalna.

Introduction

The law enforcement agencies are currently faced with the problem of countering the terrorism-related threats. Of particular interests are improvised explosive devices and weapon hidden beneath the clothing. Therefore, many research and development institutions are looking for safe and accurate stand-off technologies. Electromagnetic waves at terahertz frequencies (0.1-3.0 THz) seem to be a promising candidate for this purpose. Development and implementation of terahertz technology in security area is connected with unique features of terahertz radiation. Many explosives, e.g. Hexogen (RDX), Penthryte (PETN), and Octogen (HMX) have characteristic transmission and reflection features in the THz range [1, 2] that could help distinguish them from other common materials like clothes, human skin or metal materials. Moreover, THz electromagnetic radiation can be transmitted through clothes with small attenuation [3] and is strongly reflected by metallic objects like knives or guns [4]. THz waves pose minimal health risk to human beings or the system's operation because photon energy is very small (4.4 meV @ 1THz) [4]. The main factor that limits propagation through air is strong molecular absorption by water vapour [1, 4]. The above mentioned features cause that THz radiation can be applied in two security-orientated areas: explosives detection [2, 5] and people screening [6-9].

As far as second application is concerned, first portals [10,11] and cameras [12,13] for people screening, both passive and active, working mainly in the 0.1-0.3 THz range can be found on the market and simultaneously they still atract attention of many research groups, what results in many projects and papers [14-17]. Pure passive systems working in this wave region can detect hidden on persons objects thanks to difference in naturally emitted power between human body and the objects. Human skin emits more power than hidden items because its radiometric temperature is usually higher than the radiometric temperature of the items [18]. Moreover, emissivity of human skin, which consists of 70% of water, is usually different than emissivity of hidden dangerous metallic or dielectric materials. The combination of these two features connected with high transmission of ordinary clothes would enable a camera to look through clothes and find hidden objects like weapons, bombs etc. [6-17].

Testing of such cameras usually requires some persons carrying hidden guns, bombs or knives. Such persons can have different clothes or body temperature, what makes the measurements ambiguous. To avoid the time-consuming, tedious and expensive testing on human subjects we built a moving platform with the human phantom, which mimics a moving human being. The phantom consists of a polystyrene manikin which is covered with a number of small pipes with water. Pipes were next coated with a silicone "skin". The veins (pipes) are filled with heated water to obtain the same temperature as human body. The phantom is made of non-metallic materials and is placed on a moving wirelessly-controlled platform with four wheels.

According to our best knowledge, it is a first attempt to manufacture such a phantom for the THz range, although similar tests are commonly used in the infrared range with good results [19].

The phantom was tested by means of thermal and terahertz cameras. The similarities between images for a person and the phantom dressed in various sets of clothes are sufficient for the considered applications. Temperature stability of the phantom was also analysed in time with satisfactory results.

Construction of the terahertz phantom

It is commonly known that a naked human body is not uniformly heated, but its temperature varies in the range about 29-36^{o}C depending on the person age, fatness, health conditions and many other factors. Therefore, the phantom was not designed to have homogeneous temperature on the whole surface but we assumed some range in which the temperature can varies. The naked body is not so important in normal operation of screening cameras and we assumed that the person (and the phantom) should be at least partially dressed. In this case the temperature on some places of a person can decrease down to about 25^{o}C and even lower depending on number and kind of clothes layers.

Due to the fact that we planned to use a flat moving platform, application of the phantom with normal length of legs could have caused a lot of problems connected with mechanical stability of the system. Hence, it was decided to replace lower parts of the legs with a box for a temperature controller.

During design of the phantom we took into account the human body, whose skin consists of many veins filled up with circulating heated blood. The veins, through the arteries, are connected with the heart, which pump the blood into all parts of the body. In practice, it is hard to mimic such a complicated structure, but for the testing of cameras, we built a substitute, which in our opinion fulfill the requirements.

The phantom is made of non-metallic materials and can be heated up to 36°C in some points to obtain the same temperature as human body. It is placed on the moving wirelessly-controlled platform with four wheels (Fig. 1). The phantom can be dressed with a set of ordinary clothes and can be equipped with some dangerous (e.g. guns, bombs) and non-dangerous (e.g. wallet) items. The phantom is wirelessly controlled (movement and temperature) from a personal computer by means of a LabView based software.

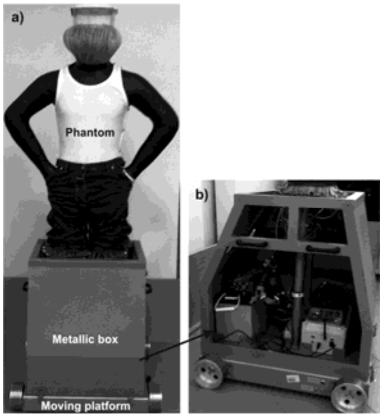

Fig.1. Photo of the terahertz human phantom (a) with the moving platform and the metallic box (b)

The skeleton of the phantom consists of a 110-cm long polystyrene manikin (Fig. 2a) which was vertically covered with 150 plastic pipes with internal and external diameter of 4mm and 5mm, respectively (Fig. 2b). The distance between the pipes is not longer than 3 mm to avoid inhomogeneities in heat transfer.

The pipes glued to the manikin were next coated with a silicone resin (Fig. 2c), which was chosen experimentally taking into account good thermal conductivity and maximum emissivity. The developed phantom is light and quite fragile. To increase its stiffness, especially during start and brake of the platform, when the relatively tall phantom is susceptible to deflection, we inserted a long plastic rod into each leg of the manikin. The weight of the skeleton with pipes and the silicone resin "skin" is about 5 kilos.

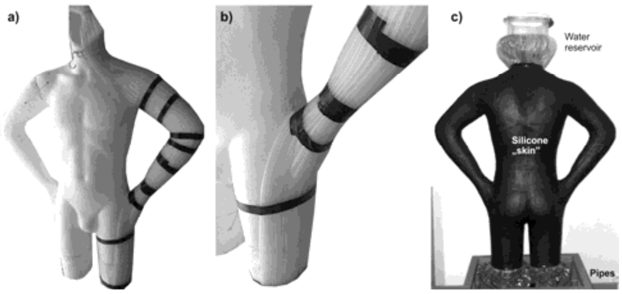

Fig.2. Terahertz Phantom of human body: the polystyrene manikin partially covered with pipes (a, b), ready-to-use phantom (c)

As expected, we observed temperature differences between the upward and downward water streams thanks to heat transfer mainly to the silicone skin. Therefore, to minimize this phenomenon we applied a complicated arrangements of pipes (Fig. 3).

The upper ends of the pipes are connected to a water reservoir (a head of the phantom), while the lower ends of the pipes through a set of pipes with wider diameters (rings: I-V) reach inlet and outlet arteries (Fig. 3b). We determined experimentally, that water from the inlet artery should be directed upward through the 80% of pipes to the reservoir. Only 20% of pipes is exploited to direct water gravitationally from the reservoir downward. For each leg, we applied four upward rings (Fig. 3b, solid line, no. I, II, IV, V) and one downward ring (dashed line, no. III). We grouped the smallest pipes which leave the rings into sections (Fig. 3b). Each section consists of the downward pipe (colder, dashed line), which is surrounded by a few upward pipes (hotter, solid lines). Thanks to such arrangement, the surface should be uniformly heated.

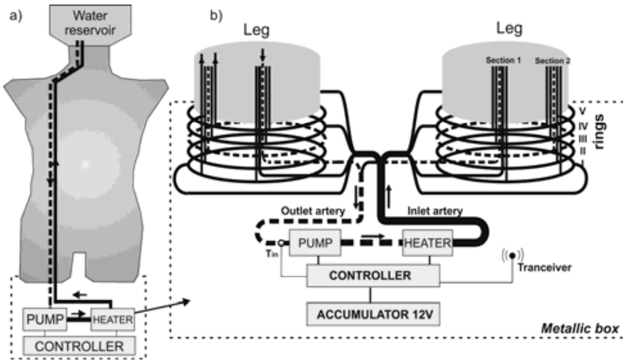

Fig.3. The terahertz phantom of human body: a scheme (a) and the detailed layout of upward and downward pipes (b)

A pump (from *Bühler Motor* company), which is situated in the lower part of the phantom in a metallic box, sucks the heated water from the outlet artery and pumps it through a 300W heater, the inlet artery and the pipes to the water reservoir (Fig. 3). Next, the water from the reservoir comes back through the pipes and the outlet artery to the pump.

We applied the DS18B20 digital thermometer (T_{in}) situated in the end of the outlet artery, which provides 9-bit Celsius temperature measurements, to control and stabilize the temperature of the liquid. The position of the thermometer was chosen experimentally.

The 12VDC accumulator with 100Ah capacity supplies the controller, which next controls the pump, the heater and the thermometer. The controller with a 433 MHz transceiver is wirelessly monitored by the LabView-based software. The software reads the temperature from the thermometer and compares it to the set value. If the temperature (T_{in}) rises above or falls down below the limit, the controller switches the heater off or on, respectively. T_{in} can be adjusted in the range up to 33°C, what results in maximum temperature about 37°C on the naked body of the phantom. We usually tested the phantom with T_{in}=31°C what results in maximum similarity to persons.

The flat moving wirelessly-controlled platform (Fig. 1) with four wheels provides the required maneuverability and load up to 100 kg. Thanks to 4 independent DC motors, this robot can operate on flat surfaces and can go forward and backward with speed up to 400 mm/s as well as turn and rotate. The platform is equipped with a set of flat 12 VDC/7.2Ah accumulators to feed the platform, a controller with a 868MHz radio transceiver, and a set of 4 ultrasonic sensors to localize the platform and to avoid collision with obstacles. For normal operation, the platform is placed inside an enclosure (7x5m) made of 40 cm high walls to ensure proper conditions for the ultrasonic sensors.

The moving phantom is independently fed from the internal accumulators and is wirelessly controlled from a PC, which is situated nearby. The LabView-based software can be used for remote control of movement.

The phantom with the metallic box installed on the moving phantom is 185 cm high and its weight is equal to about 70 kg including about 5 litres of water.

The phantom is equipped with a set of ordinary clothes (made mainly of cotton and other popular materials): boxer shorts, vests, T-shirts, trousers, shirts, sweaters, jackets, dresses and belts (Fig. 4a). We purchased some fake weapons (small and regular pistols, a revolver, knives etc.) with necessary holsters (Fig. 4b). Moreover, we prepared five imitations of Body Borne Improvised Explosive Devices (BBIED) - metallic and non-metallic items, that can be hidden under the clothes and can mimics the original bombs (Fig. 4c).

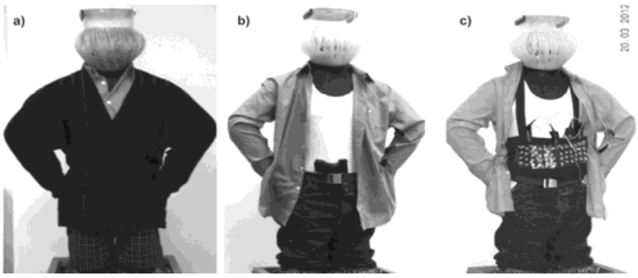

Fig.4. Photos of the ready-to-use moving platform. The phantom dressed with: clothes (a) gun (c) and BBIED (c)

Measurement arrangement and results

The phantom should be seen in the THz range similarly to man to prove usefulness for testing. Having this in mind, we compared the THz images taken for phantom and a man (height: 190cm, weight: 90 kg). During tests both targets (the phantom and the person) were naked as well as dressed with an ordinary cotton shirt and a sweater. Since the THz image is rather blurred, we also measured both objects by means of a thermal camera to see temperature distributions and temperature stability in time.

For the thermal tests we applied the VIGOcam v50 from VIGO. This thermal camera uses a microbolometer Focal Plane Array with 384x288 pixels in the 8-14 μm range. The camera was connected to a PC by means of Ethernet and the thermal images could be acquired, visualized and recorded by THERM software. With this camera: (i) for various clothing arrangements we simultaneously analyzed the temperature distribution on the phantom's and person's surface as well as (ii) we determined the maximum and minimum temperature on the phantom surface during stabilization.

Simultaneously, the phantom was also observed by the terahertz camera TS4 from ThruVision Ltd. The camera can detect natural human thermal radiation at the frequency 0.25 THz thanks to the fact that clothing transmits well in this range. A heterodyne detection method bases on a GaAs Schottky mixer combined with a local oscillator [20]. The number of pixels in the THz image is 80 x 150; frame rate is 6 Hz. The distance camera-target can be in the range 3-15 meters. The TS4 can detect objects hidden under clothes (bombs, guns, knives, wallets, belts, etc.) due to their different temperature and emissivity in comparison to a human body. In the middle of the THz aperture, a small visible camera is installed to observe a scene. The camera is connected to the PC by Ethernet. Thanks to the ThruViewer software, the terahertz and visible images can be visualized independently or THz image can be superimposed on the visible image. Due to a fixed field of view, the camera was mounted horizontally to recorded two objects (the person and the phantom) simultaneously. It is important, because the camera has an automatic gain control system and images recorded individually could have the same brightness for different temperatures of the objects. The THz camera weights about 20 kg and was mounted on a pan/tilt head, which was next fixed to a trolley with a vertically moving platform.

A distance between both cameras and the targets was 6 meters. The measurements were carried out in a laboratory with a stable temperature of about 22^{o}C and a relative humidity of about 40%. The phantom was stabilized at the temperature T_{in}=31^{o}C.

Figure 5a presents a thermal image of both naked targets. The phantom's temperature (T_{in}) was stabilized to 31^{o}C. As expected, the temperature of the human body surface is uneven due to its inherent properties – the hottest region of the neck reaches 36^{o}C, while the coldest on stomach - 29^{o}C. On the other side, the naked image of the phantom reveals some oblique stripes, which are connected with a black plastic tape used to keep the pipes together (see Fig. 2 a,b) as well as vertical hotter and colder lines which results from uneven distribution of heat inside the pipes. Since the most probable place to hide dangerous items is situated in the chest and stomach region, we focused our attention on the rectangular areas depicted in Fig. 8a and determined the mean temperature inside both regions. We obtained 31.7±0.2^{o}C for the person and 31.6±0.2^{o}C for the phantom, what seems to be a satisfactory result.

Simultaneously, we acquired the THz image of both targets by means of TS4 camera (Fig. 5b). Due to poorer resolution and sensitivity of the THz camera, the obtained images are blurred but the contours of the targets are clearly seen. Intensity of both targets is similar and inhomogeneity visible in case of the thermal image is not observed.

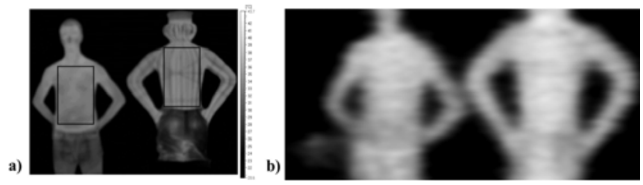

Fig. 5. Comparison of images of the naked phantom (right) and the person (left) acquired by: the thermal (a) and the THz (b) camera.

Moreover, during two hours, every two minutes, we measured the maximum (T_{max}) and minimum (T_{min}) temperature on the phantom's surface inside the rectangular areas depicted in Fig. 5a. The obtained temperature stabilities (Fig. 6) and their standard deviations in the range 0.1-0.2^{o}C seems to be sufficient for the expected applications. We also present the temperature stability of the heating liquid measured by the digital thermometer - T_{in}=30.94±0.05^{o}C.

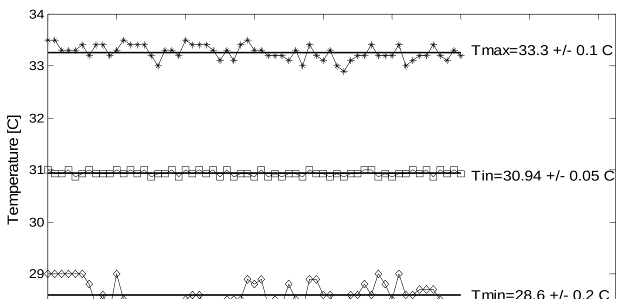

Fig. 6. Maximum (T_{max}) and minimum (T_{min}) temperature measured on the phantom's surface inside the area determined in Fig. 8a during two hours. Temperature of the heating liquid (T_{in}) in the same time.

Next figures present the thermal and the THz images taken for the phantom and the man clothed in trousers and: a cotton shirt with short sleeves (Fig.7) and a cotton shirt with long sleeves and a sweater (Fig. 8). We can notice nearly the same temperature of a person and human phantom both in the "skin" region and the region covered with the clothes. Brightness of both objects is nearly the same in the THz image. The resolution of the THz camera is poorer in comparison to the thermal camera and therefore the THz images are less clear but shape of the body is clearly seen.

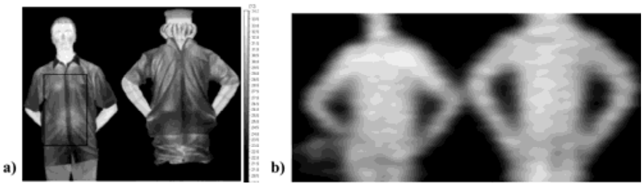

Fig.7. The objects dressed with the shirt with short sleeves: thermal (a) and THz image (b)

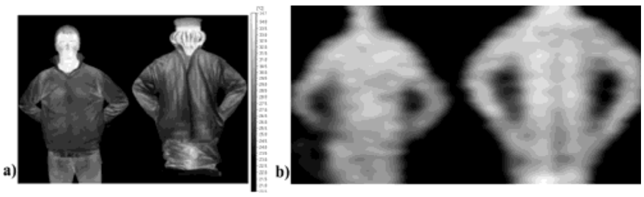

Fig.8. The objects dressed with the shirt with long sleeves and the sweater: thermal (a) and THz image (b)

Moreover, during 2 hours we measured the temperature stability of the phantom dressed with the shirt with short sleeves - maximum (T_{max}) and minimum (T_{min}) temperature inside the rectangular area depicted in Fig. 10a. We also recorded the maximum temperature on the phantom's forearm, which is not covered with the shirt (T_{arm}) and the temperature stability of the heating liquid measured by the digital thermometer - T_{in}=30.96±0.05^{o}C. Also in this case stability depicted in Fig. 9 is satisfactory.

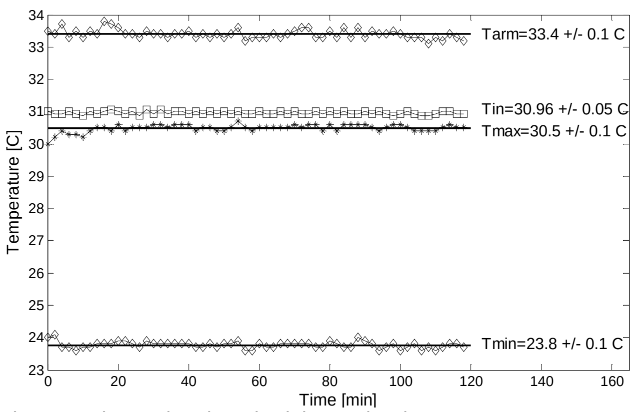

Fig.9. Maximum (T_{max}) and minimum (T_{min}) temperature measured on the phantom's surface inside the area determined in Fig. 10a during two hours. Temperature of the heating liquid (T_{in}) and maximum temperature of the phantom's arm (T_{arm}) in the same time

Finally, we also compared THz images of the objects with a 25-cm long pistol hidden under clothes (Fig. 10). The objects was dressed with the cotton shirts. The pistol is seen in the same way as dark regions with shape resembling the hidden item.

Summary

We report on the terahertz human phantom which was designed for evaluation of the terahertz cameras. The phantom was constructed of many pipes with heated water which cover the polystyrene manikin. The pipes were next coated with silicone "skin". The complicated system is responsible for thermal stabilization and movement of the device.

We obtained satisfactory similarities between the man and the phantom observed in the terahertz and the infrared regions. In the case of the naked objects, we obtained the mean temperature 31.7±0.2^{o}C for the person and 31.6±0.2^{o}C for the phantom, what is the satisfactory result. For the dressed phantom, the standard deviation of the temperature is in the range 0.1-0.2^{o}C, what also meets our requirements.

Due to poor resolution of the THz camera, we could compare the THz images of the phantom and the person only qualitatively. Brightness of both targets is very similar in the naked and dress cases, while intensities of the hidden items and its shapes are comparable.

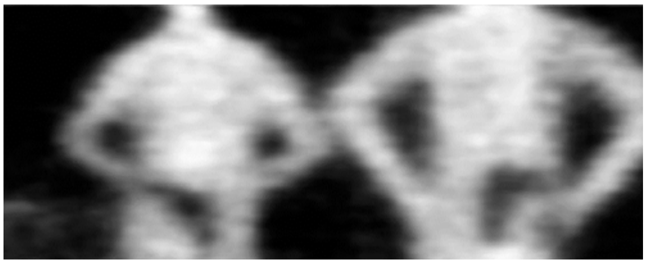

Fig.10. THz image of the objects dressed with the cotton shirt with hidden items: the metallic cylinder (a) and the pistol (b)

This construction, which mimics the behavior of human beings, can be useful for performance evaluation of the terahertz cameras in the way which is free from all disadvantages connected with screening people. Since the performance of the currently available terahertz cameras is limited and the images are rather blurred, scientists are looking for the image processing techniques and algorithms which can improved the original images and the phantom can be applied for independent evaluation of these methods.

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