Study on the Applicability of Passive Millimeter Wave Imaging Technology in Real Fire

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Abstract. In the scene of the fire, fire fighting and rescue troubled firefighters quickly the main impediment to rescue trapped personnel is high fever of smoke and fire, existing hand-held infrared imaging devices are usually used to monitor the combustion temperature, to search for hidden fire action such as content, cannot penetrate smoke fire, fire inside the high temperature environment will also be harmful to its imaging effect. This paper design a paragraph 1 to fire for fire fighting and rescue typical application background of passive millimeter wave imaging, analysis of fire under the condition of the realization of the millimeter wave imaging technology means and interference factors, verification of millimeter wave smoke fire environment through typical performance, break through the limitations of the existing fire imaging technology, make up for the inadequacy of infrared imaging devices, can effectively improve the efficiency of reconnaissance, shorten the rescue time and improve the security of firefighters and trapped personnel.

1. Introduction

Passive Millimeter Wave is also called Passive Millimeter Wave (Passive Millimeter Wave, PMMW) in the field of imaging technology, at present is mainly used in non-contact security check, aircraft its auxiliary system under low visibility, and because of its good smoke, fog penetrability and concealment, also widely used in military field. The wavelength of PMMW is between infrared and microwave. Compared with microwave, PMMW can obtain narrower beam with the same antenna size and provide higher angular resolution. Compared with ir and PMMW in its several atmospheric window (35 GHZ, 94 GHZ, 140 GHZ, 220 GHZ) is far less than the former, the attenuation and infrared detection is highly affected by the temperature, when the environmental temperature uniformity reliable to reflect the situation, PMMW because of its good penetrability is suitable for the working environment in smoke flame cut off, with all-weather work ability [1].

Early PMMW imaging systems were often too large and had poor temperature sensitivity and spatial resolution. Since the 1980s, with the emergence of single chip microwave integrated circuit (MMIC), GaAs and InP semiconductor technology, PMMW devices have made significant progress, making a breakthrough in PMMW imaging system, which has been significantly improved in system size, imaging speed, spatial resolution and other aspects [2]. PMMW tends to be mature in technical
development, but its main application field does not involve fire detection. The development of PMMW camera suitable for fire detection can not only help fire detection, but also have a broad market prospect.

2. Passive millimeter wave technology system composition

PMMW imaging system in general by the antenna and the scanning control mechanism, radiometer receiver, signal and image processing unit, image display device, by scanning mechanism to control of the antenna system, make it with a fixed beam scanning of target object, receiver antenna beam will reside when the target and background light temperature rise and fall into the corresponding low frequency signal, through the amplifier and the signal processing images, sent to the image display device shows bright temperature distribution. Among them, the function of the feeder antenna is to radiate the rf power from the feeder to the reflective surface or lens in the form of electromagnetic wave, so that the appropriate field distribution can be generated on the aperture to form the required sharp beam or shaped beam. At the same time, the leakage power from the edge of the reflector or lens is minimized in order to achieve the maximum gain.

The main technical indexes of PMMW imaging system are working frequency, imaging resolution, temperature sensitivity and frame rate. Selecting the appropriate working frequency and beam incidence Angle can detect the corresponding target. By receiving the imaging resolution is 3 db beam width to describe antenna, as in (1).

$$\Theta_{3dB} = \frac{\lambda}{D}$$

It can be seen that in the case of a certain wavelength, only the size of the antenna can be increased in order to improve the imaging resolution of the system in the aspect of hardware. The super-resolution algorithm developed in recent years and the image restoration and fusion technology can achieve the same purpose in the aspect of software, which is more economical and efficient. Temperature sensitivity is the minimum detectable temperature. Low noise receiver can achieve shorter integration time and higher sensitivity to a large extent.

3. Analysis of main disturbance factors in fire site

When PMMW imaging technology is applied to the outdoor environment, due to the natural cold background of the sky, different objects can form a high contrast of bright temperature through the combination of self-radiation and reflected sky background radiation, generally up to 50-100K. Effective detection images can be formed through the millimeter wave detector. In the indoor application, excluding the influence of the sky radiation background, the distribution of bright temperature presented by the object is only of the order of k, which is extremely demanding for the sensitivity of the integrated processing of the detector, and the multipath effect generated by the indoor environment will also affect the imaging effect. In general, security check and other applications are mainly aimed at relatively fixed space, which can be used for pre-correction of radiation background and multipath effect. However, this problem is more serious in the complex and unknown environment of fire site, and may even affect the effectiveness of MMW radiated image.

The key problems of PMMW fire field imaging are that the indoor scene characteristic radiation contrast is not high enough, the high-temperature radiation source interference is serious, and the smoke and smoke flame penetrability factors have risks. Fire environment, radiation PMMW imaging system receives the final target of apparent temperature distribution is the result of a combination, roughly include clothing, the temperature of the body's own outward radiation and flame radiation temperature and the surrounding environment, the radiation temperature of all kinds of radiation, after repeated reflection and transmission through the interface to the antenna, eventually forming the apparent temperature distribution of the target. Because the millimeter wave radiation energy of an object is much smaller than that of infrared radiation, and some objects with high reflectivity but low emissivity in the outdoor environment cannot accurately display their bright temperature distribution images.
Fire burning heat of the flame in the same object makes flame around the solid, liquid, free electronic disturbance occurs, and the flame temperature of each part is different and lead to this part of the free electronic disturbance degree is different, so different from electronic excited state transition to release by the ground state energy is different, the measured electromagnetic spectrum distribution. Studies have shown that the emissivity of particles in combustion flame is directly proportional to the radiation area, but inversely proportional to the wavelength of flame radiation [3]. These particles have the characteristics of the radiation wavelength continuity, according to the law of displacement of Wayne lambda, as in (2).

$$\lambda_m T = A$$  \hspace{1cm} (2)

With the increase of flame temperature, the radiation of electromagnetic wave wavelength gradually shortened, when combustion flame temperature of 300°C or so, the flame can radiate very strong infrared light; when the temperature rise to about 3000°C, the flame is almost in a state of incandescent, the wavelength of visible light radiation contains very much. As you can see, in the general indoor fire temperature below 1000°C, flame of millimeter wave radiation to environmental disturbance, but due to the low radiation energy, the interference is not obvious, can still be effective imaging under the high sensitivity of the detector.

4. Experimental study on millimeter wave imaging under real fire condition

For the special application of fire rescue, the typical scene has a large amount of smoke and dust, visibility is very poor, can not get the scene information through optical means. At the same time, there are many high-temperature fire sources in the fire field, and the thermal radiation situation is extremely complex, so infrared devices cannot effectively detect the scene. In the face of fire detection requirements, traditional optical or infrared imaging equipment cannot play a role, and imaging means with certain perspective ability are required for fire detection [4]. Passive millimeter wave imaging based on the millimeter spectrum of the radiation produced by the object itself can realize the object detection.

4.1. Design parameters of millimeter wave fire detection imager

In the research field of PMMW imaging technology research, institute of China university of the people's police and CLP group 29 after its tracking and part of the test and research, has completed preliminary validation without source of millimeter wave imaging principle, 0.1 THz spectrum integrated product development ability, this technology will be based on the planar hybrid integrated, through using SIP technology for receiving arrays further integration, to support the realization of portable imaging equipment. The research team carried out research on the emergency rescue problems in the indoor closed space scene, focused on solving the detection and imaging problems under the typical application background of fire rescue, broke through the imaging technology that can penetrate smoke and flame, and formed the prototype principle. Under the background of fire rescue, fire detection imaging of enclosed space is realized.

Team in China, the application of infrared imaging equipment defects in fire detection, mainly focus on the high sensitivity receiving radiation and high-performance multi-beam antenna design, through the high sensitive array and the processing of subtle differences of radiation detection, through the use of an array antenna beam direction and algorithm reduce the sidelobe interference and the influence of the multipath, design developed an can be used in the fire rescue fire scout imaging apparatus.

Research team developed PMMW imaging in fire scene prototype (as shown in figure 1) using 0.1 THz focal plane imaging system, a prototype form mainly has the THz wave lens and feed array antenna servo mechanism, control, and scanning, video signal collecting unit, intermediate frequency detection and image processing amplification device, terahertz detection front-end, wedge lens focal plane system and the scanning extension mechanism. Achieve real-time, all passive, low - cost camera. The working frequency of the camera is 0.1THz (100GHz), and the resolution can reach 20cm@10m based on the diameter of 300mm. The detector is a single channel, which can form the field of view with pitch Angle.
7 and azimuth Angle 16.8. The sensitivity of bright temperature is better than 1k, and the imaging distance is greater than 10m.

At present, the research team has developed a single-channel scanning principle prototype to verify the PMMW radiation imaging mechanism, indoor imaging effect and the penetration of the prototype to obstacles such as smoke and flame, as well as the synergistic ability with infrared imaging to achieve a certain degree of image fusion technology.

4.2. Experimental study on millimeter wave imager for fire detection and detection

To verify the imaging stability and reliability of the prototype, the research team conducted several experiments of different sizes for different experimental purposes.

4.2.1. Field test. On August 15, 2017, in order to verify the penetrability of the passive imaging system based on the millimeter wave radiation characteristics to the flame smoke and the resolution characteristics of the small-caliber portable millimeter wave imaging prototype, the research team completed the experimental test of the low-cost millimeter wave passive imaging system for the flame penetrability at dujiangyan 853 test site. This experiment mainly has two aspects of the test content. One is the recognition of metal objects by the experimental millimeter-wave imaging system in the case of flameless smoke. Second, the recognition of human body by the experimental millimeter-wave imaging system in the case of flameless smoke [5].

As shown in FIG. 2, during the test, the brazier is placed between the millimeter wave imaging system and the detected object, and the three are in the same straight line. The distance between them can be adjusted according to the test needs. The brazier fires, producing flames and smoke that form a barrier between the imaging device and the object being detected. During the experiment, the MMW imaging system imaged the detected objects respectively in the condition of unignition and after ignition. This scheme can meet the test requirements of verifying the flame penetration characteristics of millimeter wave imaging system [6].

![Figure 2. Schematic diagram of the test scenario](image-url)
1) Imaging of a metal

To verify the imaging of metal objects by the millimeter-wave imaging system, the research team selected a metal plate of 0.5m*0.5m for the detected metal object, and placed it on a carton of appropriate height, so that the height of the metal plate matches the detection field of the imaging system. The distance between the brazier and the metal plate is 2m. After ignition, the brazier can generate a flame with a width height of about 0.8m*1.5m, and the metal plate can be completely blocked in the direction of the field of view of the imaging system.

![No fire in front of metal plate](image1)

![There is a fire in front of the metal plate](image2)

**Figure 3.** Original results of metal plate imaging before and after the ignition of the brazier (distance between the metal plate and the system =5m)

At the beginning of the experiment, the brazier was not ignited, and the millimeter-wave imaging system was used to image the metal plate. Then, keep the test scene unchanged and ignite the brazier. After the flame smoke meets the test requirements and the metal plate can be completely blocked in the field of view of the imaging system, the millimeter-wave imaging system will image the metal plate and save the imaging data of each time. (Figure 3 shows the imaging results.)

2) Imaging of the human body

The second part of the experiment is to verify the imaging effect of millimeter wave imaging system on human body. The test method is the same as that of the millimeter-wave imaging system for metal imaging, except that the detected object is replaced by a human body (acted by the tester). During the test, the human stood 2.5m behind the brazier, in a straight line with the imaging system and brazier. The flame cross section size produced after the ignition of the braziers reaches 0.8m2m, which can completely cover the human body in the field of view of the imaging system [7].

In the process of the test, the imaging system imaged the human body when the brazier was not ignited and when the ignition produced the required flame smoke. In the process of the imaging system's scanning imaging, the experimenter as the detected object should maintain the stability of the body posture to ensure the authenticity of the imaging effect. It should be noted that before and after the ignition of the brazier, the posture of the experimenter as the detected object cannot be completely consistent, so there will be differences in the human posture in the imaging results [8]. Figure 4. Shows the imaging results:

![No fire](image3)

![There is a fire in front of the body](image4)

**Figure 4.** Imaging results of the millimeter wave imaging equipment on human body (the distance between human and the system =5m)
3) The experimental conclusion

Experimental results show that the passive imaging system based on millimeter wave radiation has strong penetrability to flame smoke. From the millimeter-wave imaging results of metal plate and human body under the two conditions of flame-free smoke, the shielding of flame smoke has no obvious influence on the imaging effect of the millimeter-wave imaging system. The small-caliber portable millimeter wave imaging prototype has the ability to detect metal and human body under the circumstance of outdoor radiation background and relatively simple detection environment.

4.2.2. Indoor real fire test. On June 24, 2018, the research team conducted tests at dujiangyan test site of Sichuan fire research institute of the ministry of public security to verify the imaging of smoke and flame penetration on human body under different conditions in indoor environment. See figure 5.

According to the test results, it can be seen that after indoor ignition, the flame and smoke are very large, and when the flame and smoke completely cover the imaging personnel, the human body image contour is still clearly visible. The experimental conclusion can be drawn that the millimeter-wave passive imaging system can image the human body in indoor scenes and in common fire scenes, indicating that the solution of fire field imaging technology is feasible. See figure 6.

5. Summary
In summary, for the special application of fire rescue, there is a large amount of smoke and dust in the typical scene, and the visibility is very poor, so the scene information cannot be obtained by optical means. At the same time, there are many high-temperature fire sources in the fire field, and the thermal radiation situation is extremely complex, so infrared devices cannot effectively detect the scene. In the face of fire detection requirements, traditional optical or infrared imaging equipment can not play a role, need to have a certain perspective ability of imaging means for fire detection. Passive millimeter wave imaging based on the millimeter spectrum of the radiation produced by the object itself can realize object detection. It is not interfered by infrared radiation and has strong penetrability to smoke particles. It is an ideal method for fire detection.

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