Comparison of Detection Technology for Runway Incursion Prevention in Airport Hot Spot

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Abstract: The prevention of runway incursion in hot spot of airports has always been one of the research hot spots in the field of international civil aviation. The detection of aircraft and vehicles in hot spots of airports has important significance in preventing runway incursion. This paper briefly introduces and analyzes several major technical systems used in the detection of active targets in hot spots of airports, and points out that microwave phased-array radar can provide parameters such as the distance, angle, speed, and direction of detection of targets. Compared with the traditional detection technology system, microwave phased-array radar has the advantages of high detection accuracy, low comprehensive cost, and easier acceptance.

1. Introduction
The FAA defines a hot spot as a location on an airport movement area with a history of potential risk of collision or runway incursion, and where heightened attention by pilots and drivers is necessary. By identifying hot spots, airports can provide safer route planning and guide path for aircraft or vehicles.

The International Civil Aviation Organization (ICAO) defines runway incursions as "Any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle or person on the protected area of a surface designated for the landing and take-off of aircraft." In order to effectively prevent runway incursions and reduce the impact of human factors, relevant domestic and foreign civil aviation research organizations have continued to conduct research and issued a series of standard specifications.

Stop Bars and Runway Status Lights (RWSL) systems recommended by ICAO can provide pilots and vehicle drivers with additional runway intrusion alerts. ICAO Doc 9157 AN / 901 states that the on-off control of navigation lights is an important capability of the Advanced Surface Movement Guidance and Control Systems (A-SMGCS)\(^{1}\). As a means of route selective guidance, the technology provides navigation light guidance and auxiliary control functions. Doc 9157 also discusses the technical principle of controlling the stop bars. This technology has a certain degree of automation, which detects the position status of aircraft and vehicles in a set area through position sensors, and combines the ATC process of the airport to decide and control the switch of stop bars.

The FAA has been studying the runway status lights (RWSL) system and final approach runway occupancy signal (FAROS) to reduce the risk of runway incursions since the last century. With the development of technology, the application of these technologies in airports is getting better and better.
The Runway Status Lights (RWSL) system mainly uses data from the Airport Surface Detection Equipment Model X (ASDE-X) as the monitoring data source required by the RWSL system, so as to control the runway entry lights (RELS) and takeoff holding lights (THLs) at the appropriate time, and alert pilots and vehicle drivers to the unsafe state of the runway directly[2].

In China, the prevention of runway incursions mainly depends on the manual command of the controller-pilot voice communication method. With the continuous increase of flights in recent years, runway incursions have occurred in many airports, and related institutions have also paid more attention to the use of technical means to prevent runway intrusion. Some airports have had the technology of stop bars through technical renovation and expansion. With the support of East China Air Traffic Management Bureau of CAAC in cooperation with various parties, the first domestic demonstration application of the runway status lights system have been launched at Shanghai Hongqiao Airport.

2. Necessity of runway intrusion detection at airport hot spot

For the Runway Status Lights (RWSL) system and Stop Bars, the problem the system focuses on is to reduce the risk of runway incursions. The main objects that need to enter the runway are aircraft and vehicles. Therefore, the hot spots that the system focuses on are mainly near the crossings of aircraft or vehicles entering and leaving the runway. According to the design requirements of the flight area, runway holding positions must be constructed at taxiway/runway intersections[3] (which are designated positions used to protect runways, obstacle limits, or critical / sensitive ILS / MLS areas. Unless specifically approved by the airport control tower, all taxiing aircraft and vehicles must stop and wait there.) Therefore, both ICAO and FAA have used the area near the runway waiting position as a hot spot, and adopted different technical means to monitor the aircraft and vehicles that entry and exit the area. ICAO, in its technical description of stop bars in annex 14, volume I (7th edition), stipulates that stop bars shall be controlled manually or automatically by the air traffic control department and shall be installed at each holding position on the runway[4]. In Doc 9157 (4th edition) 10.5.2, a certain degree of automatic control of stop bars is explained: in accordance with the conditions of the tower control process, the position sensor can be used to control the stop bars[1].

The FAA explained the installation position of the runway entry light (REL) in AC150 / 5340-30J, requiring that the first REL should be installed in front of the runway holding position sign[5]. The switch of the runway access light is automatically controlled by the monitoring data source provided by the x-mode airport scene detection (ASDE-X, Airport Surface Detection Equipment Model X). The runway status lights (RWSL) system is designed with the FAA as the reference standard. The surveillance data obtained by the system for airport scene targets mainly comes from external surveillance sensors such as scene radar, multi-point positioning, ADS-B, etc. Due to the positioning error of the monitoring data itself, aircraft and vehicles located in the hot spot of the holding position of the runway cannot be accurately located, which may affect the judgment of the system on the use of the runway, and affect the switch control strategy algorithm and implementation of the runway status lights. And most domestic airports, aircraft, vehicles and other facilities are still in the process of upgrading. The use of passive surveillance data alone cannot cover all aircraft and vehicles. Therefore, it is necessary to refer to the automatic control method of stop bars in ICAO, and use position sensors for active detection at the runway waiting position to achieve full coverage of aircraft and vehicles in hot spots.

3. Detection technology system to prevent runway Incursion

At present, the main technologies used in airport scene active target surveillance and detection are scene surveillance radar, multi-point positioning system, ADS-B, video and infrared imaging, induction coils, leaky cables, microwave boundaries, etc. Among them, scene surveillance radar, multi-point positioning system, ADS-B and other technologies belong to the scope of the ASDE-X technical system defined by the FAA. Due to limited installation mode and coverage, the range resolution and azimuth resolution range of scene surveillance radar is relatively large. For example,
the SCANTER2001 radar from TERMA of Denmark has an azimuth resolution of 20 meters (at a distance of 2,000 meters) and a range resolution of 15 meters, which cannot meet the accurate positioning requirements of the RWSL system; Multi-point positioning and ADS-B are limited by random errors in their positioning accuracy range, affecting the accurate logic position of the aircraft or vehicle and the runway status lights in the hot spot, especially near the runway waiting position. Because its passive detection, it needs to work through the launch equipment on board or on the vehicle to provide positioning information to the system. In the current situation that aircraft and vehicles are not compulsorily required to deploy corresponding launching equipment, this technical system cannot guarantee complete coverage of all aircraft and vehicles, and therefore requires accurate positioning equipment to assist in active detection.

Video and infrared imaging, induction coils, leaky cables, microwave boundaries and other technical systems are non-contact active detection technologies. By deploying detection sensors of the corresponding technical system in hot spots, it can effectively detect aircraft and vehicles passing through the area. And it can assist the system to accurately analyze the exact positions of aircraft and vehicles, and determine the use status of the runway, so as to correctly determine the runway status of logic and control judgment.

3.1 Video and infrared imaging position sensors

Video images are a popular detection and sensing method in recent years. It uses computer vision technology to process, analyze, and understand the video signals collected in hot spots without human intervention, and automatically discovers the aircraft or vehicles that enter hot spots. However, video acquisition is mainly based on visible light for imaging, so video image can work normally in good weather, but it is difficult to image in low illumination at night. And it is extremely vulnerable to adverse weather conditions, making it difficult to achieve all-weather detection; Infrared thermal imaging uses infrared radiation generated by all objects above absolute zero (-273℃) in nature. This radiation contains the characteristic information of the object. The infrared signal is used to photoelectrically convert the power signal radiated from the heating part of the object to simulate the corresponding spatial distribution of the surface temperature of the objects. After processing, the image that can be distinguished by human vision can be formed. Video images and infrared imaging are non-contact detection technologies. Although infrared imaging can intuitively observe the temperature of aircraft or vehicles, it cannot be identified in detail. Visible light can make up for this shortcoming. These two technologies not only can complement each other when detecting together, realize all-weather detection, and not be disturbed by the electromagnetic environment, but also have high detection accuracy and provide intuitive image perception to workers. However, due to the false color image recorded by infrared imaging, it has no correlation with visible light, and thermal diffusion effect leads to the difficulty of registration and fusion of actual images. In the practical condition of airport runway application, the aircraft or vehicle, as a huge heat source, will generate thermal trace profile during the movement, which also brings interference to the detection of video image and infrared imaging. What’s more, due to the limitation of the installation height of detection equipment, the high temperature heat wave generated by the surface in summer will also have an impact on the imaging equipment. In addition, the use of two sensors will increase the size of the equipment, which is not suitable for installation near the road surface, and the cost is high.

Figure 1 Visible light and infrared integrated position sensor
3.2 Infrared radiation position sensor

The infrared radiation position sensor is a detector that mainly uses the light beam blocking method. Its basic structure includes a transmitter, a receiver, a beam intensity indicator, and an optical lens. It works by using infrared light-emitting diodes to emit infrared rays invisible to the human eye, which are then focused by an optical lens to allow the light to reach long distances until it is received by a photosensitive transistor at the receiver. When an object passes the detection area, it will block the infrared rays emitted by the transmitter. Since the receiver cannot receive the infrared ray, it will issue an alarm. Common active infrared detectors have two beams, three beams and four beams, ranging from 30 to 300 meters, and some manufacturers produce "light walls" with multiple beams at a distance, which are mainly used in some special places. Before the development of other non-contact detection technologies, infrared radiation, as a simple and low-cost technology, has been widely used and occupied a large market share.

However, as the detection medium of infrared radiation, the infrared energy is not concentrated and is easily diffused. In an ideal environment, with the increase of the emission distance, the ideal intensity of the infrared beam and the emission distance show an inverse square attenuation. In addition, it is more susceptible to weather interference and weakens penetration in natural weather such as rain, snow, fog, wind, and strong light; And interference such as tree shaking and animals moving will cause an immediate attenuation of infrared emission intensity or beam deviation, then the receiver cannot receive the complete beam, which will frequently cause false alarms, so the product operation is greatly affected.

3.3 Induction coil position sensor

The induction coil position sensor is a sensor based on the principle of electromagnetic induction. The induction coil is usually buried with a certain length of ring-shaped insulating coil under the roadbed that needs to detect the aircraft or vehicle. The induction coil passes a certain working current. When an aircraft or a vehicle passes through the coil or stops on the coil, the magnetic flux in the coil will be changed, causing the coil loop inductance to change, then the detector can detect the change in the inductance to determine the condition of the passing aircraft or vehicle. There are generally two methods for detecting the change in inductance: one is to detect the change in phase by using a phase latch and a phase comparator; the other is to detect its oscillation frequency using a coupling circuit formed by a toroidal coil. The induction coil is also a widely used detection sensor.

The advantages of the induction coil are that it is widely used, reliable and cheap; the disadvantage is that the airport pavement needs to be destroyed during construction, which is not conducive to the reconstruction of the airport; and metal cables have the characteristics of thermal expansion and contraction, so improper construction can easily cause road cracks; Besides, in the actual construction, it is also necessary to consider that in the case of increasing airport traffic, when the sensor cannot work normally due to aging of the metal cable, insufficient tensile strength, acid and alkali corrosion or deformation of the road surface (sedimentation, crack, friction, etc.), it will face huge maintenance costs in the later period.
3.4 Leaky cable position sensor
Leaky cable is also commonly referred to as leaky induction cable. It is a coaxial cable with a special structure. The outer conductor is periodically opened with a certain shape of slot along the length. It generally consists of two leaky cables buried in the road surface, a transmitter and a receiver, one of which is connected with the transmitter to transmit energy outward, and the other is connected with the receiver for receiving energy. The high-frequency electromagnetic energy emitted by the transmitter is transmitted outward through the transmitting cable, and part of the energy is coupled to the receiving cable. The space between the transmitting and receiving cables forms an oval electromagnetic field detection area. When an aircraft or a vehicle moves through this area, it causes electromagnetic field disturbance and can be detected by the detector, which generates an alarm signal. Non-metallic or non-living organisms, such as branches, have very weak interference to electromagnetic fields. Although they may move in the detecting area, they generally do not cause electromagnetic field disturbances or trigger alarms; and by adjusting the sensitivity of the detector, the interference of small animals, such as birds, moving in the detecting area can be filtered out to achieve the purpose of effective protection.

3.5 Microwave radiation position sensor
The microwave radiation position sensor (microwave radiation radar) is mainly composed of a microwave generator, a transmitting antenna, a receiving antenna, a signal detector, a signal analysis and an alarm controller. During operation, the transmitter transmits a modulated microwave signal directly. Part of the beam reaches the receiver directly (similar to infrared radiation), and part of the beam reaches the receiver via the environment (including the ground, walls, and other objects in the detection area). There is an invisible three-dimensional detection area between the transmitter and the receiver, the size of which depends on the type of antennas, the distance between the transmitter and the receiver, and the sensitivity set by the receiver. When an aircraft or vehicle enters the detection
area, interference such as blocking and scattering occurs to the transmitting signal at the transmitter, which causes changes in the receiving power and field intensity of the signal. The signal processor analyzes the received signal by using the field interference principle or beam blocking principle, and gives warning or alarm signals.

Figure 5 Microwave radiation position sensor

Microwave radiation position sensor is a very mature detection technology. It is usually installed in open areas. It requires the flat ground, no obstructions, and linear installation, which is more in line with the environment of airport field. In China, the frequencies applicable to civilian microwave radars mainly include 10 ~ 10.5GHz, 24 ~ 24.25GHz, 47 ~ 47.2GHz, 71 ~ 81GHz, 122.25 ~ 123GHz, etc. According to the dedicated frequency range (IEEE Standard Letter Designations for radar-frequency Bands, IEEE Std 521tm-2002) assigned to radars by the international telecommunication union (ITU), the main frequency ranges used by radars operating in x-band (8 ~ 12GHz) and k-band (18 ~ 27GHz) are 8.5 ~ 10.68GHz and 24.05 ~ 24.25GHz\[^5\]. Compared with light waves (infrared, visible and ultraviolet light), the propagation loss of microwave in these bands is much less in rainy, snowy, cloudy, foggy, windy and other severe weather conditions, so it has better environmental adaptability. And the microwave radar uses wireless electromagnetic wave as the detection medium, which is not affected by weather conditions and has good all-weather adaptability. In addition, although microwave radar uses "civil frequency", which is also called industrial-science-medical (ISM) frequency or non-declared frequency in foreign countries, the interaction between them needs to be evaluated due to the existence of many aviation radio devices in the working environment of the airport.

3.6 Regional microwave detection position sensor

Regional microwave detection position sensor (microwave phased array radar) is a new type of detection sensor. At present, most of the sensor radars in the market are in the frequency range of k-band assigned by the ITU. Microwave phased array radar products consist of analog components such as transmit (TX), receive (RX), radio frequency (RF), and clock, as well as digital components such as ADC, MCU, and digital signal processor (DSP).

Microwave phased array radar not only adopts integrated transmission and reception technology, but also has a multi-antenna phased array composite structure, and a wide-angle, linear frequency-modulated continuous wave system. When working, the modulated signal is generated by local oscillation of the signal generator, and then transmitted directly by the transmitter. The modulated signal is reflected by different objects in the environment (including all obstacles in the detection area of the ground, buildings, vehicles and people, etc.), and the radar receiver captures the echo signal and constructs an omni-directional stereo detection area between the radar transmitter and the receiver; By mixing, filtering, canceling and other processing of echo signals, noise signals such as ground clutter are removed, and the change signals caused by real targets in the environment are screened out, and the warning or alarm signals are analyzed and output. Based on multiple digital signal processing techniques of the measured target, such as the delay effect in the distance domain and the Doppler effect in the speed domain, the microwave phased array radar can accurately output parameters such as the distance, angle, speed, movement and direction of the target in the detection area.
Figure 6 Regional microwave detection position sensor

Microwave phased array radar technology was first used in military fields such as ground long-distance early warning systems, airborne and ship-based antiaerial system, airborne and ship-based system, gun position measurement, and shooting range measurement. With the advancement of microwave devices and hybrid microwave integrated circuit technology, the production cost of microwave chips or microwave system-on-chips (SOC) has decreased year by year, providing the possibility for the wide application of phased array radar in the civilian field; In the field of transportation application, some well-known companies abroad include Spotter RF in the United States, Innosent in Germany, etc., and some mature companies in China include Trans-Microwave, Hunan NovaSky Electronic Technology co., ltd, etc. Compared with traditional position detection technology, microwave phased array radar technology has the advantages of flexible beam pointing, high detection accuracy, large target capacity, rich detection information, strong anti-interference ability, high sensitivity, and strong environmental adaptability.

4. Comparison of detection technology systems of runway incursion prevention

For the non-contact active detection technology system adopted by the airport in the hot spot, this paper sorts out the following table for comparison. From the comparison of various technical systems, it can be found that microwave radiation radar and phased array radar have more comprehensive advantages from the aspects of installation convenience, environmental adaptability, target detection capability, intelligent application, technological advancement and cost.

| Table 1 Comparison of main detection technology systems adopted in airport hot spot |
|----------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                                   | video surveillance | infrared beam induction coil leaking cable microwave radiation phased array radar |
| installation and configuration    | complex          | convenient      | complex         | complex         | convenient      | convenient      |
| light environment                 | daytime          | day / night     | day / night     | day / night     | day / night     | day / night     |
| detection principle              | picture processing | beam interruption electromagnetic induction narrow area; short distance field interference, beam blocking | beam reflection, digital signal processing |
| target information               | detection target, identification | detection target | detection target | detection target, distance, accuracy |
| factors of false alarm           | sudden changes in light, severe weather, small moving targets, etc. | severe weather, small moving targets, etc. | none | soil humidity, magnetic field interference, metal objects, etc. | small moving targets | reflection of irregularly moving objects |
| range filtering                  | have             | have not        | have not        | have not        | have not        | have            |
5. Conclusion
At present, domestic and international airports have applied the sensors of technical systems mentioned above. Microwave radiation position sensors are widely used, especially in key detection areas such as airport boundaries, runway holding positions, and rapid taxiway exits. For example, the ERMO series of microwave radio-beam radar products from CIAS are deployed and installed at several airports in Italy, the United States, Canada, and other countries, and have been approved by the Italian military. The 310B series of microwave radars from Southwest Microwave, Inc. USA have also been deployed and installed in many domestic airports to ensure the operation of the airports. Due to the technical principle, the microwave radar can only judge whether there is an object invasion and cannot provide more target information, so there are many restrictions on the deployment and installation and the use of sensor data in the system.

With the development of technology, phased array radar technology can continuously scan the detection area, accurately detect the distance, angle, speed and other information of the invading target all day long, and actively track and give early warning to the real target. The detected target information can also provide more accurate detection assistance for the moving target in the hot spot of the airport. Compared to the microwave radar, the phased array radar is based on a more advanced technology detection principle, and the integrated design of the transceiver also reduces the difficulty of construction. In addition, phased array radar and microwave radar adopt similar detection technology, which is more easily accepted by airport users.

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