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Foreign object debris surveillance network for runway security

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Abstract

Purpose – Foreign object debris (FOD) poses a significant hazard to aviation safety and brings huge economic losses to the aerospace industry due to aircraft damage and out-of-service delays. Different schemes and sensors have been utilized for FOD detection. This paper aims to look into a video-based FOD detection system for airport runway security and propose a scheme for FOD surveillance network establishment.

Design/methodology/approach – The FOD detection algorithm for the system is analyzed in detail, including four steps of pre-processing, background subtraction, post-processing and FOD location.

Findings – The overall algorithm is applied to two sets of live video images. The results show that the algorithm is effective for FOD targets of different shades under different lighting conditions. The proposed system is also evaluated by the ground-truth data collected at Nanyang Airport.

Practical implications – The runway security can be greatly increased by designing an affordable video-based FOD detection system.

Originality/value – The paper presents critical techniques of video-based FOD detection system. The scheme for FOD surveillance network, as a significant part of aviation risk management at airports, is applicable and extensible.

Keywords FOD, Network, Aviation safety, Detection, Aviation, Surveillance, Aerospace industry, Detection, Security

Paper type Research paper

Introduction

Foreign object debris (FOD) includes any object located in an inappropriate location in the runway environment with the capacity to injure airport or passengers and damage aircraft (NAS-412, 1997). The most noted FOD-related accident takes us back to 25 July 2000, when 100 passengers, nine crew members and four people on the ground were killed when Air France Flight 4590 crashed after departing from Charles de Gaulle International Airport near Paris. The aircraft had run over the debris on the runway that had fallen from an aircraft that took off about 4 min earlier (Patterson, 2008). FOD costs the aerospace industry over $4 billion per year in direct costs, as well as indirect costs from delays, aircraft changes and unscheduled maintenance. Since the tragedy and the economic loss have attracted increasing international attention to FOD-risk management, many countries initiate their research on runway hazard management systems for automatic FOD detection. The European Organization for the Safety of Air Navigation released a preliminary assessment of FOD detection technologies in 2006, while the Federal Aviation Administration (FAA) conducted trials of the four leading systems from QinetiQ, Stratech, Xsight Systems and Trex Enterprises during 2007 and 2008, and the study results were published in 2009 (O'Donnell, 2009). However, for the requirements of securing proprietary data, little study has been reported on specific techniques for FOD detection system.

Beihang University, with the cooperation of China Academy of Civil Aviation Science and Technology (CACAST), is also developing a lost-cost video-based experimental system for airport runway security. Following the preliminary system design experiences (Xu *et al.*, 2009), this paper mainly deals with the improvements on FOD detection algorithm. Two sets of live video images under different illuminations are used to test the detection capability of the improved algorithm for FODs of different colors and different shapes. Otherwise, more supervision techniques are being required for aviation risk management at airports. In this paper, the proposed FOD detection technology is integrated into this extensible platform as well.

The remainder of this paper is organized as follows. Second section overviews the available techniques for FOD surveillance at airports. An in-house video system is analyzed in detail in third section. The proposed FOD detection algorithm is discussed. Compared with the original algorithm, the current algorithm makes a great progress in suppressing noise and eliminating the effect of color camouflage. The experimental results against the two sets of test data and the ground-truth

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images collected at the airport are presented. Fourth section then contemplates an ideal FOD surveillance network for airport runway security. Finally, some conclusions close the paper in fifth section.

Survey of available techniques for FOD detection

Besides human observation, advanced technologies are now available for improved FOD detection, including capabilities for continuous monitoring on runways and other aircraft movement areas to supplement the capabilities of airport personnel. A summary of the system categories using different methods and sensors to perform the mission of detecting FOD has been given by FAA.

Human observation, which sets a bottom line for the performance of FOD detection systems, is the most traditional method. At present, airport personnel still serve as the primary tool for FOD detection on runway surfaces, supporting regularly scheduled and special inspections. However, airport managers around the world have recognized that these manual means are not good enough, and more advanced devices are urgently needed.

Millimeter wave (MMW) radar is the earliest supplemental technical equipment. A 94.5 GHz MMW radar has been used to continuously scan the designated pavement surfaces to detect FOD (Beasley *et al.*, 2004). Generally, two or three units are located for each runway, 50 m or more from the center line. The system is able to detect a metallic cylindrical target measuring 3.0 cm high and 3.8 cm in diameter at ranges of up to 1 km. The best advantage is its flexibility to day-night and all-weather conditions. MMW radar can also be mounted on top of a vehicle and scans the surface in front of the vehicle when moving. Such a system (78-81 GHz) was developed by Trex Enterprises and operated at Chicago's Midway International Airport (O'Donnell, 2009). Working staff staying on this mobile platform can remove the debris as soon as FOD is detected.

An optical camera is another popular means for FOD detection. Such system uses a high-resolution camera that visually scans the runway surface. Generally, five to eight units are located for each runway, 150 m or more from the center line. Sophisticated image processing software is developed adapting to changing lighting and surface conditions. The system is able to detect a 2.0 cm object target at ranges of up to 300 m using only ambient lighting. When FOD is found, the system provides an instant image of the debris.

In recent years, there has been a trend towards FOD detection with combined sensors which has complementary advantages. Xsight Systems develops a system using a small hybrid unit that contains both a 77 GHz MMW radar and an optical camera mounted next to the runway edge lights, covering an area of 1,500-3,500 m^2. Exiting power for the edge light can be utilized. Accordingly, an ideal location is chosen with low installation costs. Its high resolution (each pixel in the image represents 2 mm of FOD) reduces the risk of generating false alarms (Vogel, 2008). A design scheme for FOD surveillance network given in fourth section also supports multi-sensor integration applications.

Video system design and analysis

With the cooperation of CACAST, an experimental video-based FOD detection system is developed by Beihang University. The design of the video-based FOD detection system could be applied to other systems adopting different sensors. The camera provides a continuous inspection of the runway. A digital video image is collected by a capture card and processed by in-house algorithm in real-time software. The system is described comprehensively in this section, which is divided into two parts of FOD detection algorithm and experimental results.

FOD detection algorithm

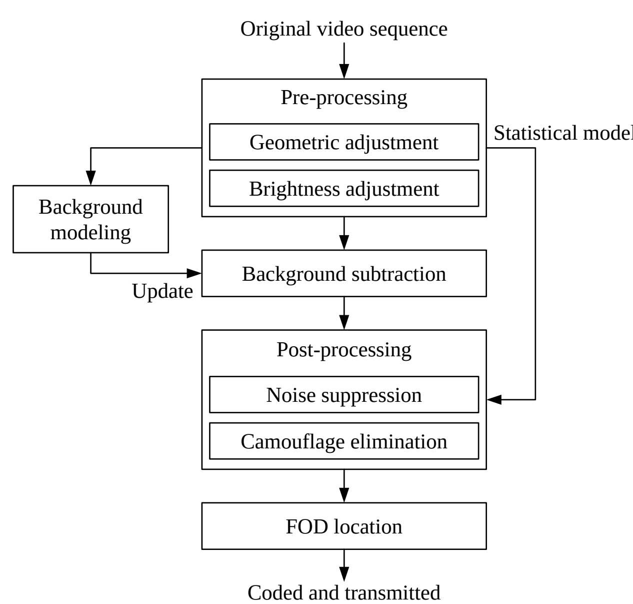
As it is shown in Figure 1, FOD detection algorithm is the core of our experimental system, which is composed of pre-processing, background subtraction, post-processing and FOD location. The background image is updated adaptively by the background extraction module. Compared with the previous algorithm (Xu *et al.*, 2009), some new techniques are added to the stage of background subtraction and post-processing. The problems of noise suppression and color camouflage elimination are perfectly solved in post-processing. Depending on this improved algorithm, the system automatically detects, locates and alerts operators to potentially dangerous FOD.

Pre-processing

Before change detection, pre-processing methods are given for rejection of the unimportant changes caused by the slight camera motion or the strength changes of the light sources in the scene. In this step, geometric adjustment and brightness adjustment are involved to suppress these interferences (Radke *et al.*, 2005).

For this application, geometric adjustment is used to reject the changes resulting from the camera motion. When the surveillance area is relatively rigid and the camera motion is small, registration is always performed using spatial transformations such as projective transformation to remove these variations. Many techniques have been proposed to solve the problem in many different forms. The general method is to align the raw images from the same video sequence into the

Figure 1 Flowchart of FOD detection algorithm



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same coordinate system (Zitova' and Flusser, 2003). Hence, we do not discuss the algorithms in detail here.

Illumination variation is another unimportant change, which is eliminated by brightness adjustment. Two typical techniques, intensity normalization and homomorphic filtering, are well studied to compensate for illumination variations.

Intensity normalization is one of the earliest methods still in use for brightness adjustment (Shi and Govindaraju, 2004). With the assumption that the data have Gaussian distribution, so that grayscale of each pixel is normalized as:

$$\tilde{I}_1[x,y] = \frac{I_0[x,y] - \mu_0}{\sigma_0}\,\sigma_1 + \mu_1, \tag{1}$$

where $\tilde{I}_1[x,y]$ is the normalized value of each pixel, $I_0[x,y]$ is the original value of the source data, μ_0 and μ_1 are the mean values of the source and reference data, respectively, and σ_0 and σ_1 are standard deviations of the source and reference data, respectively.

Homomorphic filtering (Jirik and Taxt, 2006) can also be used for illumination-invariant transformation. The observed image is separated into two components of illumination I_i and reflectance I_r, which is denoted as below:

$$I[x,y] = I_i[x,y] \cdot I_r[x,y]. \tag{2}$$

Because the high-frequency components are assumed to represent mostly the reflectance, whereas the low-frequency components are assumed to represent mostly the illumination, the high-pass filter is used to suppress low frequencies in the log-intensity domain:

$$\ln I[x,y] = \ln I_i[x,y] + \ln I_r[x,y].$$

Subsequently, the left reflectance component is processed by the background subtraction step.

Background subtraction

Background subtraction is a popular approach to detect intrusion objects in an image sequence under a stationary camera, which is very sensitive to environment changes without promptly updating the background. The main difficulty in designing a robust background subtraction algorithm is the selection of a detection threshold θ to find the change mask:

$$M[x,y] = \Big| I[x,y] - B[x,y]; \Big| \underset{B}{\overset{T}{\gtrless}} \theta, \tag{3}$$

where T denotes target detection while B denotes background. The pixels values for the background model are not always fixed due to image noise, which can be modeled with a zero-mean Gaussian distribution $N(0,\sigma^2)$ over time. In addition, more adaptive and robust methods such as mixture-of-Gaussians and non-parametric models can also be applied for thresholding of the subtracted result (Elgammal *et al.*, 2002).

Since the background changes with time due to variations of the surrounding environment, the background model is usually updated periodically in engineering applications. The simplest background modeling technique is to calculate an average image of the scene with no intrusion objects. Alternatively, principle component analysis can be applied to a set of pre-processed images. The principle component corresponding to the largest eigenvalue is assumed to reflect the unchanged part of the sequence, which can be treated as the background image.

Another background modeling scheme is independent component analysis (ICA), whose goal is to find a linear representation of non-Gaussian data so that the estimated sources are statistically independent, or as independent as possible (Tsai and Lai, 2009). The ICA model is shown as:

$$\mathbf{x} = \mathbf{A}\mathbf{s}, \tag{4}$$

where the observed data denoted by $\mathbf{x}$ is a group of vectors $\mathbf{x}_1, \ldots, \mathbf{x}_n$, the source data denoted by $\mathbf{s}$ cannot be observed directly and $\mathbf{A}$ is the mixing matrix.

Let us assume that the components $\mathbf{s}$ are statistically independent. After estimating the matrix $\mathbf{A}$, we can compute its inverse or generalized inverse, say $\mathbf{W}$, and obtain the independent components simply by:

$$\mathbf{s} = \mathbf{W}\mathbf{x}. \tag{5}$$

Main methods for ICA estimation include non-Gaussian (e.g. high-order moment and negentropy), maximum likelihood estimation and minimization of mutual information. Before applying ICA on the experimental data, some pre-processing should be done first. Techniques such as centering and whitening could make the ICA estimation simpler and better conditioned.

Since the FOD and the stationary background are considered to be independent, ICA-based background subtraction algorithm can be applied to obtain the de-mixing matrix that can separate two highly correlated images into intrusion objects and still background. The approach can effectively segment intrusion objects under illumination changes without extra pre-processing for FOD detection applications.

Post-processing

In spite of good background modeling, there are still some false positives and incompletely detected targets across the image after background subtraction, so noise suppression and camouflage elimination are applied on initial change masks in post-processing based on the statistical model given by the original image.

Median filtering and morphological processing are two typical techniques for noise reduction (Elgammal *et al.*, 2002; Xu *et al.*, 2009). Although these methods can be effective in some cases, they operate only on the initial change mask, ignoring the original image statistics. The dilemma could be solved by inspecting the neighboring labels of positives in the initial change mask through a Markov random field (MRF) model. The label of each pixel is computed based on prior probabilities according to its neighboring labels. Therefore, the decision rule for noise suppression at $[x,y]$ is (McHugh *et al.*, 2009):

$$\frac{P_T(I[x,y])}{P_B(I[x,y])} \underset{B}{\overset{T}{\gtrless}} \gamma \frac{P(E = e^B)}{P(E = e^T)}, \tag{6}$$

where E is a MRF, e^B denotes the label field around when $e[x,y] = 0$ and e^T denotes the case when $e[x,y] = 1$. The parameter γ is selected to control the influence of MRF model. Obviously, a pixel surrounded by target labels is more likely to be labeled as a target than a pixel with background neighbors.

In some cases, FOD is difficult to detect and usually missing due to its high color similarity with the background. A spatially target detection method is proposed for camouflage elimination

(McHugh, 2008). The idea is based on the assumption that real targets are usually smooth connected regions. A kernel-based approach is used, e.g. Gaussian distribution, to estimate the pixels from the original frame:

$$P_T(I[x,y]) = \frac{1}{|\mathbf{S}|}\sum_{(x,y)\in\mathbf{S}} K(I[x,y] - I[x_0,y_0]) \mathop{\gtrless}_{B}^{T} \eta, \qquad (7)$$

where $\mathbf{S}$ denotes the neighborhoods around $[x_0, y_0]$ in the original image, a window centered at $[x_0, y_0]$ which is detected as target after noise suppression. It can be seen from equation (7) that detected probability of the neighborhood pixels depend on their similarity degrees with $[x_0, y_0]$. This means that the target statistical model is estimated after pre-processing and used in camouflage elimination to fill the missing regions.

FOD location

After the above three steps, the connected regions left in the image are defined as FOD targets. By means of region labeling, the pixels of each disconnected target region in the binary PPI image are labeled with the same number. On this basis, the measurements including center coordinates (x_c, y_c) and the size of each target represented by pixel number n are extracted. The coordinate origin is set at the center of display. Then, we define the location of each target as:

$$x_c = \sum_{(x,y)\in\mathbf{S}} \frac{x}{n}, \quad y_c = \sum_{(x,y)\in\mathbf{S}} \frac{y}{n}. \qquad (8)$$

Finally, the extracted FOD properties are coded and transmitted under the proposed network in fourth section.

Experimental results

The proposed algorithm was tested on two sets of live video images under different illuminations. We used a camera to collect data with FOD targets with different shades (white, light grey, dark grey and black) on asphalt pavement. The test images in the experiments were 480×640 pixels in wide and 8-bit gray levels.

Figure 2 shows the overall process for FOD detection in shadow. Eight FOD targets, four cylinders and four cubes, are added to asphalt pavement. Figure 2(a) is the original frame, where colors of different sides of each target vary according to different illumination angles. Figure 2(b) shows the initial change mask, where the background is subtracted but a number of false positives remain and most parts of some FODs are missing due to its high similarity with the background. After noise suppression, all false positives composed of only a few pixels are rejected by the addition of an MRF model, with the result shown in Figure 2(c). The MRF approach improves the detection performance over the morphological methods. It reduces false alarms without influence on the already detected regions. To eliminate the camouflage effects and improve the detection performance, detected probability of the neighborhood pixels around the target-labeled pixel is calculated using the statistical model given by the original frame. The Gaussian kernel with $\sigma^2 = 1$ is used and the window is 5×5 pixel. The gaps inside the targets are converged and the boundaries grow to certain extent (Figure 2(d)). Finally, as is shown in Figure 2(e), eight targets are all detected and located correctly.

Figure 3 shows the overall process for FOD detection in sunshine coming from behind the targets. Figure 3(a) is the original frame. The detection of shadows is a source of confusion for subsequent processing. However, it is tolerable for engineering application because the shadow is always connected to the object. Figure 3(b) shows the initial change mask. Figure 3(c) and (d) are the results after noise suppression and camouflage elimination. The shadows of targets are also segmented as targets, seriously affecting the detection results. In fact, the interference of shadows improves the target size and reduces the detection difficulty, which can be utilized in engineering applications. Figure 3(e) shows the detection results. There is sometimes more than one sign for each FOD due to its shadow.

This subsection also presents the experimental results from the image sequence collected at Nanyang Airport, Henan Province, October 2008, to evaluate the performance of the proposed optical FOD detection algorithm. The ground-truth images in the experiments were $2{,}304 \times 3{,}072$ pixels in wide. Figure 4 is the detection results of a frame collected in the morning with gentle light. Three screws (Figure 4 left), less than 3 cm in length, were placed on the runway to test our experimental system. All three FODs are detected successfully, with objects description illustrated in Table I.

System design for airport-based FOD surveillance applications

Currently, a number of advanced technologies are being used for aviation safety management at airports. However, the lack of inherent integration poses a substantial challenge. The diversity and the large number of sensors make the network establishment very challenging. Each surveillance system has its own independent detection and data processing architecture. Once new detection equipment is needed and installed at airports, the overall platform has to be rebuilt. All these challenges call for a new compatible and extensible network, attracting intensive research worldwide. In this section, a scheme for FOD detection with multiple sensors is proposed as an extensible network platform for aviation risk management at airports. Figure 5 shows the architecture of this network.

Several sensors are used jointly for each unit to provide airports with a continuous automated monitoring of their runways. A MMW radar is used to give uninterrupted coverage of the runway, triggering accurate identification of the FODs which is achieved by a high-resolution visible light camera for daytime and an infrared camera at night. Target detection algorithm is adopted for information extraction from the original data collected by different sensors. Before the transmission through wired or wireless network, the FOD properties extracted by specific algorithm are encoded following an in-house coding scheme. The code structure should contain all attributes of the targets, including time, type, quantity, material and locations, etc. In the air-traffic control center, the code is received and read before risk assessment. Different emergency responses are taken according to situations with different risk levels. Integrated graphical user interface is available over network to control all functions of the sensors, so multiple technical staff can access the target data from any sensor in real time and make appropriate decisions remotely. For further investigation, with the identification of FOD locations stored in database over long periods of time, a map with potential problem areas highlighted is provided, allowing efforts to be focused on the most threatening areas.

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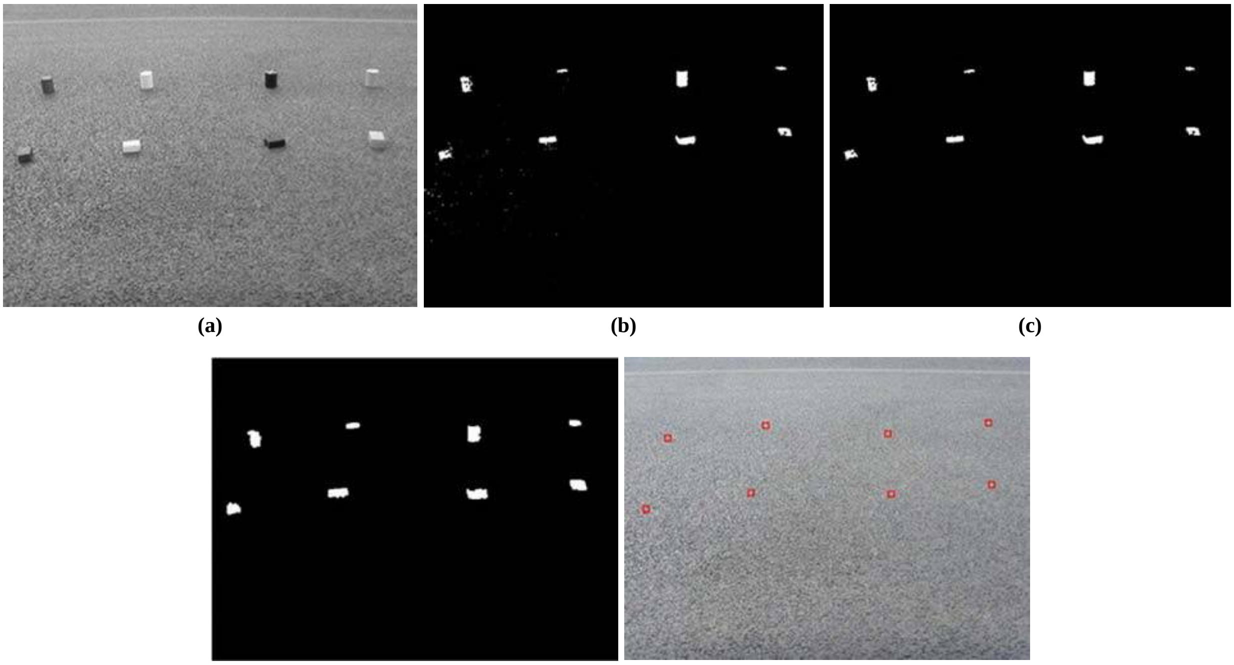
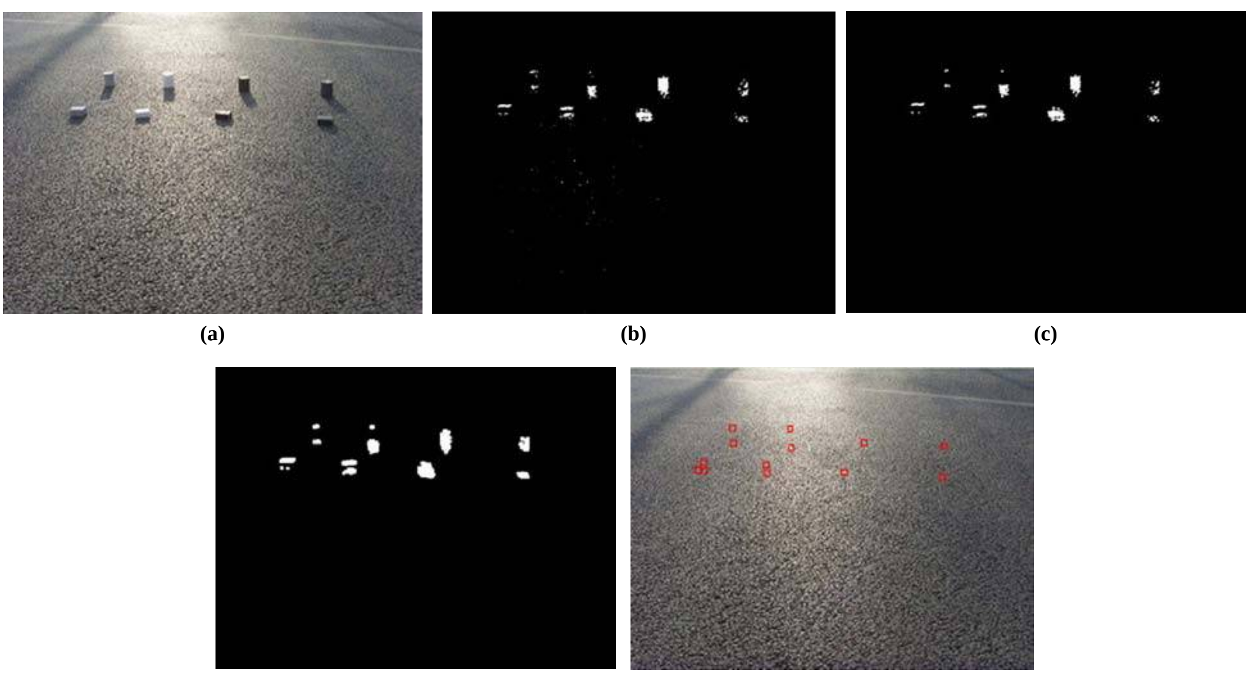
Figure 2 Detection results for FOD in shadow



(a) (b) (c) (d) (e)

Notes: (a) Original frame; (b) initial change mask; (c) result after noise suppression; (d) result after camouflage elimination; (e) FOD location

Figure 3 Detection results for FOD in sunshine



(a) (b) (c) (d) (e)

Notes: (a) Original frame; (b) initial change mask; (c) result after noise suppression; (d) result after camouflage elimination; (e) FOD location

Conclusion

FOD surveillance network is indispensable for airport security management. The proposed FOD detection scheme is based on background subtraction, which is a widely used approach for detecting invaders in videos from a static camera. The pre-processing stage can handle the situations where the scene contains small motion and illumination variation. The background modeling updates periodically and adapts to environment changes promptly. The post-processing stage is

Figure 4 FOD detection results for real video

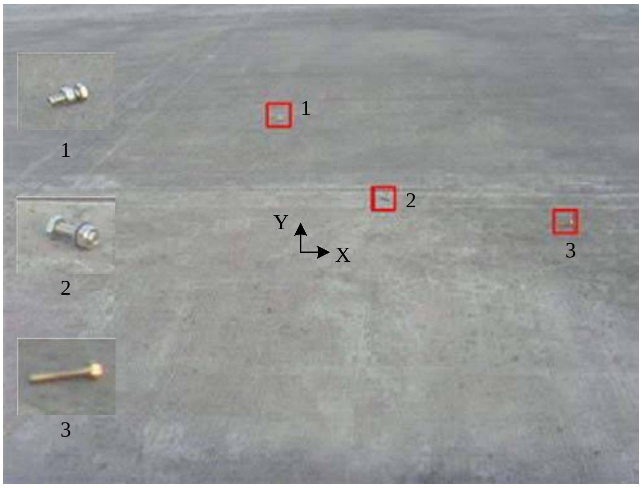
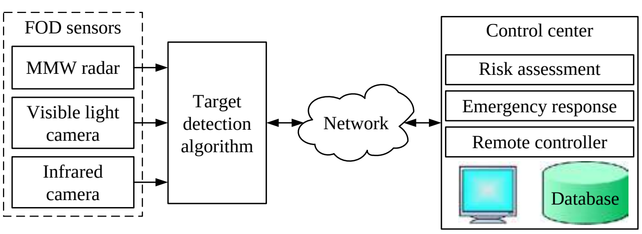


Table I FOD property descriptions

Time	08:13:10, October 16, 2008
Type	Screws
Quantity	3
Material	Steel
Location	(−43, 123); (62, 42); (245, 18)

Figure 5 FOD surveillance network for runway security



added to suppress false alarms. The scheme is also worth using for reference with other type of sensors, e.g. MMW radar and infrared camera. Otherwise, in this paper, RGB color images are converted into gray level first, before formal processing. Actually, RGB information may be used to discriminate between targets and their shadows (Elgammal *et al.*, 2002), which is neglected herein and needs further investigation.

An establishment scheme for aviation risk management platform is proposed, which is convenient to future extension and complement. FOD surveillance system is integrated for aviation risk management. Multiple sensors are jointly used and remotely controlled for perfect detection. MMW radar is often used for preliminary FOD location regardless of illumination variance, and an optical detection device is adopted for precise identification. Flexible coding methods can be used for more unified and standard information transmission. As more detection subsystems added to the platform, e.g. avian radar system and wind hazard detection system, its advantages and effectiveness will be maximized and extended.

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