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A Vision-based Infrared Decoy Tracking Algorithm for Air Conditioner Spot Cooling

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Abstract: Air conditioner has become one of the most common electrical appliances in every household. With the increase in their demand, the challenge to reduce the energy usage of air conditioner has become a subject of intense study in recent years. Spot cooling is one of the methods that can reduce the energy wastage. In this method, a control algorithm is implemented to actively track the location of users and direct the air conditioner's air flow to these targeted areas. This can make the cooling more efficient since the air conditioner does not need to cool down the entire room. By selectively directing the air flow, the users can still achieve the same cooling comfort. This paper proposed a technique of spot cooling for air conditioner using infrared (IR) camera and a decoy. The decoy is based on IR light emitting diodes arranged in a specific pattern. The IR camera captures the video of the room to locate the position of the decoy. Image processing techniques include thresholding and template matching are used for the decoy detection. Once the decoy is detected, the movement of the decoy is tracked by using a Kalman filter. To test the performance of the proposed method, a prototype system was implemented on a Raspberry Pi board and the accuracy of detection was evaluated. Experimental results showed that the system is able to detect the position of decoy with 98% accuracy in both day and night-time conditions.

Keywords: Image processing, indoor positioning, object detection, object tracking, spot cooling.

1. Introduction

The global temperature record shows an upward trend in recent years [1]. Following the hot weather, the demand for air conditioner is increasing rapidly especially in the emerging countries. With the rise in income and living standards, many households today can afford to have at least one air conditioner. Based on the statistics compiled by The Japan Refrigeration and Air Conditioning Industry Association, the demand for air conditioners reached 16.4 million units in Asia (excluding Japan and China) with an overall yearly increment of 4.2% [2]. Fig. 1 shows the increase in demand for air conditioner from year 2010 to 2016.

A study by the International Energy Agency reported that the use of space cooling has accounted for about one fifth of the total electricity usage in buildings around the world. They predicted that over the next three decades, the use of air conditioners will become one of the top drivers of global electricity demand [3].

The continuous increase in energy demand from air conditioner has triggered a lot of researches to find ways to reduce its energy consumption. The most popular innovation is the inverter technology. This technology can control the speed of the air conditioner's compressor motor by varying the frequency of the power supply [4]. This allows a more efficient control of the motor's speed to suit the cooling of different room temperatures.

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Although inverter technology for air conditioner can reduce its energy consumption, the current cooling method is still not very efficient since it often cools down the entire room or space regardless of the presence of human. Through controlling the direction of air flow to a targeted cooling spot, it is possible to achieve the same cooling effect with reduced energy consumption. This concept is known as spot cooling, which helps to reduce the energy usage without sacrificing too much on the consumer's cooling comfort.

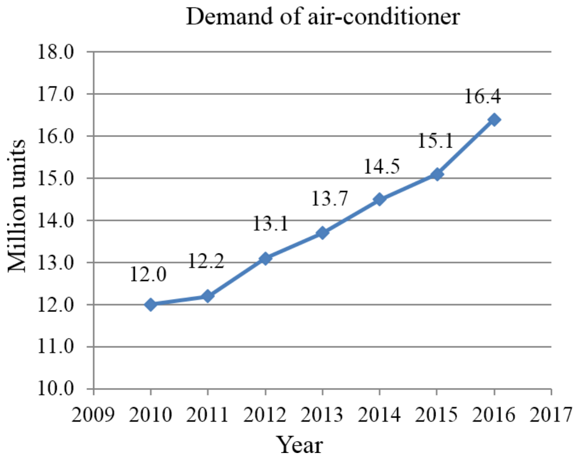


Fig. 1 - Demand of air conditioner in Asia (excluding Japan and China)

To achieve spot cooling, an effective indoor positioning technology is needed to allow the system to locate the user. Global Positioning System (GPS) is a very effective way for outdoor object positioning application, but its accuracy is extremely low in indoor environment. This is due to the lack of line-of-sight transmission channel between the global positioning satellites and the receiver [5].

Radio Frequency Identification (RFID) is another common approach for indoor positioning. Wong et al. [6] used particle swarm optimization and artificial neural network to improve the accuracy of RFID indoor positioning system. Another research by Yao et al. [7] used dual channels RFID to solve the multipath signal propagation problem to reduce the position estimation error. However, the RFID approach is not suitable for air conditioner's spot cooling application as it needs to install several RFID transmitters and receivers. The cost of the system is too high and may not be viable for spot cooling implementation in a domestic air conditioner.

Another possible approach of indoor positioning for spot cooling is by using Light Emitting Diode (LED). This method has more advantages compared to RFID as it can provide better positioning accuracy and requires lower operational cost. Besides, it does not cause any electromagnetic interference problem.

The techniques for indoor positioning using either LED or RFID communication can be divided into three main types which are based on either triangulation, proximity or imaging techniques [8].

(1) Triangulation: This technique requires the distance measurement of the targeted location from at least three reference locations. Distance measurement can be done by using receiver signal strength or time of arrival techniques.
(2) Proximity: In this technique, a grid of beacons is used for object positioning. The targeted location is determined based on the signals received from the beacons located near to the target [9]. The positioning accuracy is dependent on the resolution of the grid.
(3) Imaging technique: The targeted position is determined using a camera and a visible or infrared light source. Positioning is achieved by analyzing the location of the light source in the captured image [10].

The first two methods require several transmitters and they utilize data communication between the transmitters and receiver for location estimation. This is not suitable for air conditioner's spot cooling application since several transmitters need to be installed in the cooling area.

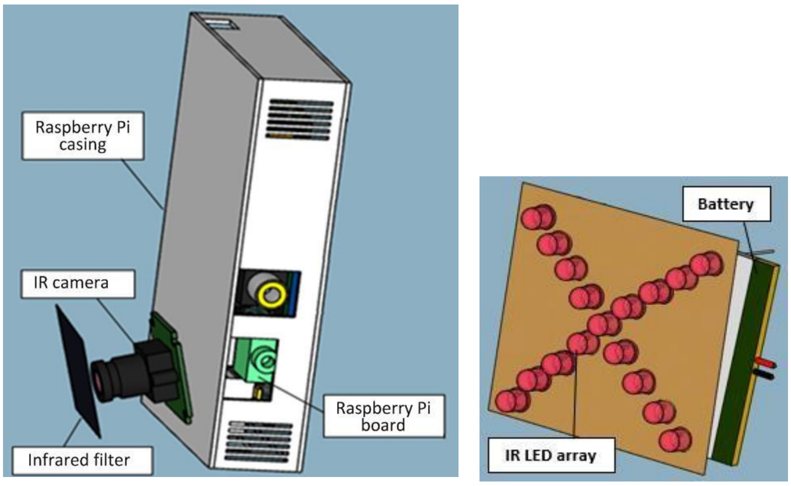
The third method uses a camera to capture the image of the cooling area and applies image processing techniques to identify the targeted location for cooling. It requires one camera and a visible or infrared light source to mark the targeted cooling area. The light source could consist of several LED arranged in a specific pattern that can be detected from the captured image. This method is low cost, yet it can provide accurate positioning for spot cooling.

In this paper, a method of spot cooling which can be implemented in air conditioner is proposed. The method is based on the image processing technique that consists of a controller board, an infrared camera and an IR LED decoy. The decoy is used to mark the location of the targeted cooling area where the air flow is to be directed. It is designed to be unique and has minimal interference from other infrared light sources. Image processing techniques include thresholding and template matching are used to detect the location of decoy from the captured images. Kalman filter is used to track the movement of the detected decoy in consecutive video frames. Besides accuracy, the proposed spot cooling method has the advantages of fast respond time and short lock-in time.

2. Material and Method

The hardware of the proposed spot cooling system consists of two main components which are the controller and a decoy. In this research, a prototype system is developed using the Raspberry Pi 3 (RPI) computer board as the main controller. An infrared camera is connected to the RPI to capture the images of the cooling area and track the location of the decoy. Infrared camera is used because it is able to capture images of the decoy even under poor lighting condition. Therefore, the system works in both day and night-time.

The prototype for the main controller is shown in Fig. 2(a). The infrared camera is secured at the front surface of the module with some downward tilt angles so that it can capture the whole scene of the cooling area. A floppy disk film acting as an infrared filter is attached at the lens of the camera to filter out visible light. Thus, only infrared light is captured in the images to ease the image processing tasks to detect the infrared LED decoy.



(a) (b)

Fig. 2 - Drawing of the prototype spot cooling system (a) the main controller, (b) the IR LED decoy

The design of the decoy is shown in Fig. 2(b). The infrared LED array is arranged in an 'X' shape so that the system is able to distinguish the decoy from other infrared sources which could interfere the detection of the decoy. A blinking circuit is implemented into the decoy system to blink the LED at low duty cycle to reduce its power consumption.

2.1 Field of View of the Spot Cooling System

The field of view (FOV) of the proposed spot cooling system is identified to understand the extent of the observable area that it can cover at any given moment. The result is shown in the highlighted region in Fig. 3 which represents the FOV of the infrared camera used. This FOV should be enough to cover the service area of an ordinary household air conditioner unit.

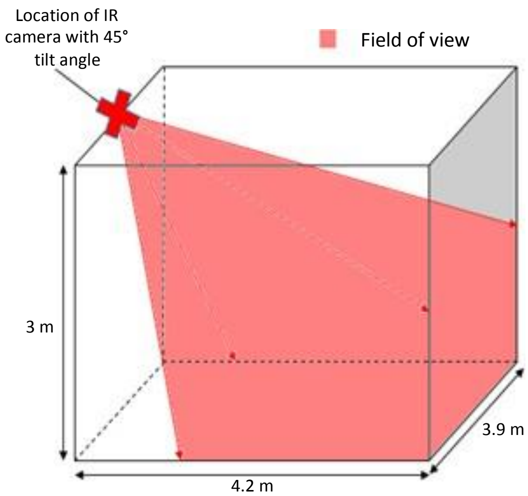


Fig. 3 - Field of view of the IR camera

2.2 Detection and Tracking Algorithms

The detection algorithm of the spot cooling system consists of 4 main components which are: 1) image acquisition to capture the image using the infrared camera; 2) image thresholding to process the image and remove the unwanted background noises; 3) template matching to detect the decoy, and 4) Kalman filter to track the movement of the decoy in the video frames. The algorithm is developed and tested on Matlab and Simulink platform before transferring to the RPI board. Fig. 4 shows the overall processing flow of the spot cooling system.

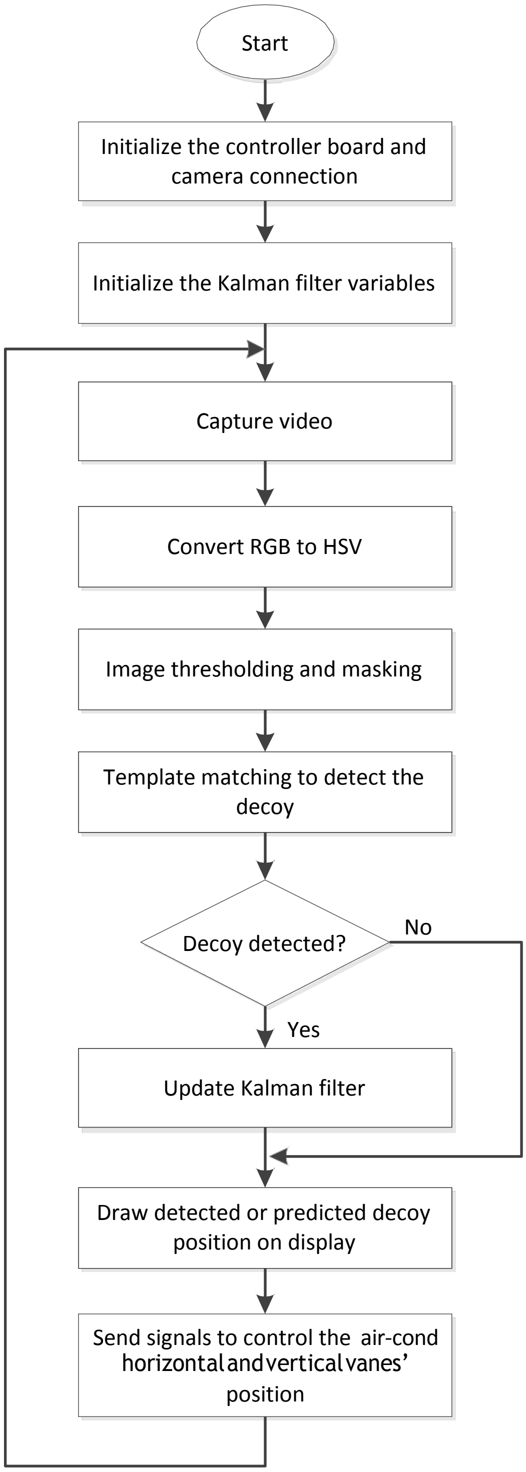


Fig. 4 - Flowchart of the proposed spot cooling system

The details of the algorithms are explained as following:

(1) Image Acquisition:

The image acquisition is performed by the infrared camera. Once the system is activated, the camera continuously captures the image in the cooling area at 20 frames per second. The resolution of the image used is 640×480 pixels which is sufficient for the detection of the decoy.

(2) Image Thresholding and Masking:

The captured image is then converted from RGB to HSV colour space. HSV is used in this study since this colour space separates the intensity component from the hue (colour). For the detection of decoy from infrared images, the use of the intensity component is adequate. After the conversion, the image is thresholded to remove the unnecessary background object with low intensity. The threshold level used is empirically determined in the experiment. A mask is then created based on the thresholding result and it is used to map into the original image. After this process, the resulting image only consists of the decoy's IR LED light and possibly other IR sources in the area.

(3) Template Matching:

Template matching technique is used to differentiate the decoy from other IR sources. A template image which resembles the pattern of the decoy's LED arrangement is used. The correlation between the template and the detected IR sources in the processed image is calculated using the Fast Normalized Cross Correlation method [11]. A higher correlation value indicates a higher percentage of similarity between the template and the image. By analysing the correlation values, the non-decoy IR sources in the image can be removed.

(4) Kalman Filtering:

Once a decoy is detected, a tracking function based on Kalman filter is used to track the movement of the decoy in consecutive image frames. Kalman filter is used to smooth out the tracking process. In case the view of the decoy is obstructed, Kalman filter can still give accurate prediction of the decoy's location since it incorporates noise and other inaccuracies in the tracking process [12].

Tracking using Kalman filter is done in two phases which are the *prediction phase* and the *correction phase*. The prediction phase projects forward in time using the state model to estimate the state of the variables in the next time step as given by the following equations:

$$\overline{X}^{t} = DX^{t-1} + W \quad (1)$$

$$\overline{\Sigma}^{t} = D\Sigma^{t-1}D^{t} + Q^{t} \quad (2)$$

Where X^{t-1} is the state variable representing the coordinate of the decoy in the image plane and t is the time step. $\overline{X}^{t}$, $\overline{\Sigma}^{t}$ and D are the state prediction, state transition matrix and the error covariance prediction respectively. Q is the covariance of the process noise W.

In the correction phase, the current observation Z^t is used to update the state variable X^t and the error covariance Σ^t as given in the following equations:

$$X^{t} = \overline{X}^{t} + K^{t}[Z^{t} - M\overline{X}^{t}] \quad (3)$$

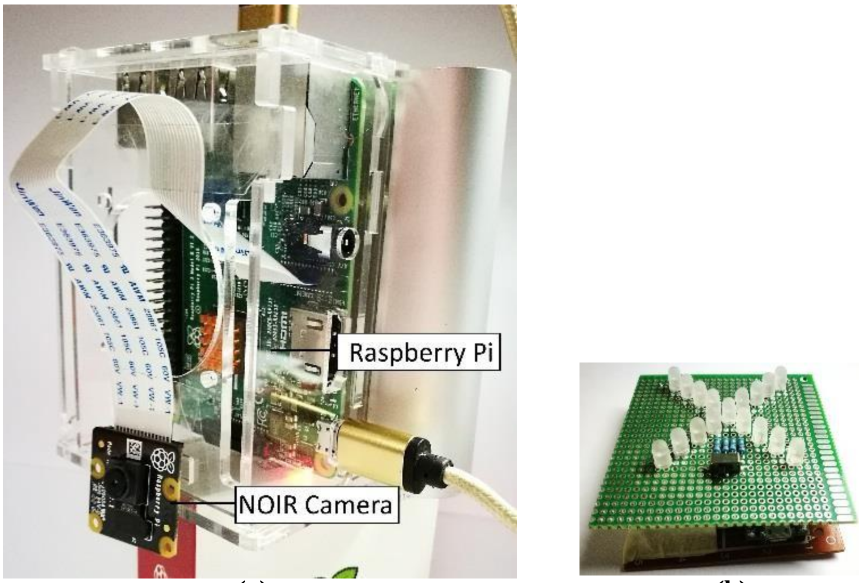
$$\Sigma^{t} = \overline{\Sigma}^{t} - K^{t} M \overline{\Sigma}^{t} \quad (4)$$

$$K^{t} = \frac{\Sigma^{t} M^{t}}{M\overline{\Sigma}^{t} M^{t} + R^{t}} \quad (5)$$

Where M, K and R are the measurement matrix, Kalman gain and the covariance of the measurement noise respectively [13]. Kalman filter can model the movement of an object in either constant velocity or constant acceleration. In this research, constant velocity is used since it is more reasonable to model the human's movement in the room as constant velocity.

3. Results and Discussion

The assembly of the prototype spot cooling system is shown in Fig. 5. The main controller and the infrared camera can be installed in front of a conventional air conditioner to capture the full view of the room. The decoy is carried by the user and placed anywhere inside the room where the air flow is to be directed.



(a) (b)

Fig. 5 - The prototype spot cooling system (a) main controller; (b) LED decoy

To evaluate the performance of the proposed spot cooling system, a test system is set up as shown in Fig. 6. The infrared camera is installed in front of an air conditioner which is 3m above the ground. The dimension of the room used in the experiment is as shown in Fig. 3. An example view of the room captured by the infrared camera without IR filter is shown in Fig.7. From the image, it can be observed that the FOV of camera can cover most of the areas of the room.

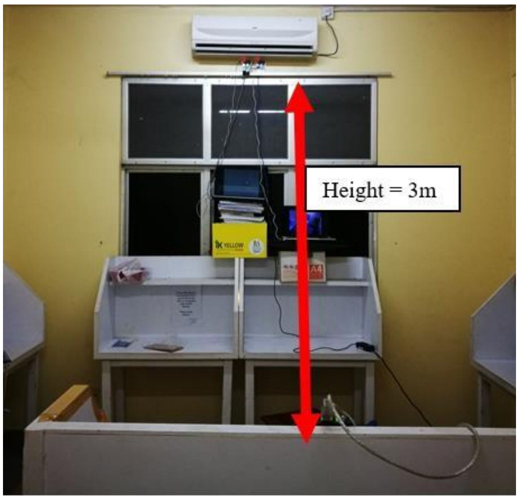


Fig. 6 - Experiment setup of the proposed spot cooling system below an air conditioner indoor unit

Fig. 7 - An example image captured by the infrared camera (without IR filter)

Once the decoy is detected, the direction of air-flow is directed to the decoy. This is done by changing the angle of the horizontal and vertical air-vanes of the air-conditioner. The angles of the air-vanes are set based on the position of the detected decoy in the image. Fig. 8 shows the mapping from the position on image to the angle of horizontal and vertical air-vanes.

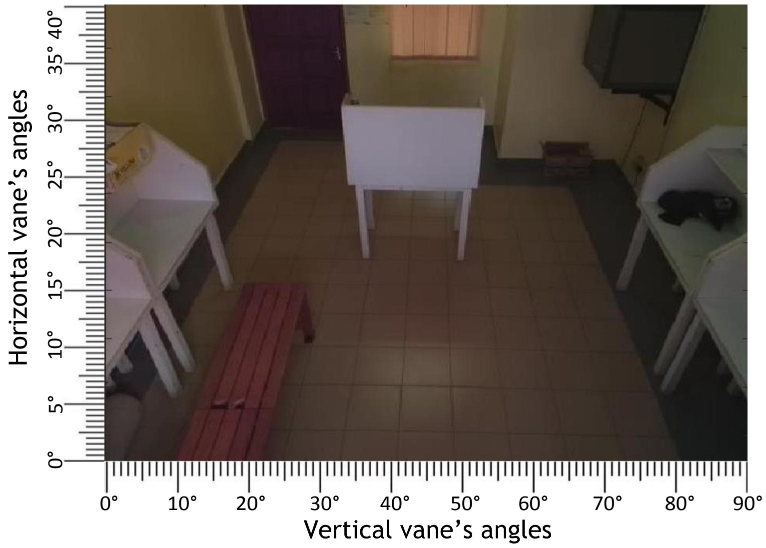


Fig. 8 - Mapping from the position on image to the angle of horizontal and vertical air-vanes of the air conditioner

The experiments conducted to test the proposed system can be divided into three parts which are: 1). Experiments on the decoy detection algorithm, 2). Experiments on the tracking function, and 3). Performance evaluation of the complete system.

3.1 Experiment on the Decoy Detection Algorithm

(1) Image Thresholding:

The infrared filter attached in front of the camera will filter out the visible light. However, during daytime, sunlight is also one of the IR sources that may interfere the detection of the decoy. Due to this unwanted IR source, the captured image has a faint background as shown in Fig. 9. To ease the detection of the decoy's IR LEDs, image thresholding is used to filter out the unwanted background. The resulting image is shown in Fig. 10. As can be seen in the figure, the faint background has been removed and only the IR LEDs source remains in the image.

Fig. 9 - Image captured by the infrared camera with an IR filter. The visible light has been supressed, but some background objects is still visible

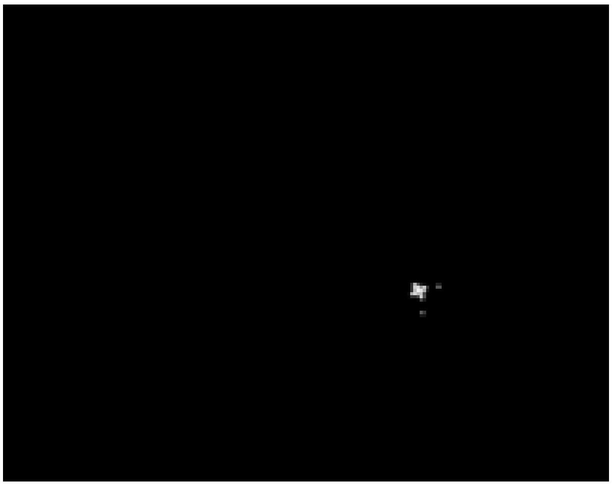


Fig. 10 - After image thresholding, the background objects have been removed and only the decoy is visible

(2) Template Matching:

Image thresholding only removes the unwanted background, but unable to identify the decoy from other IR sources. Template matching is used to verify whether the IR source is from the decoy or other objects. This is important for cases where there are other IR sources such as remote controller or indicator LED from electronic equipment in the room. Fig. 11 shows an example of image captured from a room with another IR source which is the air conditioner's remote controller.

An image that resembles the pattern of the decoy's LED as shown in Fig. 12 is used as the template. Normalised cross-correlation technique is used to measure the correlation between the template and the detected IR sources in the image. The location with the highest correlation value indicates the present of the decoy. To illustrate this, a 3D correlation graph was plotted as shown in Fig. 13. It can be observed that the location of the decoy can be easily determined since it produces a higher correlation value than the other IR source. The detected decoy is then marked with a square box in the output image as shown in Fig. 14. In our test, there is no detection error from the template matching since the arrangement of the IR LED on the decoy is very distinctive from other IR sources.

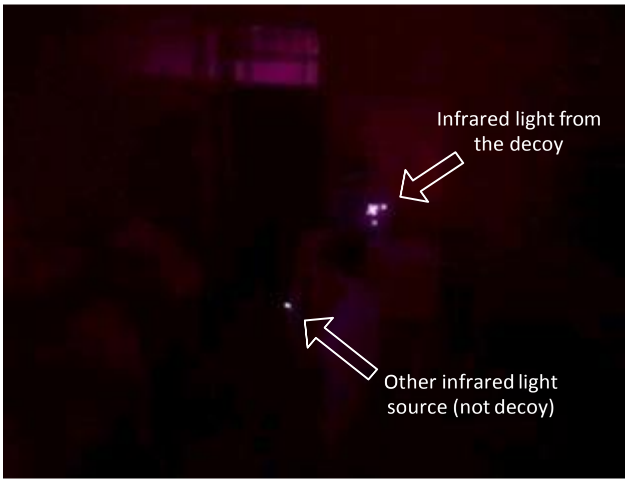


Fig. 11 - Decoy with another IR source

Fig. 12 - The template image used in the template matching

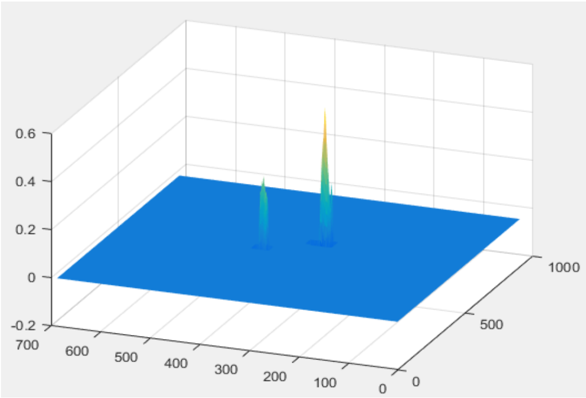


Fig. 13 - 3D plot of the cross correlation values for the two infrared light sources

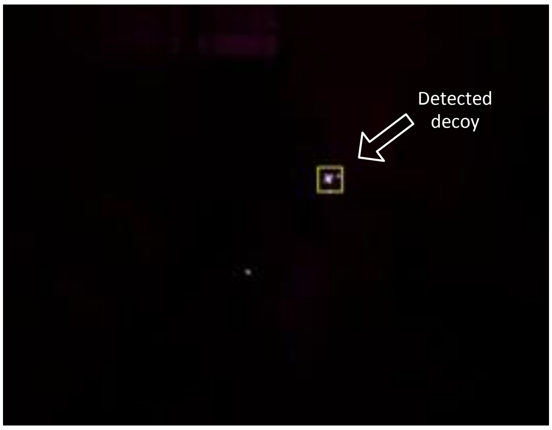


Fig. 14 - The light source with higher cross correlation value is identified as decoy and marked with a square box

3.2 Experiment on the Decoy Tracking Function

An experiment was setup to test the Kalman filter tracking function. In this experiment, a person holding the decoy walked across the room, but at some points along the path the decoy was obstructed by a table. The results are shown in Fig. 15. The red dots mark the locations of the detection results from template matching while the blue dots mark the decoy's location given by the Kalman filter. As shown in the figure, when the decoy is obstructed, template matching fails to detect the decoy. This is shown in the image where the red dots stop at the middle as the decoy is blocked by a table. However, Kalman filter is still able to predict the location of the decoy based on its previous information and continues to track the position of the decoy based in the prediction. This result shows that Kalman filter is able to overcome the problem when the decoy is momentary obstructed.

Fig. 15 - Decoy's detection results using template matching (red dots) and Kalman filter (blue dots)

3.3 Performance Evaluation of the Spot Cooling System

The implemented system was put to test by installing it in a room as shown in Fig. 7. The steps carried out in the test are described below and illustrated in Fig. 16:

(1) The system was powered up. The user carried the decoy, starting from the front, walked to the back of the room.
(2) The user then walked horizontally across the room with the decoy not obstructed from the camera view.
(3) The user walked horizontally again across the room, but this time the decoy was momentary obstructed by the table (as indicated by the dotted line).
(4) The user walked to the back of the table and stayed there for 5 seconds with the decoy obstructed.
(5) The user walked around the room randomly, with the present of other IR sources.

Two sessions of the tests were carried out, one in the afternoon and the other at night. Each session lasted for four minutes and the test videos were recorded.

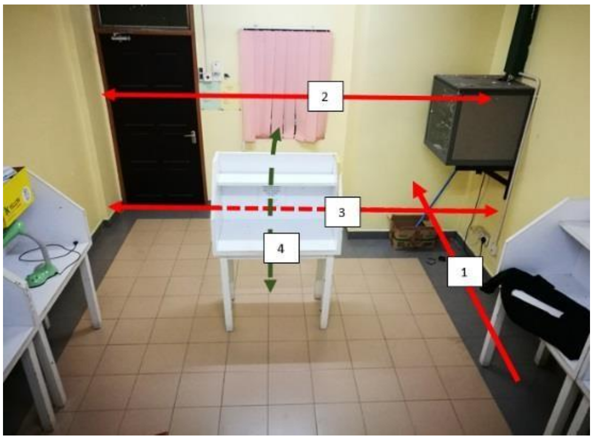


Fig. 16 - Experiments to test the proposed spot cooling system

From the resulting videos, each image frames were analysed and the number of True Detection (TD) and False Detection (FD) were calculated. True Detection is when the decoy is correctly detected while False Detection occurred when the decoy is either missed or wrongly detected. For a detection to be counted as True Detection, the detected square box must have at least 50% overlapping with the ground truth's square box. The Correct Detection Rate is then calculated by using the following equation:

$$\text{Correct Detection Rate} = \frac{TD}{TD + FD} \times 100\% \quad (6)$$

The results are presented in Table 1. It shows that the proposed method is able to successfully detect the location of decoy with correct detection rate of over 98% in both day and night-time conditions. The high detection results proved that the proposed method is feasible to be used for spot cooling implementation in air conditioner. The system can be integrated into any air conditioner to control the direction of airflow to the targeted cooling area. This provides the same cooling comfort to the user without needing to cool down the entire room and thus reduce the energy wastage.

Table 1 - The detection performance of the system

Test Condition	Number of Correct Detections	Number of False Detections	Correct Detection Rate (%)
Day time	3531	55	98.47
Night time	2915	49	98.35

4. Conclusion

This paper proposed a method of spot cooling for air conditioner. The method is based on a controller with infrared camera and a decoy. The camera continuously captures the images of the room to detect and track the position of the decoy where the air-flow is to be directed. The image processing techniques used for the decoy detection are based on image thresholding and template matching. The detected decoy is then tracked by using a Kalman filter. The proposed method was implemented on a Raspberry Pi board and tested during day and night-time. The results showed that it is able to detect the position of decoy with 98% accuracy. This system can be integrated into any conventional household air conditioner. It can help to reduce the energy usage by dynamically tracking a decoy which marks the targeted cooling area and directing its airflow to the area. The user can experience the same cooling comfort without needing to cool down the entire room.

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