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Thermal distribution monitoring of the container data center by a fast infrared image fusion technique

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ABSTRACT

This paper develops a thermal distribution monitoring (TDM) method for a container data center (CDC). First, the image is divided into hot and non-hot regions and their corner and edge features are extracted. Then, the regions that are blended by fast infrared image fusion (FIIF) technique, named as hot spot fusion; otherwise, non-hot spot fusion. In the experiments, the study tests seven benchmarks from Octets, SPi Corporation, and Kimura's literature. The results show the proposed method achieves good performance for recognizing physical position of hot spots. We also test five actual Inventec CDC images which consist of angles from 0 to 45 degree in different field of view (FOV). The method is validated to be applicable to the container data center or ordinary data center with high density of equipment. The experimental results show that the image fusion is efficient to find hot spot position for the management information system (MIS).

1. Introduction

As the applications of e-mail, social networks, online games and Internet activities have increased, the number of data centers has rapidly grown in the past few years. The annual growth rate of global servers is expected to be a number between 11% to 15% [1]. The data center is in fact the backbone of the information and communication technology (ICT) industry since it provides core infrastructure and software for global interactive connections. A conventional data center appears to be a normal office building. However, its power consumption always surprises the data center manager. According to Gartner's report [2], a common data center power consumption for a whole year is equivalent to the electricity consumed by 25,000 households. Rasmussen's studies [3] reported that global data center electricity consumption has reached more than 40 trillion Watt-hours. The data center power consumption in the United States has accounted for 1.5% of total electricity consumption [4] while the proportion of the future will be doubled [5]. The increased use of "cloud" computing for virtual collaboration, location- independent productivity and software-as-a-service (SaaS) flexibility has increased anxiety over a looming data center energy crisis.

Many data centers have been installed with adequate cooling capacity to support information technology (IT) infrastructure. There exist numbers of hot spots, which are defined as areas of elevated temperature at the inlet side of computer equipment. This can typically be attributed to either a lack of cooling capacity or inability to deliver cooling where it is needed. The following data show the usage of cooling systems results in such high power consumption. The power to the cooling systems has been observed to be much higher than that of the IT equipment, which is 50% and 30%, respectively [6], while the other equipment including PDU, UPS, switch power supply and lighting consume the rest 20% of the total energy.

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Since new generation servers consume more than 675 W/U electricity in less rack space after 2009 [6], hot spot damage has become a major concern of the data center. That is to say, the threat of overheating is a chief concern among modern data center operators. The presence of hot spots continues to hamper the efficiency of today's high-density computer equipment. Avoiding the problem is particularly essential for a container type data center for extremely high power density. For example, the average power density exceeds 14 kW/m^2 for a demonstrated container data center developed by Winstron, a server maker in Taiwan.

The characteristics of a hot spot are the dynamic changes of the locations as the workload migrates among severs. The range of temperature fluctuation reaches degrees in different areas of a server room and 20 degrees inside server cabinets [7]. Furthermore, the hot spot may occur not only on the surface of motherboards but also on the network switches or other electrical devices with abnormal conditions. There have been a lot of studies focusing on monitoring hot spot for data centers [7,8]. These studies aimed to facilitate visually locating hot spots and inefficiently cooled equipment so as to help data center managers in taking appropriate measures. However, Gartner reported that measurement and monitoring of data center energy use will remain immature through 2011 [9,10].

The threat of overheating is a major concern for data center operators as it may cause server failure and poor PUE. It is important for the operator to monitor the thermal condition of the data center in a safe and cost effective way. Past studies aimed to facilitate visually locating hot spots and inefficiently cooled equipment. Practically, the temperature data is collected using traditional thermometers and the results provided refer to point information. Though the accuracy can be improved by increasing the measurement points, the disadvantage exists due to the inflexibility in changing the location of thermometers. The flexibility can be modified by installing the thermometers in a remote robot. However, as the location of hot spots changes dynamically with workload migrating among servers, the approach provides time delay information. This paper develops the TDM method based on fast infrared image fusion technique. The method enables the operator to identify the thermal distribution based on the fusion results from visible and invisible images. The organization of the rest of this paper is as follows. In Section 2, the relative work of image fusion is discussed; in Section 3, a fast infrared image fusion technique is given. Experiment results are demonstrated in Section 4. Finally, Section 5 concludes the work.

2. Relative work

The applications and issues of data centers have been extensively discussed. Hung et al. [11] have proposed a framework for a user to create a virtual environment in the cloud for running mobile applications. However, improving computation power has been the focus of data center industry. Due to green energy and safety issues, the focus has shifted to thermal and cooling management in the data center. Several novel monitoring approaches were proposed. Li et al. [12] used an analytical model to study the temperature-dependent thermal shock resistance parameters of Ultra-high Temperature Ceramics (UHTCs). Zheng and Chen [13] proposed a 3D stochastic finite element method for the failure probability analysis of high temperature components subjected to random loadings. Practically, a mobile robot was used to carry a thermal sensor to scan a data center in which the thermal information of server racks was collected [14]. Temperature data were gathered by the thermal sensor to depict a thermal map of the computer room. The dynamic temperature can be continuously monitored by watching the two dimension map for computer room managers.

Early approaches captured infrared (IR) images of hot spots in two dimensional manners. However, owing to lack of information of visible image, the applicability of those thermal maps to on-site safety monitoring is limited. For example, thermal images often cannot give an intuitive indication for recognizing which rack, server, switch or other equipment is generating abnormal heat.

Fusion is an important technique within many disparate fields such as remote sensing, robotics and medical applications. The techniques include the simplest method of pixel averaging to more complicated methods such as principal component analysis and wavelet transform fusion. A number of publications on image fusion focus mainly on hardware devices, theoretical modeling and algorithms (e.g. US patent [15–19]).

US patent [15] proposed a methodology for forming a composite color image fusion from a set of N gray level images that take advantage of the natural decomposition of color spaces into two-dimensional chromaticity planes and one-dimensional intensity. The method can be applied to the color fusion of thermal infrared and reflective domain images whereby chromaticity representation of this fusion is invariant to changes in reflective illumination. However, controlling input fusion parameters, α and β are usually unknown to the user.

US patent [16] employed a feature and background selection method for fusion and merging video imagery from multiple sources. The approach permits a real-time, high pixel rate operation with hardware implementation of moderate cost and complexity. Furthermore, image enhancement by frequency content specification is another advantage of the approach. The flexibility permits application to many video formats and rates. However, in the patent, the sensors generating the video imagery are typically responsive to different types of spectral content in the scene being scanned, such as visible and infra-red or short and long wave-length infra-red, etc.

US patent [17] applied the weight-average method to fuse a composite image. The weights for the images are determined based on the characteristics of the images while the summation for all weights is subject to one. The applied approach is straightforward and efficient; however, the fusion efficiency depends on the determination of the weights. Moreover, the detail information of each image may be carelessly neglected and the distinguished characteristics of the original images cannot be observed from the fused image.

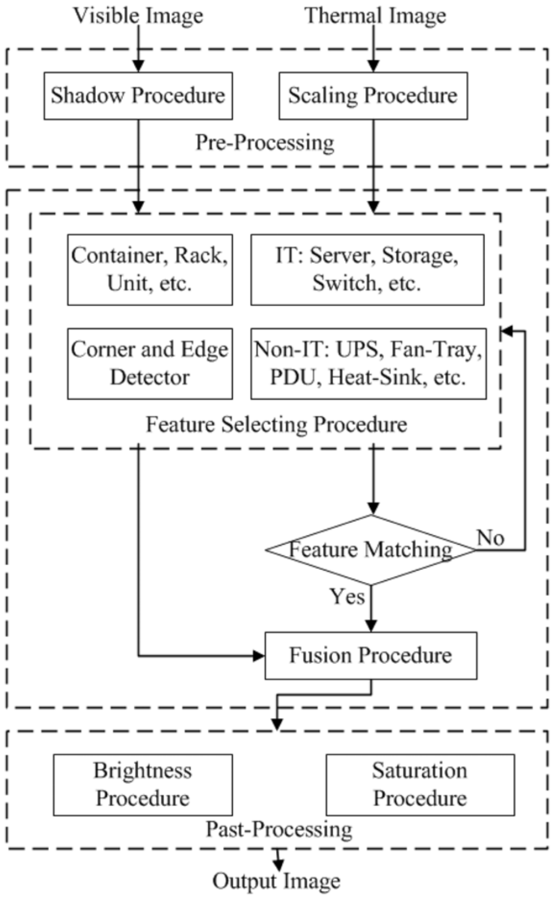


Fig. 1. Flowchart of fast infrared image fusion technique.

Chen [20] applied the principle component analysis (PCA) method for image fusion. However, the description in 3-D dimensions is missing for the fused results. A wavelet decompose method was employed to solve image fusion problems (e.g. Hill [21] and Rockinger [22]). The vivid information of images can be observed via the method; however, there exists bias in fused results due to different fusion rules. In addition to wavelet decompose, Gonzalea [23] and Jin [24] further employed principle component analysis to transfer the original images before the wavelet decomposition. In their research, the image fusion rules are preceded during the decomposing process. However, the computing process may be time consuming.

Jyothi [25] formulated evolutionary computation to estimate the optimal combinations of parameters. The noise during the fusion process can be efficiently reduced by a non-linear fusion device that provides comprehensive information. Mitianoudis and Stathaki [26] proposed a method that estimated the optimal intensity range of the fused image via optimization of an image fusion index. The proposed approach enhanced the performance of the self-trained independent component analysis (ICA) based on a fusion framework, and identified the actual optimal of the fusion performance index.

Past studies have proposed the monitoring approaches in which the temperature data were gathered by thermal sensors. The studies on image fusion focused mainly on hardware devices, theoretical modeling and algorithms. This paper aims to provide a safety and cost effective method and improve the identification of the physical position of hot spots in the data center. The paper employs the classic image fusion technique to monitor the thermal condition of the data center. The proposed method is further applied to a container data center so as to verify the usefulness of the method.

3. Fast infrared image fusion technique

Fig. 1 shows the flowchart of the FIIF technique. As shown in Fig. 1, the thermal and visible images from the same location are captured, in which the images are processed by scaling and shadow procedures, respectively. Then, the feature selecting procedure is applied to determine whether the non-hot region comes from the low temperature of light loaded equipment or a pure non-hot source based on IT, non-IT, rack and container. If the non-hot region comes from a pure non-hot source, the blue-base project method is further employed to process the area. As for the hot region, the brightness detective method is applied to estimate the brightness of the area. If the brightness value lies between brightness object thresholds, the brightness enhancement (lighten) method is preceded; otherwise, the screen method is employed for the value being between brightness thresholds of non-hot source object. The information of the hot and non-hot regions can then be obtained. The fused heterogeneous image is further derived by individually blending the hot-spot and non-hot images to their corresponding visible image. The procedures are described as follows.

3.1. Shadow procedure for visible image

The shadow procedure of a visible image $I_v(x, y)$ can be expressed as follows:

$$I_v = \begin{cases} 2 \cdot I_v \cdot inv\,(I_v) + I_v \cdot (1 - 2 \cdot inv\,(I_v)), & inv\,(I_v) < 5 \\ \sqrt{I} \cdot (2 \cdot inv\,(I_v) - 1) + 2 \cdot I_v \cdot (1 - inv\,(I_v)), & \text{otherwise}, \end{cases} \tag{1}$$

where (x, y) represents the coordinates of the image and I_v and $inv(I_v)$ are the visible image and its inverse, respectively.

3.2. Scaling procedure for thermal image

The temperature scale adjustment procedure of a thermal image $I_t(x, y)$ can be formulated as follows:

$$I_t = f\,(I_t, T_t) = I_t \cdot \frac{T_t - \min\,(T_t)}{\max\,(T_t) - \min\,(T_t)}, \tag{2}$$

where (x, y) denotes the coordinates of the image, $\max(T_t)$ and $\min(T_t)$ represent the maximized and minimized temperature of the thermal image, respectively.

3.3. Feature selecting procedure for image

The procedure for detecting whether the image is located in feature areas is designed by the corner/edge response function [27]. Let us first consider the measure of corner response, R, which is a function of α and β alone, on grounds of rotational invariance. It is attractive to use $Trace(M)$ and $Det(M)$ in the formulation, as this avoids the explicit eigenvalue decomposition of M, thus

$$\begin{aligned} &Trace\,(M) = \alpha + \beta \\ &Det\,(M) = \alpha \cdot \beta. \end{aligned} \tag{3}$$

Consider the following inspired formulation for the corner response:

$$R = Det\,(M) - k \cdot Trace^2\,(M), \tag{4}$$

where R represents the contours of constants, the value of k has to be determined empirically, and in the common literature values in the range from 0.01 to 0.15 have been reported as feasible.

3.4. Fusion procedure and transparency

There are three methods, as expressed in Figs. 2–4 [28], to build the fusion model in blending the visible image with the thermal image. The procedures are based on a general formulation that includes an opacity factor o or a transparency factor τ. The general formulation can be further expressed as:

$$I_{trans} = f\,(I_v, I_t, \tau) = (1 - \tau) \cdot f\,(I_v, I_t) + \tau \cdot I_v, \tag{5}$$

where $\tau = 1 - o$ represents a coefficient of the transparency for user adjustment, I_{trans} is the transparency image, I_v and I_t denote visible and thermal images, respectively.

4. Experimental results

In the experiment, the visible image is captured by a CMOS sensor at 1600 × 1200 pixels with 24 bit true colors. The thermal image is captured by an uncooled FPA microbolometer at 160 × 120 pixels with a resolution of 25 μm [29]. The program for the work has been coded by using Visual Studio 2010 in a machine of the configuration Intel® Core™ 2 i5 CPU M450 @ 2.40 GHz Processor and 4 GB of Physical Memory.

4.1. Algorithm validation

To validate the effectiveness of our proposed method, experiment results were compared with seven representative image sets which are provided by Octets, SPi, and Kimura. The first dataset contains images from the surveillance sequences,

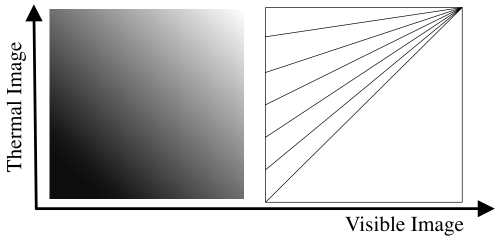


Fig. 2. Fusion model: screen method.

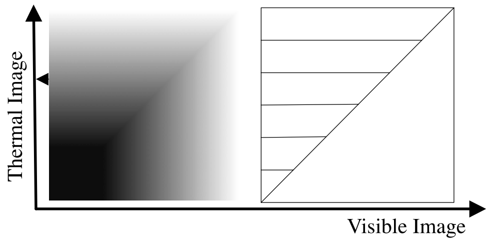


Fig. 3. Fusion model: lighten method.

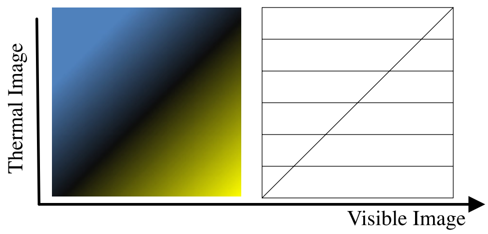


Fig. 4. Fusion model: RGB method.

which are used by the image fusion community [30]. The second dataset is provided by SPi, an IR camera company, on website [31]. The third example is a publicly available benchmark dataset from Kimura for testing and evaluating an image mixing function for thermograph [32]. In the last dataset, the fusion data is gathered from a wide variety of applications including R&D, engine and boiler room, and process monitoring.

The left-hand side images of Figs. 5–11 are the original samples of IR images. It is difficult to recognize the shapes and positions of the heat sources as a comparison with the physical photographs in the middle of Figs. 5–11. When the proposed algorithm is employed to generate the new images as shown on the right-hand side of the figures, the hot or cold area can be identified more quickly and clearly. These examples validate the effectiveness of the proposed algorithm.

4.2. *Application to the container data center*

In the section, the proposed method is applied to identify the position of hot spots on the rack in the container data center. Heat density in a data center increases quickly when the traffic of network switches and hard drives increases. The insufficient heat dissipation often reduces the performance of electronic components and shortens the lifespan of these equipments. Image fusion can be used to monitor heat which is released by the management information system (MIS) of a data center. Blending a visible image to an IR image can be helpful to identify the hot spot position on the equipment, as well as to grasp an entire image of the physical environment as shown in Figs. 12 and 13. The abnormal heat release and position can be found quickly from the blended images.

Servers emit a large amount of heat when they work. Data center managers are now very keen to technologically advance rack maintainability. The IT industry is now aware of rack manufacturers who are capable of developing efficient thermal management for the needs of conserving the environment. Fig. 14 illustrates the result of thermal image blend from visible images of racks in a container data center. Data center managers can fine-tune the workload migration or balance and utilize the Cloud OS based on the results of fusion images. Applying image fusion for fan trays and heat-sinks allows MIS to inspect side ranges of non-IT facilities for hidden problems, as potential dangerous faults such as loose connections, corroded elements, and insulator defects typically create heat. Figs. 15 and 16 are taken at non-IT equipments in a container data center.

Fig. 5. Octets: clean source image and its fusing image.

Fig. 6. Octets: noise source image and its fusing image.

Fig. 7. SPi: example of clean source images.

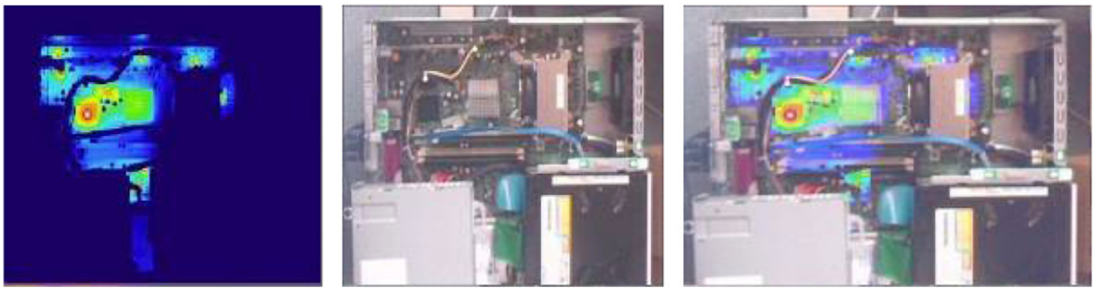


Fig. 8. Kimura: example of electronic component.

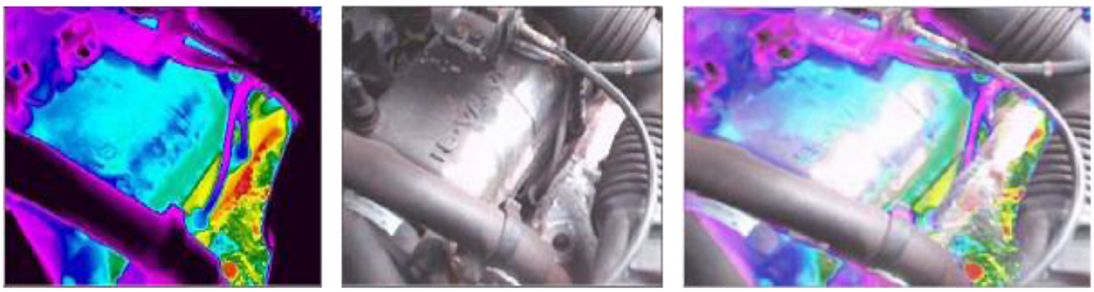


Fig. 9. Kimura: example of engine room.

Fig. 10. Kimura: example of boiler room.

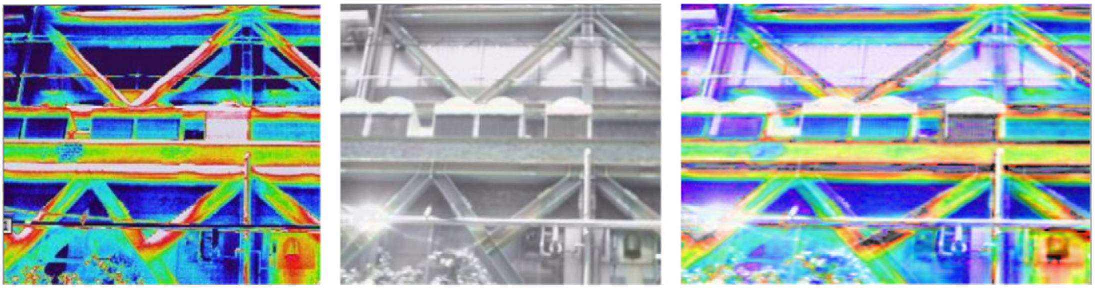


Fig. 11. Kimura: example of building construction.

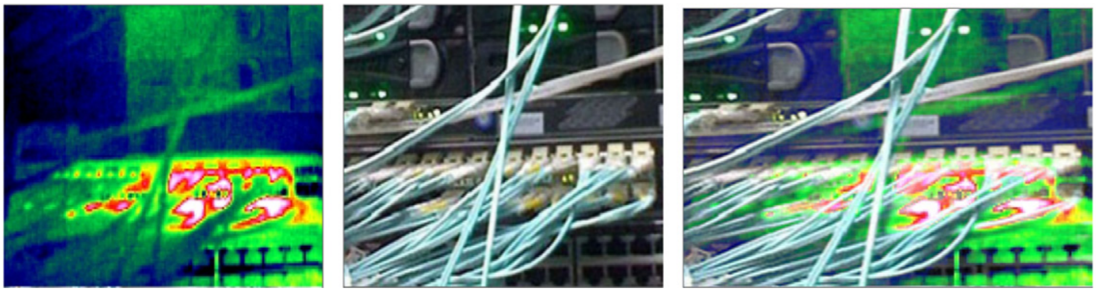


Fig. 12. Example of single switch component.

Fig. 13. Example of several switch and storage components.

4.3. Experiments with dynamical changes of hot spots

Fig. 17 shows the racks in a container data center, in which the thermal is generated from a service node, compute node and storage node in the rack. In the section, the proposed method is applied to inspect the hot spot as well as the dynamic temperature in a container data center. As shown in Fig. 17, the image is captured by the sensor, setting up against the rack. Tables 1 and 2 show the thermal, visible and fusion images in different locations of the rack using multiple cameras and in the same location of the rack using a single camera as time elapses in Cloud OS, respectively. Table 3 shows the fusion images in different locations of the rack using a single camera as time elapses with a work-load migration in Cloud OS.

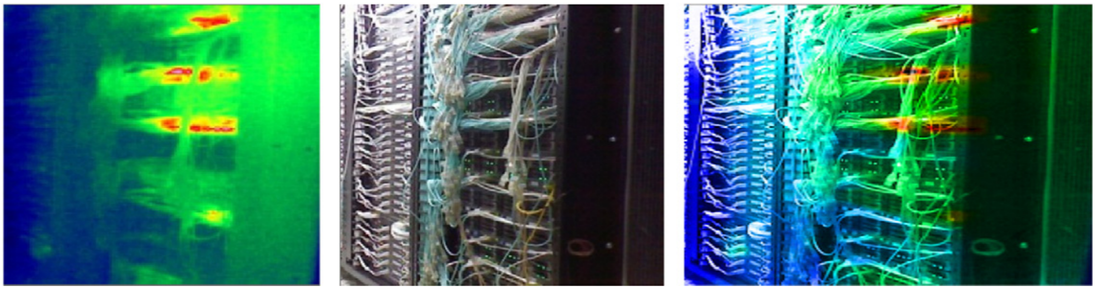


Fig. 14. Example of two racks.

Fig. 15. Example of fan tray.

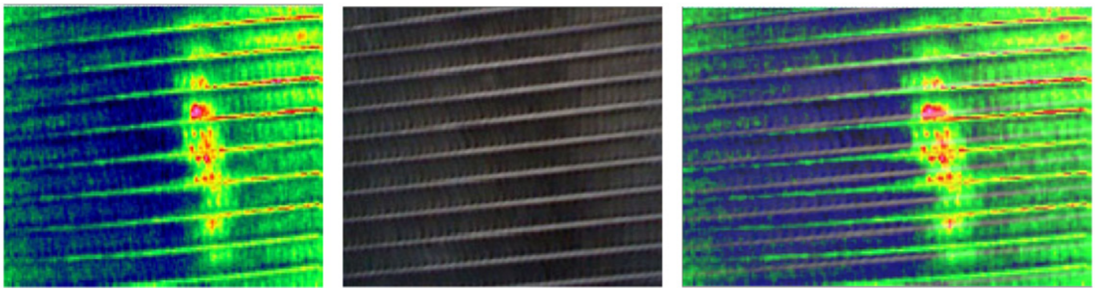
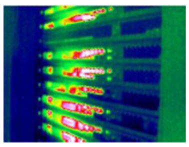
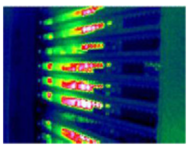
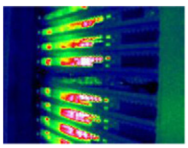


Fig. 16. Example of heat-sink.

Table 1
The thermal, visible and fusion images in different locations of the rack using multiple TDM in Cloud OS.

Position	Image		
	Thermal	Visible	Fusion
Upper			
Middle			
Bottom			

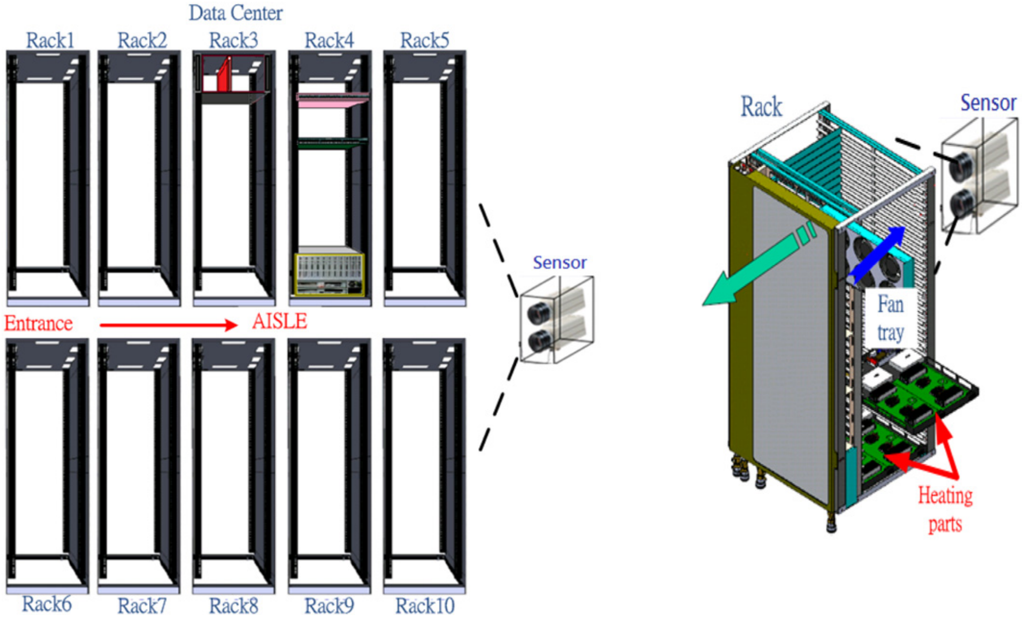


Fig. 17. The configuration of a data center.

Table 2
The thermal, visible and fusion images of the rack using single TDM as time elapses in Cloud OS.

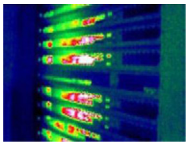
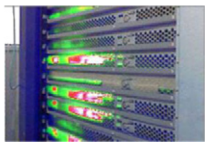
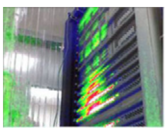
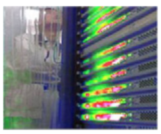
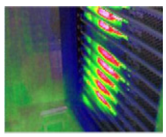
Time (s)	Image		
	Thermal	Visible	Fusion
0			
5			

Table 3
The fusion images in different locations of the rack using single TDM as time elapses during a work-load migration in Cloud OS.

Time (s)	1	2	3	4
Position	Uppermost	Mid-upper	Mid-bottom	Bottom
Fusion image				

As shown in Table 1, the fusion images result from the combinations of thermal and visible images, captured from different positions of the rack. The fusion images can provide useful information for recognizing the physical position of hot spots so as to develop the efficient thermal management. As shown in Table 2, the thermal images are taken at the same position with the time intervals of 5 s. The reduced temperature can be inspected after a work-load migration in Cloud OS.

In Table 3, the sensor is placed in the middle of the rack with a rotation device. The thermal images are captured sequentially with an interval of 1 s and a rotation of 30 degrees of the sensor. The images are captured in loops, in which the first image is obtained from the start point, i.e. the uppermost position, while the second is captured as the sensor rotates 30 degrees. i.e. mid-upper position. Furthermore, the third and forth images are captured at mid-bottom and bottom positions. Particularly, the steps of the proposed method include image input, pre-processing, feature selecting procedure, fusion procedure, past-processing, output and Cloud OS operation response time. The time intervals of the steps are at 1 s. That is to say, the proposed method can dynamically investigate the changes of temperature. The response time of migration in virtual machine needs to confirm the stability of the Cloud OS when the hot spot regions migrate to other regions with a time-delay strategy. Even so, the time response of the practical application of TDM has satisfied the specification of MIS in the Cloud Center.

5. Conclusions

This paper develops a TDM method to produce clear hot spot blending images for aiding the heat management of data centers. First, we propose the two-stage image process: feature detect and spot detect. And then we use FIIF to separate the hot spot and non-hot spots. Finally we blend each isolated spot with visible image and infrared image. In the test cases, we demonstrate the effectiveness of our TDM system that fulfills MIS requirements.

The recent approach that employed a mobile robot to collect thermal information in the data center inspired an interesting direction for depicting the distribution of hot spots in a two-dimensional manner. Improvement of recognizing the physical position of hot spots was expected especially for the container data center in which equipments are packed in a relatively small space. By adding the spatial information from the visible image to the thermal graph, tracking the position of hot spots in physical equipment can be easier. The results of this paper show that the proposed method can give improved thermal monitoring and safety control for a container data center management.

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