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HeatWave: the next generation of thermography devices

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ABSTRACT

Energy sustainability is a major challenge of the 21st century. To reduce environmental impact, changes are required not only on the supply side of the energy chain by introducing renewable energy sources, but also on the demand side by reducing energy usage and improving energy efficiency. Currently, 2D thermal imaging is used for energy auditing, which measures the thermal radiation from the surfaces of objects and represents it as a set of color-mapped images that can be analysed for the purpose of energy efficiency monitoring. A limitation of such a method for energy auditing is that it lacks information on the geometry and location of objects with reference to each other, particularly across separate images. Such a limitation prevents any quantitative analysis to be done, for example, detecting any energy performance changes before and after retrofitting. To address these limitations, we have developed a next generation thermography device called HeatWave. HeatWave is a hand-held 3D thermography device that consists of a thermal camera, a range sensor and color camera, and can be used to generate precise 3D model of objects with augmented temperature and visible information. As an operator holding the device smoothly waves it around the objects of interest, HeatWave can continuously track its own pose in space and integrate new information from the range and thermal and color cameras into a single, and precise 3D multi-modal model. Information from multiple viewpoints can be incorporated together to improve the accuracy, reliability and robustness of the global model. The approach also makes it possible to reduce any systematic errors associated with the estimation of surface temperature from the thermal images.

Keywords: HeatWave, 3D thermography, 3D mapping, handheld device, thermal-infrared

1. INTRODUCTION

Assuring sustainable energy while reducing environmental impact (e.g. greenhouse gas emissions) requires changes not only on the supply side of the energy chain but also on the demand side, by reducing energy usage and improving energy efficiency. In order to assess energy efficiency, energy auditing is often required. Current methods for energy auditing of buildings, structures, appliances or equipment include environmental sensor networks or thermal-infrared imaging cameras.¹ While environmental sensor networks provide high-temporal environment properties such as temperature at many locations, the measurements are usually spatially sparse. In addition, the installation of sensor networks requires physical modification of the environment (e.g. destructive assessment).

Alternatively, 2D thermal-infrared imaging cameras act as a non-destructive analysis tool by capturing the thermal radiation from the surfaces of objects and representing them as color-mapped images for energy efficiency monitoring. The thermal images have significantly higher spatial resolution compared to the data acquired from a sensor network. However, 2D images lack information on geometry, including the location of objects with reference to each other, particularly across separate images. Such a limitation prevents any quantitative analysis to be done, for example, detecting any changes before and after retrofitting.

To address these limitations, we have introduced the next generation of thermography devices called HeatWave. HeatWave is a hand-held 3D thermography device that can generate photorealistic 3D environment models with surface temperature information. The proposed device is comprised of a thermal-infrared camera,

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Figure 1: (a) An operator scanning the engine of a Bobcat using the HeatWave device. (b) Output 3D temperature model from HeatWave implementing the rainbow color palette. The colorbar helps to map false colors to true temperature values.

color and range camera. With the resulting 3D thermal map, inspectors are able to locate and measure geometric characteristics (e.g. area and length) of thermal irregularities (e.g. thermal defects, air leakages, heat losses and thermal bridges), which is not possible with 2D thermal imaging. Moreover, HeatWave incorporates information from multiple viewpoints to a single complete 3D model to improve the accuracy, reliability and robustness of the measurements. It is also possible to reduce any systematic errors associated with the estimation of surface temperature from thermal data such as reflection.

HeatWave can be used for a diverse range of applications such as energy efficiency monitoring, non-destructive structural, mechanical and electrical assessment, construction monitoring, fire detection, first responders and non-invasive medical diagnosis. Figure 1 illustrates a use case of HeatWave for maintenance. The operator moves HeatWave around the Bobcat engine and the 3D thermal model is generated and visualized in real-time as the data is captured. The 3D thermal model can be used to locate problems or to detect hot spots (Figure 1 (b)).

The rest of this paper is organized as follows. Section 2 introduces the HeatWave system including sensor calibration, 3D mapping and confidence-based weighted raycasting. In Section 3 we present our simultaneous multi-modal representation schemes. Section 4 demonstrates example outputs of HeatWave for different scenarios. Finally, Section 5 concludes the paper with potential future directions.

2. THE HEATWAVE SYSTEM

HeatWave is a small (less than 500 g) hand-held 3D thermography device that consists of a light-weight thermal-infrared camera, a range sensor and a visible-light camera to generate precise, dense and complete 3D models of objects with high accuracy, view independent overlaid temperature and visible information. All sensors are rigidly attached in close proximity and mounted on an ergonomic handle (Fig. 2).

As an operator holding the device smoothly waves it around a target object or set of objects, HeatWave can continuously track its position and orientation (i.e. pose) in space and simultaneously integrate new information from the range, thermal and color cameras into a single, and precise 3D multispectral model. Information from multiple viewpoints can be incorporated into a single complete 3D multispectral model to improve accuracy, reliability and robustness of the 3D global model. It is also possible to reduce any systematic errors in the thermal imaging acquired information.

Figure 2: HeatWave 3D thermography device.

The thermal-infrared camera in our current HeatWave system is an Optris PI450 with a resolution of 384 by 288 pixels, captured at 80 frames per second. This camera contains an uncooled microbolometer to detect radiation emitted from the surfaces of objects relative to their temperature with wavelengths within the long-wave infrared (LWIR) band of the electromagnetic spectrum ($7 - 14\mu\text{m}$). The presence of a temperature thermistor attached to the imaging sensor facilitates the accurate conversion of the digital output of the camera to surface temperature estimates in the scene. The NEDT (Noise-Equivalent Differential Temperature) is quoted by the manufacturer to be 40mK. A low cost ASUS Xtion Pro Live RGB-D (color and range) sensor with 30 frames per second and a resolution of 640 by 480 pixels has been used in the current HeatWave system. The Xtion has an effective range of up to four meters which is ideal for close-range 3D thermography applications.

To generate accurate and precise 3D temperature mapping, the HeatWave device needs to be geometrically and temporally calibrated. Geometric calibration is the process of estimating a set of intrinsic parameters (i.e. the focal length, focal center, and distortion parameters) for each individual modality, and estimating the relative six degrees of freedom (6DoF) transformation between the thermal-infrared camera and the RGB-D camera coordinate frames (i.e. the extrinsic parameters). Our previous work formed the basis for solving the problems of both the intrinsic calibration of the thermal-infrared camera,² and the extrinsic calibration of the multiple-modality, multi-sensor configuration.³

Intrinsic parameters of thermal-infrared camera were determined using a mask-based approach.² This method does not require any specialized chessboard with infrared lamp or fitted LEDs.⁴ The proposed method involves moving around a heated geometric pattern with square holes cut out in front of a background of uniform temperature. This is used to generate a video sequence in which the locations of the squares can be detected and tracked, and then used to estimate the intrinsic parameters.

For extrinsic calibration we used a recently proposed technique with no requirement of external artificial targets.³ The proposed method exploits natural linear features in the scene to precisely determine the rigid transformation between the coordinate frames. First, a set of 3D lines (plane intersection and boundary line segments) are extracted from the range data, and a set of 2D line segments are extracted from the thermal-infrared image. 2D-3D line correspondences are used as inputs to a nonlinear least squares optimization algorithm to jointly estimate the relative translation and rotation between the coordinate frames of range and thermal-infrared cameras.

Finally, since there is no hardware synchronization between the thermal-infrared and RGB-D cameras, we require to estimate an unknown latency between the RGB-D and thermal measurements through temporal calibration process. The temporal calibration involves capturing a series of random cyclic motions of HeatWave while pointing at a hot, bright object in front of a relatively uniform background. Then, we apply 2D blob extraction to detect and track the region of interest in both thermal-infrared and color images. The centroid locations of the blobs at each modality generate two signals that can be used to determine the latency between the two cameras.⁵ The device requires only a one-time calibration at the time of manufacturing.

2.1 3D Mapping

In order to generate consistent 3D maps of environments, the HeatWave system needs to continuously estimate its six degree of freedom (6DoF) trajectory (i.e. its position and orientation) at all times during acquisition. The challenge of concurrently building a map and estimating the trajectory of the device in an unknown environment without any external reference system is a well-known problem in the robotics community called Simultaneous Localization and Mapping (SLAM). In the HeatWave software, the 3D model is stored in GPU (Graphics Processing Unit) memory, which enables it to be updated and processed rapidly by taking advantage of parallel programming.⁶

HeatWave solely uses its range camera to estimate relative pose of the device by registering each new depth frame with the existing 3D model using the Iterative Closest Point (ICP) optimization algorithm.¹ Simultaneously, it uses the information of the new depth frame to update and optimize a dense 3D model.

Once the pose of the range camera is determined, the temporal and extrinsic calibration parameters are used to estimate the relative poses of the thermal-infrared camera for each frame. Given the estimate of the poses of all the sensors, appearance information and temperature distribution from the color and thermal-infrared cameras are overlaid on the 3D model using the proposed raycasting method in the next section.

2.2 Confidence-based Weighted Raycasting

Raycasting refers to the process of assigning estimates of surface properties to the 3D model using 2D image data. Because the HeatWave device includes a thermal-infrared imaging sensor as well as a color camera, raycasting can be used to assign both temperature and color to the model. Spatially accurate assignments are only possible because of the reliability of positional estimates for the sensor throughout the capture sequence using the method introduced in Section 2.1.

Because there are many frames captured from many viewpoints in a single data sequence, multiple temperature estimates are often available for the same discretized surface region of the model, with each estimate corresponding to a ray originating from a single pixel in a single image. With a large number of estimates available, conventional methods for raycasting may simply average the assignments from each ray to a single surface region, in order to improve accuracy beyond relying on a single (e.g. the latest) estimate. However, this approach fails to take into account the reliability of each individual estimate, which can vary considerably due to factors such as the motion of the sensor, the distance to the surface, and importantly, the angle between the sensor and the surface normal.

The proposed system implements a confidence-based weighted raycasting methodology which combines temperature estimates intelligently by considering factors that influence the reliability of each individual ray. The final temperature estimate for a surface region is determined by an averaging function, which takes as input a set of confidence-weighted temperature estimates. For the standard offline implementation, the averaging function can be applied for all temperature estimates subsequent to the scan, however, for the real-time implementation or when memory is scarce, the averaging function can instead be updated with individual values as they become available. This online averaging involves first estimating a current assignment confidence value C_A which applies to the existing estimate of the temperature of the surface region. The difference between this assignment confidence and the confidence of the latest ray C_R is then used to determine the degree to which the current assigned temperature V_A should be updated given the latest estimated temperature V_R .

First, a relative weighting Q for the latest ray is determined, as described in Equation 1.

$$Q = \begin{cases} 0, & \text{for } (\Delta \leq -b) \\ \Delta + b, & \text{for } (-b < \Delta < b) \\ 1 & \text{for } (\Delta \geq b) \end{cases} \quad (1)$$

Here, b is the “recency” bias which is a user-configurable variable. This variable can range between 0 and 1, with a higher value emphasizing more recent measurements. Δ is the difference between the existing assignment confidence C_A , and the confidence of the current ray, C_R .

The new assignment confidence C_A , and the new assignment temperature value V_A , are calculated using Equations 2 and 3 respectively.

$$C_A := Q \cdot C_R + (1 - Q) \cdot C_A \quad (2)$$

$$V_A := Q \cdot V_R + (1 - Q) \cdot V_A \quad (3)$$

The confidence value of a single ray C_R , is calculated as the product of confidence scores c_i for a set of i metrics, as shown in Equation 4.

$$C_R = \prod_{i=1}^N (c_i)^{p_i} \quad (4)$$

Each confidence score is defined as a value between 0 and 1, and can be raised to a specified power p_i , to vary the relative influence of that particular metric. For the current iteration of HeatWave, five metrics were selected based on observations of their significant effect on the reliability of raycast-based estimation. These five metrics were the following:

- c_1 : the motion-uncertainty of the camera
- c_2 : the level of lens distortion
- c_3 : the angle between the ray and the surface normal of the vertex
- c_4 : the distance of the vertex from the camera
- c_5 : the favorability of the operating conditions of the camera

3. MULTI-MODAL REPRESENTATION

The output of HeatWave is a single complete 3D multiple-modality model with high accuracy in terms of geometry, surface temperature and visual appearance. Temperature and visible information is view-independent and can be used to detect any appearance, shape, temperature or temporal changes within the environment.

Currently available visualization systems which have access to both thermal and visual data often require the operator to manually switch between visualizing the model with either temperature or color information. One compromise that is sometimes offered is to display temperature information in the form of a 2D image which is overlaid onto the conventional color representation, known as Picture-in-picture (PiP). Neither of these methods enables temperature and color information to be visualized simultaneously for the same regions of the 3D model. This prevents the operator from efficiently observing related phenomena that are each only visible in a single modality, and can easily lead to oversights during inspections. For example, without a simultaneous multi-modality representation, a text-based label and the overheating of a corresponding physical component cannot be observed at the same time.

In contrast, the dense, high-resolution 3D multi-modal model produced by HeatWave can be visualized with both thermal and visible-spectrum information simultaneously using two alternative multi-modal visualization schemes including IH Mapping and Thermal Highlighting. IH Mapping combines a hue (pure color) representing the temperature with the detailed textural information only available in the conventional visible modality. This enables a viewer to quickly get an accurate sense of temperature without the typical sacrifice of losing image detail by switching to a thermal-only representation. Thermal Highlighting preserves color from the visible spectrum representation, but overrides this with temperature information for surface regions that have abnormal temperatures. Depending on the thresholds set, this could serve the purpose of drawing attention to dangerously hot or cold temperatures, or perhaps temperatures restricted only within a specific range. These schemes are shown in Figure 3 along with the temperature-only and color-only options. Figure 3 shows a 3D model an air compressor with a compressed air dryers. As you can see the thermal only 3D model (Figure 3 (a)) lacks textural information such as brand labels but the alternative fusion schemes (Figure 3 (c) and (d))) preserve both temperature and appearance information on a single model.

Figure 3: Demonstration of alternative fusion schemes for texturing a 3D model with color and thermal data simultaneously. The model is of a subsection of a compressor unit. The (c) IH Mapping and (d) Thermal Highlighting schemes enable textural detail from the visible spectrum to be represented on the model, whilst still displaying critical temperature information.

4. RESULTS

In this section, we evaluate the performance of the HeatWave device for several 3D multi-modal mapping applications. The first example (Figure 4) shows 3D thermal model of a chiller water pump system including hot and cold spots. The three phase induction motor was overloaded which caused overheating. The 3D thermal model helps an inspector to clearly see temperature variation from different viewpoints and measure thermal irregularities. Since the model is in 3D, inspector could generate several models of the water pump system during different phases of its performance to quantitatively compare the temperature distribution variations over times.

Figure 4: 3D thermal map of a chiller water pump system using the rainbow color palette. The colorbar on the left helps to map false colors to true temperatures.

Because HeatWave consists of both a color and a thermal camera, it can provide both photorealistic and thermal 3D maps. Figure 5 illustrates two 3D maps of a water-cooled chiller system. The color only 3D map (Figure 5 (a)) reveals many details such as the colors of individual pipes and a warning sign, while the 3D thermal map (Figure 5 (b)) shows the damaged insulations of the pipes and wires that are hidden to the color model.

Figure 6 shows an area scan of a building with two HVAC cooling tower driver systems in the middle and a part of an orange airconditioning switch board. The hotspot indicates a short circuit that can potentially start

Figure 5: (a) Output 3D color model of a water-cooled chiller system. (b) Output 3D temperature model a chiller system using the rainbow color palette. The colorbar helps to map false colors to true temperature values.

Figure 6: (a) Output 3D color model of an airconditioning control system. (b) Output 3D temperature model an airconditioning control system using the rainbow color palette. The colorbar helps to map false colors to true temperature values. (c) Output of the fused model using Thermal Highlighting.

a fire. While in some cases only color (Figure 6 (a)) or thermal (Figure 6 (b)) information may be preferred individually, there are many situations in which the presentation of both forms of data in the same model (fusion) may be desired. The Thermal Highlighting (Figure 6 (c)) scheme is able to do so, whilst still enabling the user to identify hot and cold spots easily with both thermal (temperature) and color data simultaneously incorporated into a dense 3D model. Video demonstrations of more 3D thermal models can be found at the project page *.

5. CONCLUSION

For efficient and fast energy efficiency monitoring we have presented HeatWave: a handheld 3D thermography device that allows an operator to generate a highly accurate 3D model with augmented temperature and appearance information in real-time. 3D multi-modal models produced by HeatWave can be visualized with both thermal and visible-spectrum information simultaneously. This can reduce the cognitive load on the operator by allowing them to focus on a single 3D multi-modal model. Information in real-time is presented to the operator as it is being captured, assisting them in avoiding accidentally skipping parts of the scene. The proposed system is capable of address many of the limitations of 2D thermal-infrared imaging, particularly through the utilization

*<https://wiki.csiro.au/display/ASL/HeatWave>

of geometric information. HeatWave can continuously track its pose in space and integrate new information from multiple viewpoints into a single, precise 3D model to improve accuracy, and to reduce systematic errors that can occur in conventional thermal imaging such as those due to reflection. Future generation of HeatWave will include alternative pose estimations from different modalities to improve robustness of system in challenging situations. Furthermore, we will be looking into increasing the maximum size of environments that can be mapped using different SLAM solutions.⁷

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