Depth Thermography of Hot Objects in Cool Environments

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1 Abstract

Depth thermography is the idea of using temperature to find depth when usually thermal images only display two-dimensional (2-D) information. To find depth thermography a controlled environment is built where two thermal cameras monitor the object being studied perpendicular to each other. The thermal cameras are being processed through Raspberry Pi which is looking for the pixel of the brightest value and that pixel's position coordinates. When the pixel data is collected it is broadcast on a private channel to the other pi. The Pi uses both sets of pixel coordinates to find a position of depth. The computational measurement of depth needs to account for the total range of the cameras since if the cameras are too close they will be out of range from each other and will not be able to find an accurate distance. With this modification in mind, a conclusion has been reached that depth can be found to be accurate even through other mediums with some limitations.

2 Introduction

The temperature distribution for an infrared image is a two-dimensional (2-D) mapping of the thermal emission, which is electromagnetic waves that are dependent on the fluctuations of temperature [7]. The temperature measured within the image can be from any depth within the object. This results in a large loss of information in the temperature profile from not knowing where these temperatures are located within the width of the object. Depth thermography would be beneficial in mitigating these problems. Depth thermography derives temperature as a function of depth by applying the thermal-emission spectrum to the semitransparent shadow region of the object [7]. Depth thermography uses the information gathered by the temperature maps created by two infrared images at different angles to separate surface temperatures from internal temperatures. Mapping the same event at different angles allows a relationship between the 2-D images to be formed considering the highest temperature seen in one image will be seen in the other at a position where the depth of the object can be measured. This type of information output could help many fields of science and engineering such as molten-salt nuclear reactors [7].

In this project, I will examine the relationship between heat emission and depth. This will be achieved by building a controlled environment where two thermal cameras perpendicular to each other will be used for experiments. Experiments of a warmed plastic cylinder, mug of water, and chicken with bone will be tested to find the position of depth of the cylinder, mug, and bone. The outputs will be integrated and used to find a position of depth using Python code. The position of depth for these objects will be compared to the measured location and will be recorded and analyzed to determine the efficacy of depth thermography.

3 Theory

Infrared images present a temperature map that does not accurately reflect surface temperature and internal temperatures since the information is only given in 2-D. Infrared images take the highest temperature of all widths to display the image. The map will show the range of temperatures throughout the object with no information pertaining to the depth of these hotspots. This is an interesting challenge faced by those trying to record temperature throughout an object. Some scenarios would benefit from profile results showing temperature throughout the volume of an object. In applications such as hyperthermia, volumetric temperature readings would be useful. In hyperthermia treatments, where heat, sometimes in the form of lasers, is used to raise the temperature of tumors to make them more susceptible to other treatments, the inconsistent temperature measurements between the surface of the skin and the internal temperature of the tumor can make it difficult to heat tumors deep within the body without damaging organs [1]. This is an idea I study in my research that poses challenges for the clinic that contracted my research advisor.

Depth thermography can provide information on all the temperatures in the object, but for this project there is a focus on finding a single hotspot's position of depth. The infrared images are placed in grayscale to allow the viewing and analysis of the temperature of the hotspot to be simplified. White has a wavelength between 400-700 nm and black has no wavelength since black is the absence of visible light. White pixels have a value of 255 indicating the highest temperature while black has a value of 0 indicating the coldest temperature. These values are relative to the objects being measured, an object of temperature 27°C in an environment of 21°C will show white just the same as an object of temperature 49°C in the same environment. Infrared cameras interpret energy emission in a range of 700-1000 nm and since white and black have no specific wavelengths associated with them it compresses images to the barest minimum pixels requirements. This compression allows the code analysis to find a position of depth to be easier. The code scans through the image looking for the first pixel with the value 255, which given that the experiments are hot objects in cooler environments the first pixel with the value 255 will be within the object since the scale adjusts to what is being measured. The pixel with value 255 will be saved along with the pixel coordinates and once both pixel coordinates are gathered these will be how the position is found by relating the pixel coordinates to the coordinates of the position. The position of the hotspot in the image of one camera details the position of depth to the other camera.

To investigate this method of depth thermography the experimental samples will become more complex and smaller to see if the coordinates of position are accurate. The first sample will be a mug of water with a larger diameter. The water has a more universal temperature distribution than the later samples which makes it easier when creating the code to find the object. The second sample will be a plastic cylinder of a smaller diameter. This cylinder should be solid which allows for a temperature distribution that is consistent within the object. The third sample will be a chicken drumstick where the code will be measuring the temperature of the bone within the meat. Chicken bones are porous and filled with marrow which makes them poor conductors of heat [2]. Thermal diffusivity is an equation that indicates the rate at which an object heats up [2].

$$\alpha = \frac{\kappa}{\rho C_p} \tag{1}$$

The average thermal diffusivity of chicken bones is 0.776 $\frac{mm^2}{s}$ while the average thermal diffusivity of white chicken meat is 0.3621 $\frac{mm^2}{s}$. The density of the bone does depend on many factors. This calculation is done with the assumption that 30% of the chicken drumstick is bone and where the average density of the whole drumstick is 570.61 $\frac{kg}{m^3}$ [5]. This shows that chicken bones heat faster and hotter than the meat surrounding them. Given this information, the infrared images should produce results showing the bone, and the depth thermography should produce a position of depth of the bone.

4 Methods

4.1 Construction

To conduct these experiments, a protected environment is required to minimize any background radiation that would add noise to the data. In past experiments, complications arose from background emissions interfering with sample readings [7]. To limit the effect of background emission, an enclosed space is required to prevent influential factors such as reflective surfaces, drafts, direct sunlight, radiant heat, and strong lighting [3]. This habitat is built from wood and cotton due to their low thermal conductivity of $0.08 - 0.16\frac{W}{mK}$ and $0.026 - 0.065\frac{W}{mK}$ respectively [6] [4]. The two thermal cameras are placed perpendicular to each other inside the environment. This format is displayed in Figure 1 where the dashed line indicates the cotton curtain. From the middle of the top of the environment, a hook should be added for the chicken sample. A string and four toothpicks will be needed for this sample set. The coordinate system displayed is the coordinate for the camera on the left wall. Each camera has its own coordinate system which is used to process the images before being adjusted for the final depth.

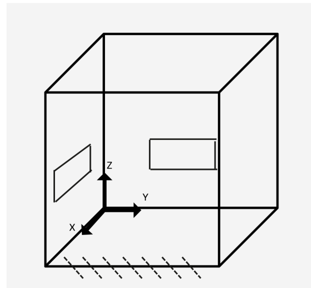

Figure 1: Proposed Habitat

The equipment used to gain and process the thermal images is two Raspberry Pi 2B+s and two MLX90640 thermal cameras. The Raspberry Pi uses Python code to take an image and find depth. To visualize the incoming data each Pi is plugged into a monitor with a mouse and keyboard. To connect the two Pis together for them to communicate an Ethernet switch is used. It is important to note that when using a switch to not plug an Ethernet cord into a wall and just one to each Pi or else the messages being sent will go to everyone on the network and not just the two Pis plugged into a private network.

4.2 Computational

Once the setup is complete the focus shifts to how to use these tools to find depth. The relationship between the two Pis is an important concept to understand how to gain depth. Raspberry Pi One is the original Pi while Raspberry Pi Two is the Pi awaiting data before starting their process. The Raspberry Pis are both coded to take pictures of the displayed thermal image and refresh five times with a refresh rate of every 9-10 seconds. This slow rate is due to the older model of Raspberry Pi so for a newer Pi model it would be faster. When Pi One completes its first cycle the data is sent to Pi Two to start its first cycle. This is so that when Pi One reaches its fifth cycle, Pi Two will be completing its fourth cycle which will be used to find depth. The reason for the five cycles is to allow enough time for the cameras to get a more accurate reading which is by the fourth cycle, but Pi One runs through a fifth cycle to allow Pi Two to obtain a fourth cycle.

The thermal images are in grayscale to more easily see the gradient of temperature and allow for less complex code. After each of the five refreshes, the image is processed for a pixel coordinate for the brightest point, which would have a pixel value of 255 which indicates white, the hottest point. Once this value is found the pixel (x,y) coordinate is saved and broadcasted to the other pi which is waiting to receive this data before doing the same process. When Pi Two has found the brightest point value and pixel coordinate it is sent back to Pi One. This cycle goes on until the fifth turn. Once the last cycle completes the pixel data is converted to find the position of the object in the box relative to the corner.

To convert pixel coordinates to coordinates of position an understanding of the coordinate system needs to be made. Each camera has a different coordinate system relative to the camera which is in use. The method of converting coordinates is outlined in Figure 2. The (D1, Y1) pixel coordinates are the coordinates for Pi One but are the depth of the object from Pi Two. Similarly, (D2, Y2) are the pixel coordinates for Pi Two but the depth from the object to Pi One. The Y coordinate for both cameras does not have any effect on depth since the cameras only see a 2-D image where y determines the height of the object from the top to the bottom of the box. Using the coordinate system of Pi One (D1, D2) is the position of depth. The conversion from pixel (D1, D2) to position (D1, D2) is done through a conversion factor of pixel to centimeter with a constant added on. The need for a constant is derived from how a camera's view is shaped. A camera's view is pointed at an angle that becomes wider the further away the focus is from the camera. Since the box is small the view of the other camera does not come into view within the range of testing distances so there is a need to add a constant of value 12.4 cm. This position is compared to the measurement obtained by hand using a ruler.

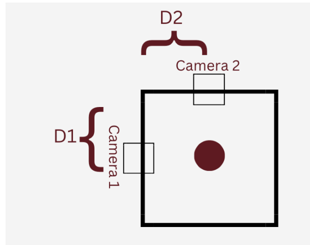

Figure 2: Depth Coordinates

4.3 Testing

To build the computational code that creates accurate data many tests have been run to adjust and modify the computational depth measurements. To test the accuracy of the computational model objects with a range of diameters were used. With each of the first two samples, the object was moved around the box to see if the readings were still accurate within a given range of the constant. The third sample set was hung on the top of the box on a hook so could not be moved. The first sample was a mug of water with a diameter of 6.9 cm. This was to see if any point on the mug could be found before moving on to more challenging objects. The second sample was a plastic cylinder of 2.8 cm diameter. The smaller diameter was to test if the computational depth measurement was still within range of the object when there was less area and a smaller range of temperature. The water was on average 35°C and the cylinder was on average 30°C where the room was of temperature 20°C. The third sample was a chicken drumstick where the head of the drumstick had a 5.8 cm diameter and the bone had a width of 1.2 cm. Since bones have a higher thermal diffusivity than meat this test was to see if the infrared cameras could detect a hotter object with a heated medium. The string was used to hold the drumstick suspended from the hook in line with the cameras. The toothpicks were placed with two toothpicks on the front of the chicken and the other two perpendicular with the front-facing toothpicks with the bone in the middle. This is used as a reference point as to where the bone lays within the drumsticks to measure the position of the bone. The chicken drumstick was heated with a 1000 Watt microwave for 30 seconds for each cycle of heating.

5 Results

For each sample, five sets of experimental data were collected. The calculated coordinates are the coordinates of the position determined by the computational model. The measured coordinates are the range of where the object was in the box measured by hand. Below are all three sets of sample data.

	Measured Coordinate (cm)	Calculated Coordinate (cm)
Experiment 1	(16.1-23, 18-24.9)	(19.56, 18.82)
Experiment 2	(15.3-22.2, 18.1-25)	(17.77, 20.56)
Experiment 3	(15.8-22.7, 18.6-25.5)	(19.56, 20.92)
Experiment 4	(15-21.9, 17.1-24)	(17.77, 17.65)
Experiment 5	(15.9-22.8, 18.2-25.1)	(16.57, 19.56)

Figure 3: Data from Mug of Water

The range of the water within the mug is determined by the diameter of the mug which was 6.9 cm. The results show that each of the points from the calculated coordinates falls within the range of the measured coordinates.

	Measured Coordinate (cm)	Calculated Coordinate (cm)
Experiment 1	(19.5-22.3, 20.5-23.3)	(21.3, 22)
Experiment 2	(19.5-22.3, 20.5-23.3)	(20.7, 22.6)
Experiment 3	(18.7-21.5, 19.3-22.1)	(19.9, 21.9)
Experiment 4	(20.5-23.3, 17.9-20.7)	(20.9, 18.2)
Experiment 5	(20.2-23, 17.5-20.3)	(22.6, 17.7)

Figure 4: Data from Plastic Cylinder

The range for the measured coordinate was 2.8 cm due to the diameter of the solid plastic cylinder. Each point from the calculated coordinate was within range of the measured coordinates.

	Measured Coordinate (cm)	Calculated Coordinate (cm)
Experiment 1	(20.5-21.7, 19.5-20.7)	(20.8, 19.9)
Experiment 2	(19.4-20.6, 20.8-22)	(20.1, 21.9)
Experiment 3	(19.4-20.6, 20.8-22)	(20.1, 21.9)
Experiment 4	(19.4-20.6, 20.8-22)	(19.6, 21.9)
Experiment 5	(20.5-21.7, 20.4-21.6)	(21.1, 21.3)

Figure 5: Data from Chicken Drumstick

The range for the measured coordinates was based on the diameter of the bone which was 1.2 cm. Experiments 2, 3, and 4 have the same range of measured coordinates since these were all tested on the same cycle of reheating. The range does not vary much since the drumsticks were hung on the same hook each time, but since the drumstick was not uniform there was still variation in the measured coordinates due to the abstract shape of the drumstick. The measured coordinate of where the bone's location was done by inserting toothpicks on both sides of the bone and then measuring the location of the toothpicks when the drumstick was in position. Each experiment was within the range of the measured coordinate.

6 Analysis

The data collected reflects the assumptions made within the theory. The position of a hotspot can be found by using the temperature map of the same event at different angles. It is interesting to note that in the chicken drumsticks sample set experiments 2 and 3 had the same calculated coordinates and were measured one after another with about 5 minutes in between. Presumably, this can attest to the accuracy of measuring a hotspot that exists in this location.

The results show that each coordinate of position falls within the range of the measured coordinates. To test the accuracy of these points the midpoints were used to determine the error analysis. It is reasonable to assume that the hotspot will not land at the midpoint within each experiment, but for the process of error analysis, we will assume that the hotspot is at the midpoint. Under these assumptions, the average percent error for each set of experiments is 8.453% for the mug, 3.489% for the cylinder, and 1.372% for the bone. It is observed that as the range of measured coordinates shrinks the error also decreases. The range for the mug of water was 6.9 cm so it is not surprising that the percent error is as large as it is since the hotspot could land anywhere within that range.

While the data does show accurate measurements of positions of depth there are limitations in regard to the region that this accuracy falls under. There is a need for a constant that changes with the position of the object relative to the camera's view. The constant that was used in this project was made for only the center of the box directly in front of both cameras. If more time was allotted for this project a function that changes the constant based on the pixel coordinate would be designed. The function would use the pixel coordinate to reference which constant pertains to that specific area and then add that on before reporting the final position of depth.

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