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Abstract

It is extremely important for the performance and success of the system to know the cooling or heating surfaces of the thermoelectric modules (TEMs) as cooler or generator, according to the heat transfer direction, and to carry out their installation correctly, taking this into account. In TEMs, the direction of heat transfer between surfaces changes depending on the applied DC direction, and while one surface of the module cools, the other heats up. In this respect, the state of the positive and negative poles in the design and production of TEMs directly affects the heat transfer direction between the module surfaces. On the other hand, the contact direction of the surfaces of the TEMs used in a designed thermoelectric system (TES) is of great importance in order to perform the heat transfer correctly without loss of performance. In this study, a system is designed to detect the heat transfer direction of TEMs using image processing techniques. The basic principle of the system is to determine the positive and negative poles of the TEMs together with the ceramic plate, using the color-based image processing method, and to determine the heat transfer direction by utilizing their relative positions. With the designed system, the heat transfer direction of TEMs at different illuminance levels is tried to be determined and successful results were obtained. As a result, it is thought that the developed system will contribute to the automatic error control for the production and assembly of TEMs.

Keywords: Thermoelectric Module, Peltier Effect, Seebeck Effect, Heat Transfer, Image Processing, Software

INTRODUCTION

The popularity of thermoelectric modules (TEMs) is increasing, and their application areas are rapidly becoming widespread due to many advantages, such as being silent, vibration-free, long-lasting, and simple. Additionally, they have no moving parts, can operate in any direction, and require no maintenance (1). Various research efforts are underway to advance the design, production, testing, and application of TEMs in thermoelectric systems (2-6).

In general, it is desired that a thermoelectric system (TES) to be designed for cooling or power generation should have high heat transfer, low power consumption and at the same time economical. In practice, only a single TEM can be used according to the desired capacity in TES design, or several TEMs can be used by connecting each other in series, parallel or cascade. The number of TEMs needed and the connection type are determined by considering the electrical and thermal parameters of the TEMs used (1).

It is extremely important for the performance and success of the system to know the cooling or heating surfaces of the TEMs as coolers or generators according to the heat transfer direction, and to carry out their installation correctly considering this situation. Because, incorrect assembly of TEMs can cause TES to perform poorly or even to work completely incorrectly in cooling or electricity production, depending on the design purpose. Hence, it is very important not to make wrong placements and to correct them immediately. In this respect, first of all, it is necessary to determine the heating and cooling surfaces of the modules to be used in the design according to the DC polarization status.

In general, it is difficult to detect the heating and cooling surfaces of the TEMs due to their simple ceramic structure and the fact that both surfaces are exactly similar to each other. Incorrect surface use affects performance negatively, especially in systems where a large number of modules are used. Conventionally, the heating and cooling surfaces of a TEM are determined either by visually checking the status of the positive (red) and negative (black) poles or by controlling the temperature with DC voltage. In addition, some manufacturers indicate in writing on the heated surface of the TEM in the direct biasing. Detection procedures made in this way may prolong the process and cause errors.

Recently, computer vision applications have become widespread with the development of image processing algorithms and software technologies. Image processing systems are widely used in industrial areas for fast and accurate detection, tracking and classification of objects. Classification of objects based on image processing can be done using shape, motion, color and texture based methods (7). Color-based classification methods are widely used because of the high processing speed and success rate (8). Determining the position of an object detected in image processing algorithms on the image is based on the principle of finding the center of gravity (9).

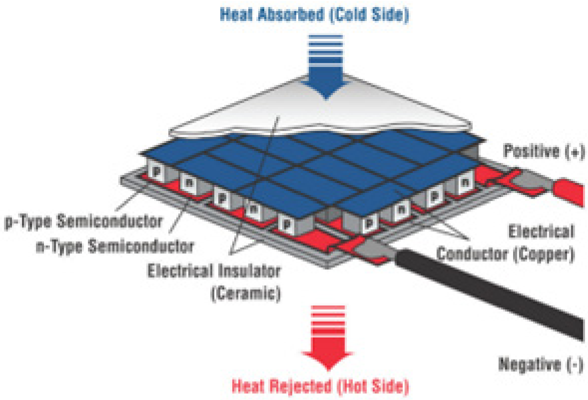
In this study, a system is designed and the performance of the system is analyzed to determine the hot side, cold side and heat transfer direction of the TEMs, using color-based image processing techniques and based on the principle of finding the center of gravity.

MATERIAL AND METHODS

Heat Transfer in Thermoelectric Module

TEMs are devices consisting of N-type and P-type semiconductor thermocouples placed in a matrix array between two external plates, electrically connected to each other in series and thermally connected to each other in parallel. In addition, they can operate both in cooler mode according to the Peltier effect principle and in generator mode according to the Seebeck effect principle. Figure 1 shows a TEM general view and structure. TEMs operating on the DC principle have two connection terminals, one being the positive (red) pole and the other being the negative (black) pole (10, 11).

(a)



(b)

Figure 1 (a) General view and (b) structure of a TEM (11)

P-type and N-type thermoelectric semiconductors form the fundamental components of heat transfer within TEMs. Negative charge carriers (electrons) are the majority charge carriers in N-type semiconductors, and positive charge carriers (halls) in P-type semiconductors. Figure 2 shows the heat transfer direction for a TEM operating in cooling and generator mode. According to the Peltier effect principle, heat transfer occurs in the direction of electron flow and hall flow through charge carriers, depending on the DC current intensity and polarization applied in TEM. As a result of the heat transfer caused by the Peltier effect, one of the sides cools and the other heats up. In other words, with the Peltier effect, heat is transferred from the cold side to the hot side, and no heat is produced. On the other hand, according to the Seebeck effect principle, a DC current is produced by the charge carriers depending on the direction of the heat transfer that occurs as a result of the temperature difference created between the surfaces in the TEM (6, 12).

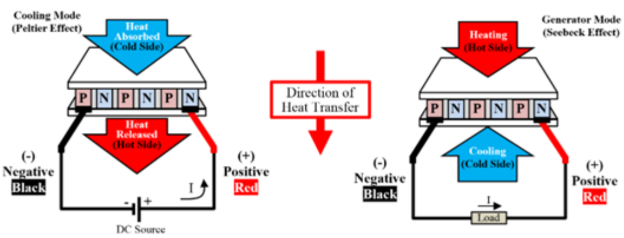
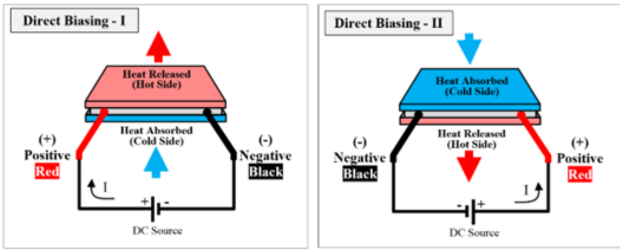
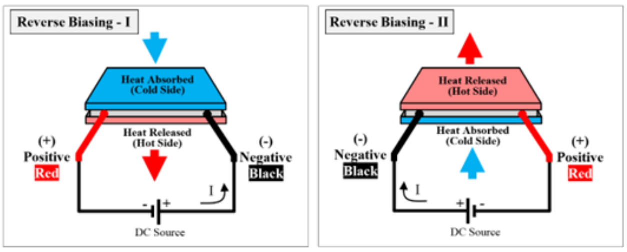


Figure 2 Direction of heat transfer in TEM

The direction of heat transfer in a TEM according to the direct and reverse biasing conditions is shown in Figure 3. TEMs generally has two connection terminals, positive (Red) and negative (black). The heat transfer direction changes depending on the positions of the positive and negative connection terminals relative to each other along with the ceramic body of the TEM. When the TEM is under direct biasing, with the positive (red) terminal positioned to the left and the negative (black) terminal to the right relative to the ceramic layer, heat transfer occurs from the lower side to the upper side. In this case, as the lower side cools, the upper side concurrently heats up. Conversely, when the TEM is direct biasing with the positive (red) terminal on the right and the negative (black) terminal on the left, the heat transfer direction reverses, flowing from the upper side to the lower side. In this scenario, while the upper side cools down, the lower side heats up. In the case of reverse biasing, heat transfer occurs opposite to that of direct biasing.



(a)



(b)

Figure 3 Direction of heat transfer in a TEM. (a) Direct biasing (b) Reverse biasing

Developed Software

The user interface of the image processing-based software developed for determining the TEM heat transfer direction is shown in Figure 4. The interface software for the operation of the system is coded in Python language and the OpenCV (Open Source Computer Vision Library) library is used for image processing, object detection and coordinate determination (9, 13).

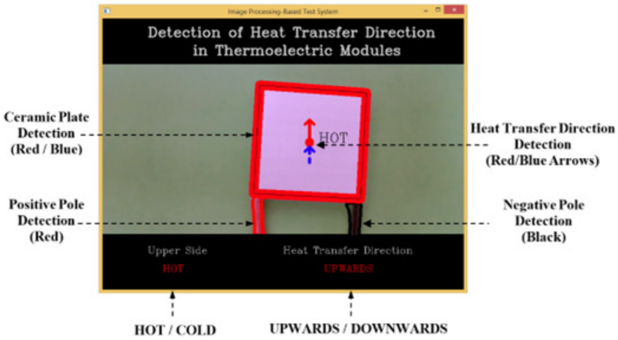


Figure 4 General overview of the software GUI

Figure 5 illustrates the 2-axis view and coordinate of a TEM. In terms of appearance, a TEM typically features a ceramic plate and two terminals distinguished by positive (red) and negative (black) poles. The points C(X,Y), P(X,Y) and N(X,Y) located in the XY plane with the origin point O(0,0) represent the centroids of the ceramic plate, the positive pole tip and the negative pole tip, respectively.

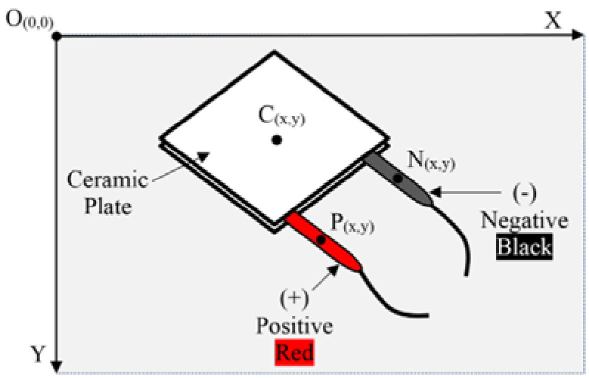


Figure 5 2-axis view and coordinate of a TEM

The flowchart for finding the hot surface, cold surface and heat transfer direction using color-based image processing in a TEM is shown in Figure 6. First of all, the positions of the positive and negative poles are determined together with the ceramic plate that forms the TEM, and the centroids C(x,y), P(x,y) and N(x,y) are determined. Mathematically, these calculations are made by calculating the zeroth and first moments from Equation 1 and the centroid from Equation 2 (14). In the next step, the position of the TEM is determined by substituting these centroids in Equation 3 and the hot side, cold side and heat transfer direction are determined.

$$M_{00} = \sum_x \sum_y I(x,y) \qquad M_{10} = \sum_x \sum_y x.I(x,y) \qquad M_{10} = \sum_x \sum_y y.I(x,y) \tag{1}$$

$$x_c = \frac{M_{10}}{M_{00}} \qquad y_c = \frac{M_{01}}{M_{00}} \tag{2}$$

$$(N_X \neq P_X) \Rightarrow \begin{cases} ((N_X - P_X) * ((N_Y + P_Y)/2 - C_Y)) < 0, & \text{"COLD"} \\ \text{otherwise,} & \text{"HOT"} \end{cases}$$
$$(N_X = P_X) \Rightarrow \begin{cases} ((N_Y - P_Y) * ((N_X + P_X)/2 - C_X)) < 0, & \text{"COLD"} \\ \text{otherwise,} & \text{"HOT"} \end{cases} \tag{3}$$

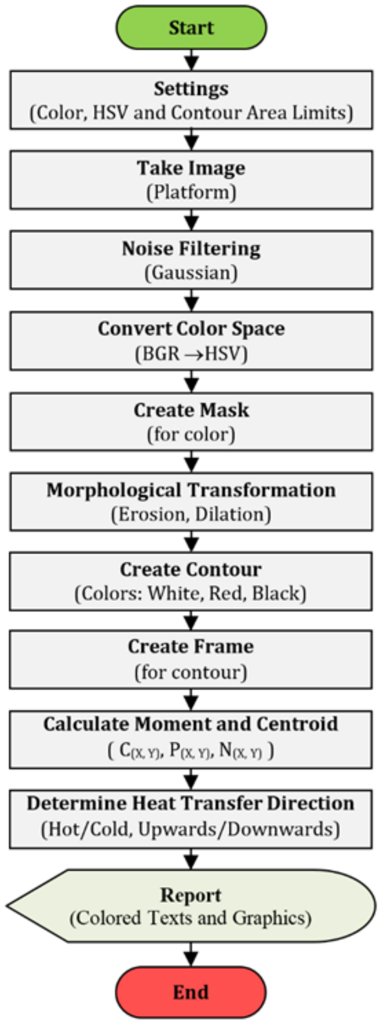


Figure 6 Flowchart for finding the heat transfer direction in TEM

When the algorithm is run, firstly colors, Hue - Saturation - Value (HSV) color space lower and upper limit values and minimum area size settings for detection are made (15, 16). HSV color space model lower and upper limit ranges for TEM colors used in the designed system are shown in Table 1. After the initial settings, an image is taken with the help of the camera and immediately Gaussian Blur filtering with size 11x11 is performed to eliminate details and noise in the image. In OpenCV image processing applications, instead of the RGB color format, the BGR (Blue-Green-Red) color format is used (9). However, since it gives better results for the detection of colored objects in image processing applications, the image is converted from BGR color space to HSV color space (17). Masking is done depending on the defined colors and their ranges. In the Morphological Transform stage, the image is rearranged by edge erosion and dilation to remove noise from the image. In this stage, a 3x3 rectangular structuring element is used by applying the erosion and dilation operating two times consecutively. A contour is created to increase the distinguishability of the detected colored regions. For each contour that provides the minimum area size for detection, a frame is first drawn and with the help of moment calculations, the centroids are found and the C(X,Y), P(X,Y) and N(X,Y) coordinates for the 2-axis are determined. In the last stage of the algorithm, the heat transfer direction is determined by using these centroids. Colorful representations with written and graphic support are made in the GUI for the results obtained. The heat transfer direction is stated in writing as Upwards/Downwards and is also shown with an arrow sign. In addition, the upper side of the TEM is colored as Blue for cold and Red for hot.

Table 1 Color ranges of the HSV color space model for TEM colors in the designed system

Reference Color	Lower Limit (H, S, V)	Upper Limit (H, S, V)
Black	(0, 0, 0)	(179, 255, 90)
White	(0, 0, 200)	(172, 111, 255)
Red	(160, 100, 100)	(179, 255, 255)

RESULTS AND DISCUSSION

In order to determine the performance of the developed software, an experimental setup is designed (Figure 7). Here, the LX-1330B model digital luxmeter is used to externally measure the illuminance level for the platform. In the experimental study, in order to obtain the colors properly, the illumination is made with white light. Within the scope of the study, the system is covered with a black fabric cover in order to eliminate the effects of the external environment.

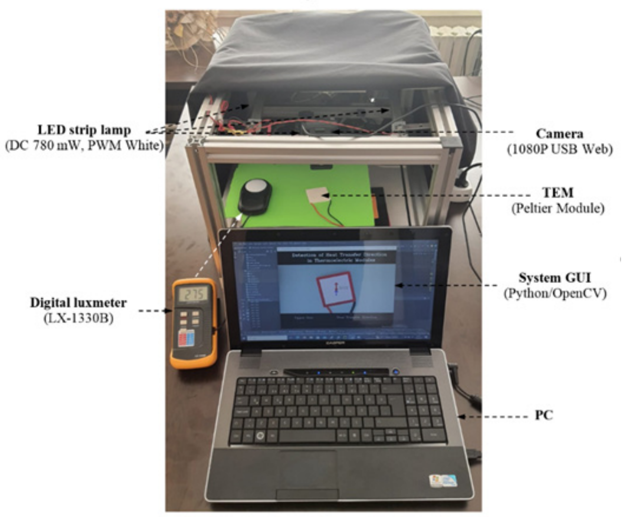


Figure 7 General view of the experimental setup

The performance of the image processing-based software developed in the study is examined at different illuminance levels. For this purpose, computer-controlled Pulse Width Modulation (PWM) based LED lighting is used in the setup to obtain illuminance levels in the range of 0-100 lx in the environment. First of all, the minimum illuminance levels required for different colors in TEM for color-based image processing in the system are investigated. The Minimum Illuminance (E_{min}) values required for successful color-based image processing for TEM in the system are determined as 13 lx for red color, 26 lx for white color and 40 lx for black color (Figure 8).

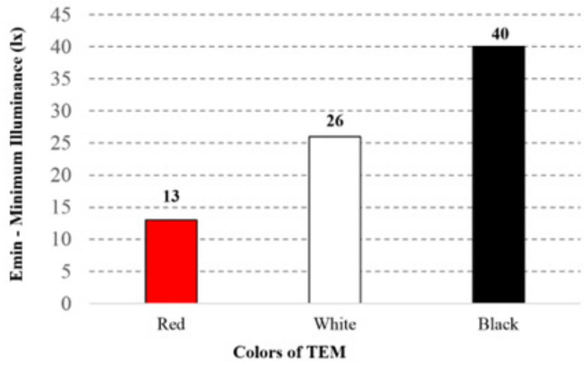


Figure 8 Minimum illumination levels required for different colors in TEM for color-based image processing

The graph given in Figure 9 shows the change in the success rate depending on the ambient illumination level in determining the heat transfer direction in TEM based on image processing. According to the results obtained, it is observed that heat transfer detection in the system is performed successfully when the illuminance level was above 40 lx, but could not be performed below 10 lx. Partially successful results are obtained at illumination levels between 10 lx and 40 lx. Figure 10 shows different GUI screenshots for successful and unsuccessful efforts to determine the heat transfer direction in the system. As can be seen from Figure 9 and Figure 10, when sufficient illumination level is provided, the system TEM can successfully detect the heat transfer direction.

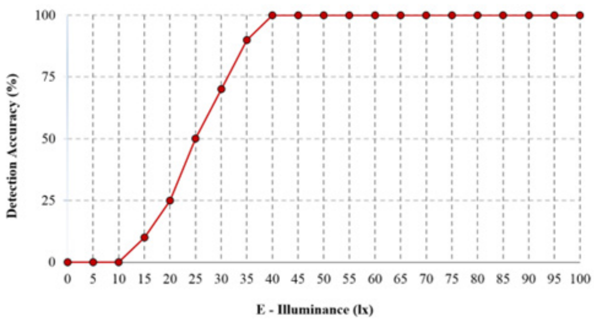
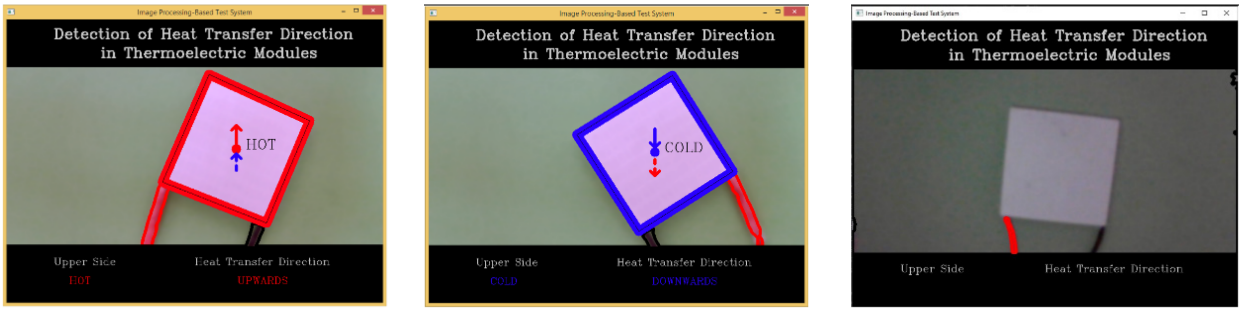


Figure 9 Change in detection accuracy according to ambient brightness level in determining the heat transfer direction based on image processing in TEM

CONCLUSION

In this study, a software-based system is designed to automatically detect the hot side, cold side and heat transfer direction of TEMs in the correct polarization, using color-based image processing techniques and based on the principle of finding the center of gravity. With the developed system, the direction of TEM heat transfer can be successfully determined even at low light levels, except when there is no object within the HSV color ranges of the TEM's ceramic surface or cables in the camera's field of view. In conclusion, it is thought that the developed system will contribute to automatic error control for the production and assembly of TEMs.

In future studies, the thermal and electrical performance of



(a) (b) (b)

Figure 10 Different GUI screenshots for studies on determining the heat transfer direction in the system (a) detection successful: upwards (b) detection successful: downwards (c) detection unsuccessful

the TE system can be calculated instantly by determining the serial or parallel placement of thermoelectric modules by image processing method and taking into account basic parametric values.

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