Separation Estimation with Thermal Cameras for Separation Monitoring in Human-Robot Collaboration

Urban B. Himmelsbach, Nikolai Hangst, Philipp Gawron, Lukas Stiglmeier and Thomas M. Wendt,
Offenburg University of Applied Sciences, Work-Life Robotics Institute, 77652 Offenburg, Germany

Abstract

Human-Robot Collaborative applications have the drawback of being less efficient than their non-collaborative counterparts. One of the main reasons is, that the robot has to slow down when a human being is within the operating space of the robot. There are different approaches on dynamic speed and separation monitoring in human-robot collaborative applications. One approach additionally differentiates between human and non-human objects to increase efficiency in speed and separation monitoring. This paper proposes to estimate the separation distance by measuring the temperature of the approaching object. Measurements show that the measured temperature of a human being decreases with 1 °C per meter distance from the sensor. This allows an estimation of separation between a robotic system and a human being.

1 Introduction

There are four different methods of collaborative operation for human-robot collaboration defined in the ISO/TS 15066: Safety-rated monitored stop, hand guiding, speed and separation monitoring (SSM) and power and force limiting operation [1]. This paper focuses on the speed and separation monitoring operation.

Speed and separation monitoring operation allows different protective separation distances that depend on the actual speed of the robot as well as on the approaching speed of the object that is about to enter the working space of the robotic application [1].

Measuring the separation between robot and an obstacle can be achieved through different methods. There are sensor systems that are external to the robotic system, meaning that they are mounted somewhere on the ceiling or on the edges of the work space of the application, therefore looking from a distance to the robot and the obstacle. Drawbacks of these systems are the higher cost of integration and installation, the inflexibility due to the installation and the possible cases of not being able to measure the distance due to shadows or the obstacle being the line of sight of the sensor system.

Other systems are mounted directly on the robot's surface or flange. These systems use capacitive, ultrasonic or infrared sensors [2, 3]. The capacitive sensors have the drawback of having a low detecting range of maximum 5 cm, where ultrasonic and infrared based sensors can measure distances of up to 15 m.

Research has shown that it might be interesting to distinguish between human and non-human objects. Thermal cameras are used to differentiate between a human and a non-human machine like an automated guided vehicle (AGV) by their temperature [4].

Having thermal cameras available in such a robotic system, the question arose if it might be possible to use the thermal information to estimate the separation between the robot and the obstacle. This is the main question in this paper that is structured as follows: Section 1 gives an introduction to the topic. Section 2 describes the methods used throughout the paper and introduces the used sensors. Section 3 explains the experimental setup and section 4 discusses the results of the measurements. The paper concludes with section 5 and gives a small outlook on the continuing research ideas.

2 Methods

This section describes the method used for estimating the separation between the robot and a human obstacle.

During measurements for differentiating human and non-human objects in robotic applications, we observed that there must be a correlation between the measured temperature and the distance to the object that the temperature was measured on.

2.1 Thermal Camera

Thermal cameras can measure the infrared energy that is emitted by any object. There are two types of passive infrared (PIR) detectors. Thermopiles and pyroelectric sensors. Passive means that there is no additional power needed to produce an output on the sensor. The electric output of a passive infrared detector is generated by the infrared radiation that impinges on the sensor [5].

The main difference between thermopiles and pyroelectric sensors is, that the pyroelectric sensor only generates an output when the impinging radiation changes and therefore the sensors temperature changes. Thermopiles can also measure a steady amount of infrared radiation [5].

Compared to the high-end cameras from FLIR there are different low-cost sensors available. For this paper we use the two sensors Evo Thermal 90 and Evo Thermal 33 from Terabee. **Figure 1** shows the two sensors. The main advantages of the sensors are their small size of 29x29x13 mm and 29x29x22 mm, the light weight of approximately 12 g, the connection via USB and their range of up to 5 m.

Figure 1 Thermal sensors from Terabee. The Evo Thermal 90 (left) and Evo Thermal 33 (right).

2.2 Emissivity

The emissivity of an object represents how well the object emits thermal radiation. It can be represented with a number between 0 and 1. An emissivity of 1.0 represents the perfect black body radiation, which is basically not possible to find in the real world. The emissivity of human skin, with an value of approximately 0.97, is very close to the black body radiation. Metals are more difficult to measure, especially when they are polished. Values for the emissivity can then be lower than 0.1 [6].
Usually a human worker wears cloth, covering most of the skin of the human being. Nonetheless, parts of the human face are usually uncovered.

2.3 Field of View and Size of Pixel

The sensors have 32 x 32 pixels and a field of view of 33° x 33° for the Evo Thermal 33 and 90° x 90° for the Evo Thermal 90. Depending on the opening angle for the field of view α and the distance d_i between the object and the sensor, the size of the observed area of one pixel x_i varies. You can calculate this size with **equation 1** according to **Figure 2**:

$$x_i = \frac{2\, d_i \tan\alpha}{Number\ of\ Pixels} \tag{1}$$

For the given sensors we can calculate the pixel sizes for different distances from the sensor. An overview is shown in **Table 1**. With 32 x 32 pixels, the Evo Thermal 33 sensor covers a square with a side length of 32 x 9,3 cm = 297,6 cm in 5 m distance and the Evo Thermal 90 a square with a side length of 10,016 m in 5 m distance.

Table 1 Pixel sizes of the sensors in different distances.

Evo Thermal 33		Evo Thermal 90	
Distance in cm	Pixel size in cm	Distance in cm	Pixel size in cm
50	0,9	50	3,1
100	1,9	100	6,3
200	3,7	200	12,5
300	5,6	300	18,8
400	7,4	400	25,0
500	9,3	500	31,3

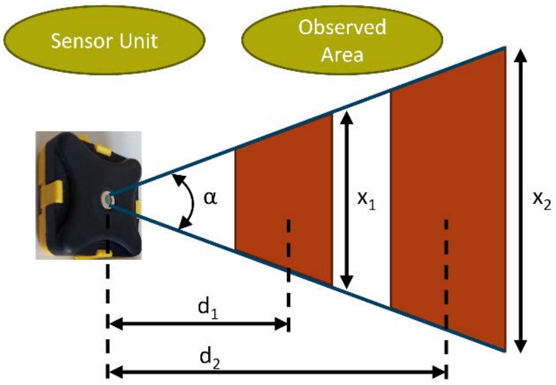

Figure 2 Overview of observed area calculation

2.4 Separation Estimation

The idea behind the paper is, that with a greater distance to the sensor, the object temperature decreases. In order to estimate the separation, we need to make a reference measurement. The bigger the size of the observed area the lower is the measured temperature because the of the lower heat flux from the object that reaches the sensor. Therefore, we predict higher temperatures at small distances to the sensor and lower temperatures for greater distances from the sensor.

Table 2 Technical specifications of the Evo Thermal 90 and Evo Thermal 33 sensors from Terabee [7].

Performance	Evo Thermal 90	Evo Thermal 33
Resolution	32 x 32 pixels	32 x 32 pixels
Field of View	90° x 90°	33° x 33°
Temp. Range	-20 °C to 670 °C	30 °C to 45 °C
Temp. Accuracy	± 2 °C	± 0.5 °C
Human Body Range	Up to 5 m	Up to 5 m
Supply Voltage	5 V	5 V
Operating Temp.	-10 °C to 65 °C	15 °C to 30 °C
Weight with Backboard	10 g	12 g
Dimensions	29 x 29 x 13 mm	29 x 29 x 22 mm

3 Experiment

The experiment uses two different sensors from Terabee, namely the Teraranger Evo Thermal 90 and the Teraranger Evo Thermal 33. The features of the sensors are shown in **Table 2**.
The sensors are connected via USB cable to a laptop running Windows 10. Matlab is used to read and analyze the data from the sensors.
A scale from 0 to 5 m with a 0.5 m indication is drawn on the floor. The sensors are positioned at the 0 m indication at a height of 180 cm in order to be able to measure the temperatures of the head of the human being. At each 0.5 m interval 100 temperature measurements are taken. Out of each of the 100 measurements of each 0.5 m step, the maximum temperature value of the 32x32 pixels is chosen and the average of the 100 measurements is calculated.

Additionally, the distance is measured with a time-of-flight sensor from Terabee, the TeraRanger Evo 3m, with a range of three meters. For each 0.5 m step, 100 distance measurements were taken.

4 Results

The results are shown in **Figures 3, 4** and **5**. **Figure 3** shows the measurement results of the EvoThermal 33 sensor. The measurement taken at 0 m represents the measurement without a human being present. The measurement shows that there is first of all a big difference of 6 °C to 10 °C between no human present and a human present within the range of 0.5 m to 5 m. In between the measurement range, the temperature changes by 4 °C. This means that we have about 0.8 °C change per meter.

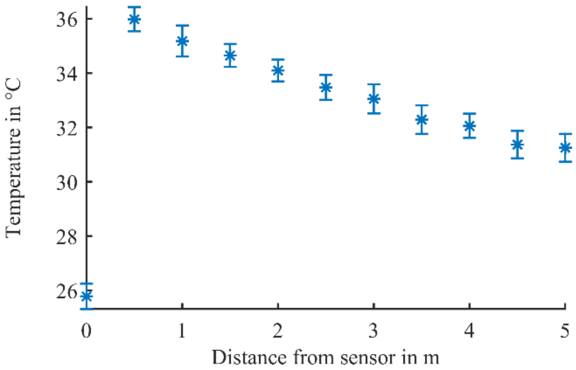

Figure 3 EvoThermal 33 measurements.

Figure 4 shows the results of the EvoThermal 90 sensor. The fist measurement at 0 m shows again the situation with no human being present in the field of view of the sensor. For this sensor we see a temperature difference between 4°C and 10 °C between no human and a human in a distance of 0.5 m to 5 m. This leads to a resolution of 1.2 °C per meter.

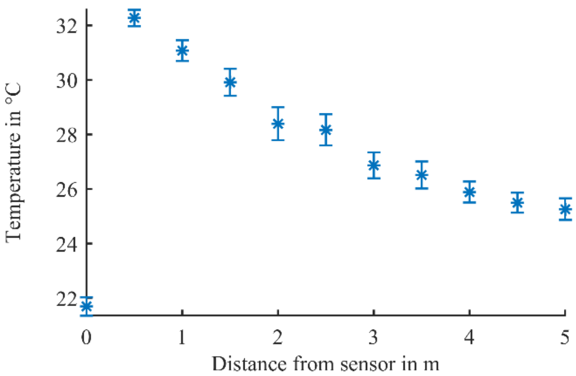

Figure 4 EvoThermal 90 measurements.

Figure 5 shows the parallel measurement of Temperature and distance with the EvoThermal 33 and the Teraranger Evo 3m. One problem was that the Teraranger Evo 3m only has a range of 3 m. Everything above 3 m gives the result infinitive and therefore can not be used in the figure and is shown as 0.

Nonetheless, **Figure 5** shows that there is an inverse correlation between the distance and the measured temperature. When the distance is 0.5 m, the temperature is 6 °C higher than in a distance of 5 m.

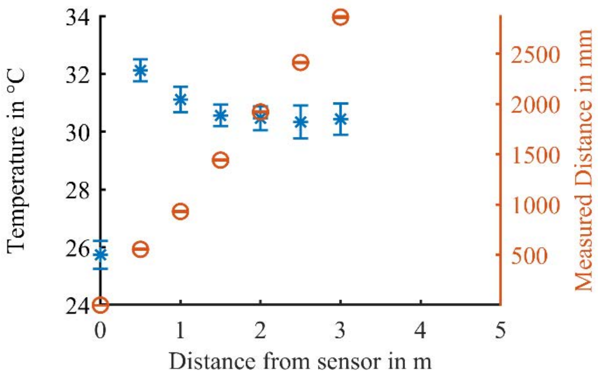

Figure 5 EvoThermal 33 and Evo3m measurements.

The measurements also show that due to the room temperature of 24 °C, there is a maximum possible distance of 10 m that could be estimated by measuring the temperature. Due to the maximum range of 5 m that was specified in the datasheets of the thermal sensors, and due to the maximum range of 3 m for the Teraranger Evo 3m, it was not possible to make experiments with distances greater than 10 m. This will be subject to future work.

5 Conclusion & Outlook

The paper proposed to estimate the separation between a human-being and a robotic system by measuring the temperature. The hypothesis was that the temperature falls with longer distances from the robotic system due to the greater size of the measurement area of a single pixel of the thermal sensor.

The experimental setup investigated how accurate the estimation of the separation between the human being and the robotic system can get. A range of 1 m to 5 m was investigated.

The results showed that the measured temperature decreases approximately with 1 °C per meter distance. The results also showed that the greater the distance to the object is, the closer the measured temperature gets to the measured room temperature. The closer the measured temperature gets to the room temperature, the less accurate is the separation estimation.

Future work will focus on how to improve the accuracy of the separation estimation with thermal sensors. Having a good estimation method, it will be combined with an infrared time-of-flight measurement to get redundancy in the overall measurement. The two methods can be combined by use of sensor fusion techniques like Kalman-Filter.

6 Literature

[1] International Organization for Standardization (2016): Technical specification ISO/TS 15066. Robots and robotic devices - collaborative robots. First edition, 2016-02-15. Vernier, Geneva, Switzerland: ISO.

[2] Kumar, Shitij; Arora, Sarthak; Sahin, Ferat (2019): Speed and Separation Monitoring using On-Robot Time-of-Flight Laser-ranging Sensor Arrays. In: 2019 IEEE 15th International Conference on Automation Science and Engineering (CASE): IEEE, S. 1684–1691.

[3] Himmelsbach, Urban B.; Wendt, Thomas M. (2020): Built-In 360 Degree Separation Monitoring for Grippers on Robotic Manipulators in Human-Robot Collaboration. In: 2020 Fourth IEEE International Conference on Robotic Computing (IRC). 2020 Fourth IEEE International Conference on Robotic Computing (IRC). Taichung, Taiwan, 09.11.2020 - 11.11.2020: IEEE, S. 156–160.

[4] Himmelsbach, Urban B., Thomas M. Wendt, Nikolai Hangst, Philipp Gawron, and Lukas Stiglmeier. 2021. "Human–Machine Differentiation in Speed and Separation Monitoring for Improved Efficiency in Human–Robot Collaboration" Sensors 21, no. 21: 7144. https://doi.org/10.3390/s21217144

[5] Fraden, Jacob (2016): Handbook of Modern Sensors. Physics, Designs, and Applications. 5., th ed. 2016. Cham: Springer International Publishing.

[6] Belliveau, R. G., DeJong, S. A., Boltin, N. D., Lu, Z., Cassidy, B. M., Morgan, S. L., & Myrick, M. (2020). Mid-infrared emissivity of nylon, cotton, acrylic, and polyester fabrics as a function of moisture content. Textile Research Journal, 90(13–14), 1431–1445. https://doi.org/10.1177/0040517519888825.

[7] Terabee (2021): TeraRanger Evo Thermal Specification Sheet. www.terabee.com/sensors-modules.