

Energy Consumption in a Collaborative Activity Monitoring System using a Companion Robot and a Wearable Device

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Abstract—In this paper, we aimed to study the energy consumption problem in a collaborative activity monitoring system (CAMS) that consists of a companion robot and a wearable device. First, we tested the energy consumption in different operation modes of the system. Based on that, we analyzed the effect of bandwidth on the time cost and energy consumption which allowed us to combine WiFi and Bluetooth together for data transmission to improve the performance of the system. Second, we preprocessed the image data on the wearable device to reduce the size of images before sending them to the robot, and analyzed the time and energy consumption cost by local computing and data transmission. Third, based on the bandwidth of WiFi and Bluetooth, the requirement of time and energy consumption, we proposed an optimization problem on image sizes in which the wearable device decides how to send the data to the robot to reduce the energy and time cost. The results showed that the relations between the bandwidth, time cost, image resolutions and energy consumption could be used to improve the performance of CAMS.

I. INTRODUCTION

Fall is a common problem among older adults, which could cause serious injuries [1]. Wearable devices and companion robots can be used to realize fall detection systems, as the wearable devices can alleviate privacy concern and provide ubiquitous sensing, while the robots have more computational resources and skills for elderly care. Energy consumption is an important issue [2] for wearable devices. An energy-inefficient wearable device have a reduced the battery life. The wireless protocol used for data transmission between the wearable device and the robot is critical

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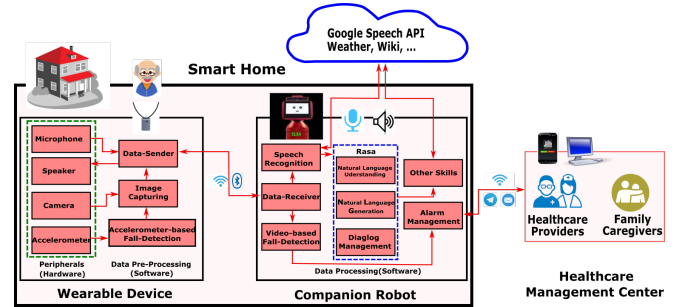


Fig. 1. The overall design of the CAMS.

to determine the energy consumption. In addition, it is worthwhile to study the energy consumption problem in the context of onboard processing vs offloading to the robot.

In our previous work [3], we have proposed a collaborative fall detection system that consists of a wearable device and a companion robot. Fig. 1 shows the developed collaborative activity monitoring system (CAMS), in which the wearable device works with the robot to monitor and understand an older adults's daily activities. The wearable camera captures images after detecting a potential fall event using the accelerometer data and transmits the images to the robot via a wireless channel. Then the robot runs a deep learning based fall detection algorithm on the received images to verify or reject the fall.

In this paper, we aim to investigate the energy consumption problem in CAMS. First, we tested the energy consumption in different operation modes of the wearable device. Based on that, we analyzed the effect of bandwidth on the time cost and energy consumption which allowed us to combine WiFi and Bluetooth together to select either WiFi or Bluetooth to send images to the robot. Second, we conducted image preprocessing on the wearable device to reduce the image size before sending to the robot, and analyzed the time cost and energy consumption in local processing and data transmission. Third, based on the actual bandwidth of WiFi and Bluetooth, the requirement of time and energy consumption, we

proposed a solution to improve the performance of the system. In this way, the wearable device can decide how to send the data to the robot in an effective way.

The rest of this paper is organized as follows: Section II introduces the related work. Section III presents the energy consumption model of the system. Section IV describes the proposed method to study the effect of bandwidth and the optimization problem on image sizes. Section V shows the experimental setup, design and simulation results. Section VI concludes our work and discusses the future work.

II. RELATED WORK

A significant amount of work has been done recently that studies energy consumption in wearable devices. Tuan *et al.* [1] designed a fall detection system using a tiny, lightweight and energy efficient wearable device. They investigated different parameters (e.g. sampling rate, transmission protocol, and transmission rate) impacting the energy consumption of the wearable device, provided a comprehensive analysis of energy consumption of the wearable in different configurations and operating conditions. But they did not address the energy consumption of wireless communication protocols nor how to combine them together to improve the performance.

When multiple wireless interfaces are available in the same device, we need to figure out which interface is more energy efficient for communication. Roy *et al.* [4] described a study on the performance of power and throughput of WiFi and Bluetooth usage in smartphones. They used the minimal ratio of the power consumed by the interface and the throughput to make the decision. However, they did not consider the situation that both WiFi and Bluetooth coexist and how these two protocols work together to improve the performance.

Kai *et al.* [5] investigated the coexistence of WiFi and cellular LTE by proposing a multi-objective optimization framework. They defined three objectives including the WiFi throughput, the LTE throughput, and the average packet delay of WiFi and employed the Non-dominated Sorting Genetic Algorithm II (NSGA-II) [6] to develop an efficient algorithm to find the complete Pareto optimal solution. However they did not consider the situation of choosing a better channel for data transmission so as to improve the system performance.

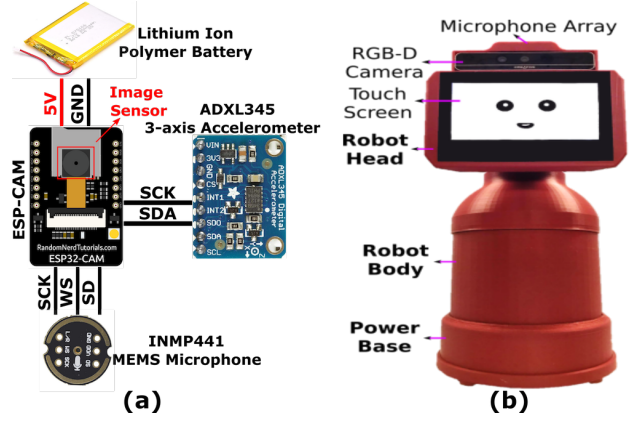


Fig. 2. The design of the Wearable Activity Monitoring Unit (a) and the companion robot (b).

III. ENERGY CONSUMPTION MODEL OF THE SYSTEM

In order to study the energy consumption problem in the CAMS, firstly, we analyzed the power consumption in different operation modes of the system. Then we collected and analyzed the relevant data including the bandwidth of WiFi and Bluetooth, power consumption when sending images, image resizing time cost and data size, etc, which will be used to formulate the optimization problems on channel selection and image sizes in Section IV.

As shown in Fig. 1, the CAMS consists of a WAMU (Wearable Activity Monitoring Unit) which integrates a mini camera, an accelerometer, a speaker, and a microphone in a small form factor, a companion robot, and a healthcare management system. Fig. 2 shows the WAMU and the robot. The ESP32-CAM [7] used in the WAMU integrates both WiFi and Bluetooth modules.

A. Power Consumption in Different Modes

As shown in Fig. 3, the system is capable of operating in 3 different modes.

1) *Standby mode*: In this mode, the accelerometer is running and the connection between the wearable device and the robot is established, but no image data is captured or transmitted.

2) *Capture mode*: In this mode, the camera is triggered, which captures 10 images and saves the images in the onboard memory. The connection between the robot and the wearable device is established as well.

3) *Transmission (TX) mode*: In this mode, the wearable device is actively transmitting image data to the robot through the wireless connection. It consumes the most power of any mode. The power

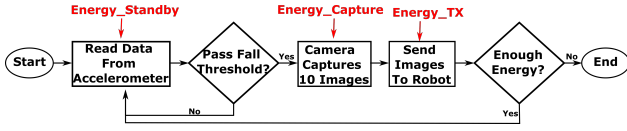


Fig. 3. The work flow of the Wearable Activity Monitoring System.

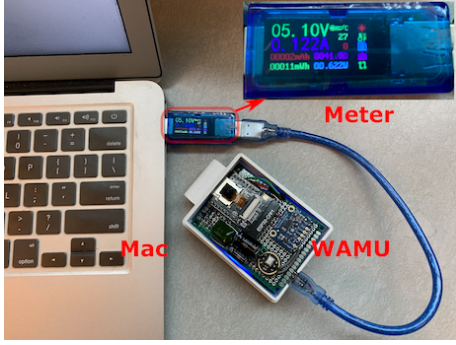


Fig. 4. The meter and circuit used to measure the power consumption.

consumption varies depending on which wireless channel (WiFi or Bluetooth) is selected and the actual bandwidth.

We employed the AT34 USB 3.0 Meter [8] as shown in Fig. 4 to measure the power consumption in terms of current. As we can see from Table I, the energy consumption of Bluetooth is slightly less than that of WiFi, and the image capturing itself does not consume much power.

TABLE I

THE ENERGY CONSUMPTION IN DIFFERENT MODES.

	Energy_Standby(mA)	Energy_Capture(mA)	Energy_TX(mA)
WiFi	124	124	220
Bluetooth	122	122	213
WiFi+Bluetooth	156	156	WiFi(220) or Bluetooth(213)

B. Bandwidth of WiFi and Bluetooth in the Environment

The bandwidth of WiFi or Bluetooth plays an important role in power consumption when transmitting data between the WAMU and the robot. In order to get the rates of the bandwidth, we used the WAMU to send an image to the robot every 6 seconds in 3 hours via WiFi and Bluetooth respectively. Fig. 5 shows that the bandwidths of WiFi and Bluetooth have different characteristics. The WiFi bandwidth is higher, but it varies significantly from 1.39 KB/s to 200 KB/s as we tested. As a comparison, the Bluetooth bandwidth is much lower but more stable, usually around 40 KB/s. With regard to the energy consumption in Table I, if

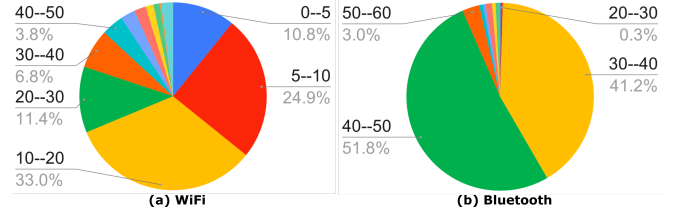


Fig. 5. The rate distribution of WiFi and Bluetooth bandwidth (KB/s).

the WiFi's bandwidth is less than that of Bluetooth, it consumes more energy as it needs more time for data transmission. Therefore it is meaningful to study the effect of bandwidth on the time cost and energy consumption in the CAMS.

C. Image Resizing

The image size apparently affects the data transmission time, thus affecting the system energy consumption. We can get different images by configuring the parameter *frame_size* [9] of the ESP32-CAM device at the beginning or by implementing an image resizing algorithm on the ESP board which resizes the image in real time. We used bilinear interpolation [10] to resize the original image which is 640x480. As we can see from Table II and Table III, the computation time and the corresponding data size with different image resolutions are different. Therefore, with respect to the bandwidth of WiFi and Bluetooth, a tradeoff should be made, which will be discussed in Section IV.

TABLE II

RESIZING TIME COST FOR ONE IMAGE WITH DIFFERENT SIZES OF IMAGES (S).

	640*480	400*296	320*240	240*176	176*144	128*160	160*120	64*64	32*32	28*28
AVG	-	3.07	2.56	2.04	1.78	1.71	1.68	1.44	1.38	1.39
MAX	-	3.17	2.67	2.14	1.87	1.78	1.76	1.52	1.45	1.46
MIN	-	2.98	2.45	1.95	1.71	1.64	1.61	1.38	1.32	1.32

TABLE III

DATA SIZE OF DIFFERENT RESOLUTIONS OF IMAGES (KB).

	640*480	400*296	320*240	240*176	176*144	128*160	160*120	64*64	32*32	28*28
AVG	14.31	7.37	5.38	3.56	2.50	2.24	2.18	1.04	0.75	0.75
MAX	24.86	12.42	9.31	6.27	4.38	3.77	3.81	1.29	0.85	0.84
MIN	8.85	4.58	3.00	2.08	1.40	1.35	1.30	0.79	0.67	0.67

IV. PROPOSED METHOD

In this section, firstly, we defined a model to analyze the effect of bandwidth on the time cost and energy consumption. Then, we defined an optimization problem on image size to minimize the

time cost and energy consumption. We used NSGA-II to generate the solutions and analyze the relations between image size, bandwidth, time cost and energy consumption. The parameters of concern are defined in Table IV.

A. The Effect of Bandwidth on Time Cost and Energy Consumption

In this part, we investigated the impact of wireless bandwidth on the time cost and energy consumption when the WAMU is sending images to the robot. We defined two functions: (F_1) is for time cost and F_2 is for energy consumption.

The time cost (F_1) and energy consumption (F_2) can be approximated by:

$$F_1 = \sum_{i=1}^n \left(\frac{x_i}{speed} + \frac{1}{c_f} \right) \quad (1)$$

$$F_2 = \sum_{i=1}^n \left(\frac{x_i}{speed} \cdot e_d + \frac{1}{c_f} \cdot e_c \right) \quad (2)$$

Here:

$$x_i = 24.86 \text{ KB} \quad (3)$$

$$c_f = 30 \quad (4)$$

$$n = 10 \quad (5)$$

$$B = 1200 \text{ mAh} \quad (6)$$

$$F_2 \leq B \quad (7)$$

$$speed = 1 - 200 \text{ KB/s for WiFi} \quad \text{or} \quad (8)$$

$$30 - 45 \text{ KB/s for Bluetooth}$$

Based on the above equations, we can see that both the time cost and energy consumption decrease as the bandwidth increases. Therefore we can select the channel with higher bandwidth, which requires us to compare the bandwidth of WiFi and Bluetooth before sending image data. In real applications, we can use the WiFi as the default channel. The actual speed can be estimated by sending the first image and calculate the time used for the transmission. As the Bluetooth bandwidth is relatively stable, only when the WiFi speed drops to a threshold value, we will switch to Bluetooth.

B. Optimization Problem on Image Size

Based on Table II and Table III, we proposed an optimization problem regarding the image size which means the resizing time cost and image size were selected from Table II and Table III respectively. The pseudo code for calculating the time cost and

TABLE IV
THE PARAMETERS OF CONCERN.

Paramter	Introduction
x_i	Size of image i
rt_i	Resizing time of image i
c_f	FPS of camera
speed	Data transfer speed through WiFi or Bluetooth
e_d	Energy consumption in the TX mode
e_c	Energy consumption in the Capture mode
e_r	Energy consumption for resizing the image
B	Battery capacity (mAh)
n	Total number of images captured

TABLE V
PSEUDO CODE FOR ESTIMATING TIME COST AND ENERGY CONSUMPTION ON IMAGE RESIZING.

```

# Time Cost:
1. initialization;
2. speed = wifi_speed;
3. for i = 1, ... , 10 do
4.   total.time += image_size / speed + 1.0 / camera_fps
   + image_resizing_time;
5. end for

# Energy Consumption:
1. initialization;
2. speed = wifi_speed;
3. energy_tx = energy consumption in the TX mode
   using WiFi;
4. energy_capture = energy consumption in the Capture
   mode with WiFi on;
5. energy_standby = energy consumption in the Standby
   mode;
6. energy_resizing = energy consumption for resizing
   the image
7. for i = 1, ... , 10 do
8.   total_energy_consum = energy_tx * image_size / speed
   + energy_capture * 1.0 / camera_fps
   + energy_resizing * image_resizing_time;
9. end for

```

energy consumption is shown in Table V. The multi-objective functions are defined as follows.

Minimize:

$$F_3 = \sum_{i=1}^n \left(\frac{x_i}{speed} + \frac{1}{c_f} + rt_i \right) \quad (9)$$

$$F_4 = \sum_{i=1}^n \left(\frac{x_i}{speed} \cdot e_d + \frac{1}{c_f} \cdot e_c + rt_i \cdot e_r \right) \quad (10)$$

Subject to:

x_i refers to Table III, rt_i refers to Table II, (4), (5), (6), and

$$e_r = 135 \text{ mA} \quad (11)$$

$$speed = 1 - 200 \text{ KB/s for WiFi} \quad (12)$$

$$F_4 \leq B \quad (13)$$

V. EXPERIMENTAL EVALUATION

A. Test setup

To analyze the effect of bandwidth on time cost and energy consumption, we used Python3.7 code to generate the results. For the optimization problem on image size, we implemented the NSGA-II on a Mac with 2-core Intel i5 CPU and 8GB memory, Python3.7 was employed to run the code. The simulations were conducted with a population size of 100, crossover rate of 0.8, mutation rate of 0.2, and maximum generation number of 1000 for all implementation.

B. Experiment and Results

1) *The Effect of Bandwidth on Time Cost and Energy Consumption:* From Table VI, we can see that, for WiFi, the minimum time cost is 1.58 s, while the maximum time cost is 248.93 s with the bandwidth of 200 KB/s and 1 KB/s respectively. While the Bluetooth is more stable than WiFi, with the time ranging from 5.86 s to 8.62 s with the bandwidth of 45 KB/s and 30 KB/s respectively. Using the combination of both channels can improve the system's performance by reducing the maximum time cost from 248.93 s to 8.62 s. In addition, Energy consumption is improved as well based on Table VII.

TABLE VI

THE TIME COST RESULTS FOR SENDING 10 IMAGES.

	Max.Time_Cost(s)	Min.Time_Cost(s)
WiFi	248.93	1.58
Bluetooth	8.62	5.86
WiFi+Bluetooth	8.62	1.58

TABLE VII

THE ENERGY CONSUMPTION RESULTS FOR SENDING 10 IMAGES.

	Max_Energy_Consumption (mA)	Min_Energy_Consumption (mA)
WiFi	54733.33	314.79
Bluetooth	1805.73	1217.37
WiFi+Bluetooth	1805.73	314.79

2) *Optimization Problem on Image Size:* Fig. 6 shows the time cost and energy consumption when the WiFi bandwidth is 10 KB/s for each image. The total time cost includes two parts: resizing time and data transmission time. Since the resizing time cost is constant, the time cost for data transmission will dominate the total time cost when the image has large sizes or the bandwidth is low.

In Fig. 7, we mapped the image resolutions in Table III to the range of 0-9, and we can see the relations between time cost, speed, energy consumption

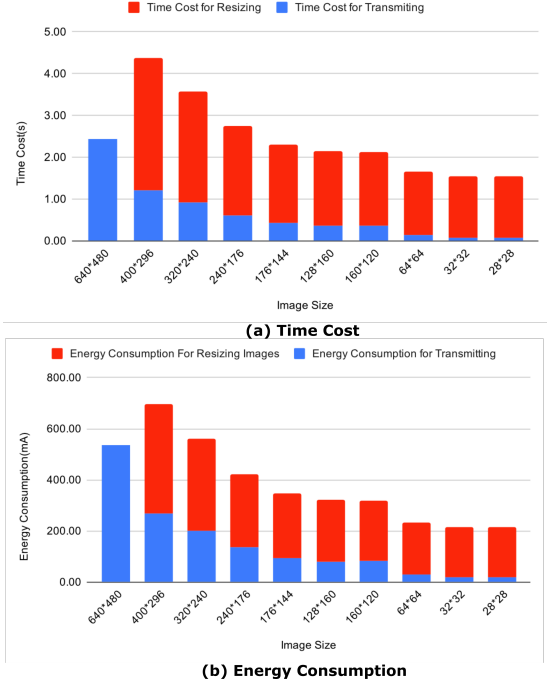


Fig. 6. Time cost (a) and energy consumption (b) with respect to the image size at 10 KB/s WiFi bandwidth for one image.

using the optimization on image size. It improves the system's performance by reducing the maximum time from 248.93 s to 23.33 s when the speed is 1 KB/s. In the red region as the speed is from 16.25 KB/s to 26.53 KB/s, there are multiple solutions because the different solutions could not dominate each other. For example, if the speed is 20 KB/s, using 640x480 takes 1.28 s and 277.6 mA, while it takes 1.53 s and 209.2 mA instead using 32x32. So we need to tradeoff time cost and energy consumption.

From Fig. 7 and Fig. 8, we can see the time cost and energy consumption trend with different bandwidth and image sizes. If the bandwidth is less than 16.25 KB/s, we could achieve better performance by reducing the sizes of images from 640x480 to smaller sizes. For a given time cost and WiFi speed, we can choose multiple image sizes as solutions. However, if the WiFi bandwidth is higher than 26.53 KB/s, reducing the image sizes is not recommended as it needs extra computation cost. And in this situation, the Bluetooth is not used as its bandwidth is around 40 KB/s with which the solution could not make sense.

VI. CONCLUSION AND FUTURE WORK

In this paper, we evaluated energy consumption of a collaborative activity monitoring system consisting of a wearable device and a companion robot. First,

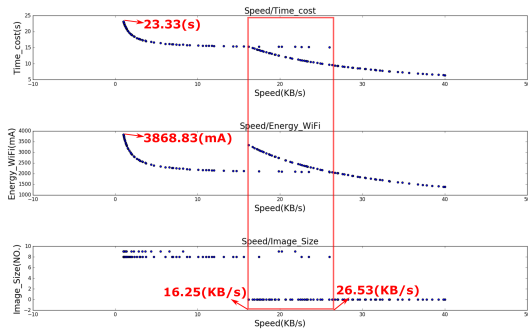


Fig. 7. Benefit of time and energy using the image resizing method for 10 images.

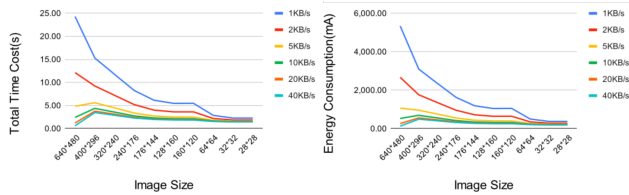


Fig. 8. Time cost and energy consumption with respect to different bandwidths of WiFi and image sizes for one image.

we analyzed the system flow and investigated the energy consumption in different operation modes. Furthermore, we analyzed the effect of bandwidth on the time cost and energy consumption which allowed the combination of WiFi and Bluetooth together for data transmission. The results demonstrated the combination of WiFi and Bluetooth could avoid the worst situation when WiFi has low bandwidth. Second, we preprocessed the image data on the wearable device to reduce the size of images before sending to the robot, and used NSGA-II to find the complete Pareto optimal solutions. We then analyzed the time and energy consumption cost by local computing and data transmission. Based on the bandwidth of WiFi and Bluetooth, the requirement of time and energy consumption, we proposed an optimization problem on image sizes to improve the performance of the system. The results showed that the proposed method could improve the performance of CAMS when the WiFi bandwidth is less than 16.25 KB/s, and the relations between the bandwidth, time and image resolutions could be used as guidelines for WAMU and robot collaboration.

For the future work, we need continue working on the energy consumption and fall detection problems, particularly in the following aspects: 1) We need to optimize the image resizing part using both hardware

and software methods. 2) We need to improve the Bluetooth part to reduce the energy consumption as Bluetooth Low Energy technology can be used. 3) We need to test the accuracy of the fall detection algorithm using different resolutions of images.

REFERENCES

- [1] T. Nguyen Gia, V. K. Sarker, I. Tcareno, A. M. Rahmani, T. Westerlund, P. Liljeberg, and H. Tenhunen, "Energy efficient wearable sensor node for IoT-based fall detection systems," *Microprocessors and Microsystems*, vol. 56, no. October 2017, pp. 34–46, 2018. [Online]. Available: <https://doi.org/10.1016/j.micpro.2017.10.014>
- [2] S. Pasricha, R. Ayoub, M. Kishinevsky, S. K. Mandal, and U. Y. Ogras, "A survey on energy management for mobile and IoT devices," *IEEE Design and Test*, vol. 37, no. 5, pp. 7–24, 2020.
- [3] F. Liang, R. Hernandez, J. Lu, B. Ong, M. J. Moore, W. Sheng, and S. Zhang, "Collaborative fall detection using a wearable device and a companion robot, journal = IEEE International Conference on Robotics and Automation, note = (in press)."
- [4] R. Friedman, A. Kogan, and Y. Krivolapov, "On power and throughput tradeoffs of WiFi and bluetooth in smartphones," *IEEE Transactions on Mobile Computing*, vol. 12, no. 7, pp. 1363–1376, 2013.
- [5] K. He and G. Yu, "Genetic algorithm for balancing wifi and LTE coexistence in the unlicensed spectrum," *IEEE Vehicular Technology Conference*, vol. 2016-July, pp. 6–10, 2016.
- [6] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, "A fast and elitist multiobjective genetic algorithm: NSGA-II," *IEEE Transactions on Evolutionary Computation*, vol. 6, no. 2, pp. 182–197, 2002.
- [7] Esp32 product. [Online]. Available: <https://www.espressif.com/en/products/socs/esp32>
- [8] Makerhawk usb 3.0 tester. [Online]. Available: <https://www.makerhawk.com>
- [9] Esp32 frame size. [Online]. Available: <https://esphome.io>
- [10] Bilinear interpolation. [Online]. Available: <https://www.sciencedirect.com/topics/engineering/bilinear-interpolation>