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Low-energy radar for handheld IR-cameras

Using mmWave radar as a complement for Multi Spectral Dynamic Imaging in handheld cameras

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Abstract

The aim of this project is to assess whether a low energy radar, more specifically the mmWave radar from Acconer could be used as a complement to the handheld cameras from FLIR, in order to improve its performance, in particular the alignment of visual and infra-red image. The specific camera used for this project is a FLIR C5 IR-camera. It was found that if the distance is known, then one could align the images more easily and by the help of the radar this could occur automatically instead of doing it manually as it is implemented today.

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1. Abbreviation list

FOV- Field of View

MSX- Multi Spectral Dynamic Imaging

FLIR- Forward Looking Infrared

RADAR- Radio Detection and Ranging

IR- Infra-Red

LIDAR- Light Detection and Ranging

MIMO- Multiple Input Multiple Output

ToF- Time of Flight

2. Introduction

2.1 Background

The FLIR company has developed a technology referred to as Multi Spectral Dynamic Imaging (MSX). The principle of this is to depict the surrounding by two cameras, one working in the IR part of the spectrum and one in the visible. By this, the sharpness of the image and the efficiency of the identification of targets can be improved, resulting in clutter-free reports and faster route solutions.

Such a camera has a number of appealing features, e.g. the ability to detect objects and their movements under night conditions. However, it also has a few drawbacks; as the two images are coming from two different cameras with separate optical axes, meaning the images are not well aligned and even a small misalignment may be very visible and cause obstacles to the end user. The alignment can be corrected with a factory calibration but the need to align will change with distance to the object. On entry level camera systems, the user has been forced to manually correct for misalignment but on more high-end systems, various distance measurement techniques are used to achieve automatic alignment. The low power radar, for distance measurement, can be directly integrated into an entry level camera for distance measurement and automatic alignment of fusion images for MSX.

A radar is defined as a technology that detects the echo of electromagnetic energy, which returns from a reflective object in order to mainly measure the distance or the depth, the angular location, and the motion of a target.

The main aim of this work is to investigate whether a low-energy radar could be a complement to a handheld camera made by the FLIR company to make measurements more efficient in cases like construction work, heavy smokey area and to make the accuracy of measuring a distance to an object more efficient than it is. If the low-energy radar has significant advantages, this will lead to not only the improvements in efficiency of measuring distance to an object but also to a lower cost process.

The target’s distance can be measured, for example, by the time it takes for electromagnetic energy to be reflected from the target, i.e., the time it takes for the echo to reach a detector. The angular location of a target can be measured by an antenna with a narrow beamwidth that follows the angle of the echo signal arriving to the detector. In a similar manner, a radar can also track a moving target, based on the electromagnetic energy reflecting from the target. In the case of a fixed radar, as used in this report, the detection will depend on the surface of the radar detector, so the limitation will be that any signal outside that area might not be counted unless the radar is shifted towards that direction or specific area.

A question of importance is how a radar can separate the target from the environment? This question can be answered by use of the Doppler effect. The Doppler effect implies that the frequency of a target increases when it approaches the observer, e.g., a radar. A radar can then separate a moving target from an undesired target at rest by use of the shift of frequency based on the Doppler effect [1]. The Doppler effect has though the limitation and that it only works for targets in motion. Hence it would not give any effect for a fixed target.

From a physical point of view, every radar can be characterized by the formula:

$$P_r = \frac{P_t G_t}{4\pi R^2} x \left(\frac{\sigma}{4\pi R^2}\right) x \, A_e \qquad (1)$$

where, P_r is the power density assessed, P_t is the power the radar radiates, G_t is the power gain from an antenna, R is a distance between the radar and the target, $\frac{\sigma}{4\pi R^2}$ is the cross-section numerator factor, and A_e is the aperture area of the effective antenna.

2.2 Different technologies & applications

There are different types of technologies for the realization of low-energy radar and even more for radar technology in general. In this thesis, the focus will be on the low energy radars, including MIMO, LIDAR, and SISO radar in comparison with the evaluation kit from Acconer, which has possibilities to be a complemental part in Handheld cameras for different user cases, mainly focused on the improvement of the MSX matching.

An example of the application of the technologies using a low energy radar is to observe through heavy smoke from fire, in order to find the depth or the distance from the radar to the target. Another application is to use the low energy radar for measuring vital signs, where breath and pulse measuring is a huge factor. It is also used for tracking humans by their motion. In this report the main focus will be to look at the distance from a target so one can assess that value and improve on the performance of the MSX.

2.3 Distance compensation

The distance compensation is a very important technique in order to know the exact distance from a target, also it makes it easier to identify the depth and the distance from a placed target.

Distance compensation has a mathematical phenomenon, which can be calculated as follows:

$$\arctan\left(\frac{d}{D}\right) * \frac{180}{\pi} * \frac{R}{FOV} \qquad (2)$$

Equation 2 implies that if one knows the parallax distance d, the distance D from the target, the FOV, and the resolution (R), one can compute how many pixels one of the images needs to be compensated with. For a proper understanding of the formula, see the Fig. 1, attached below.

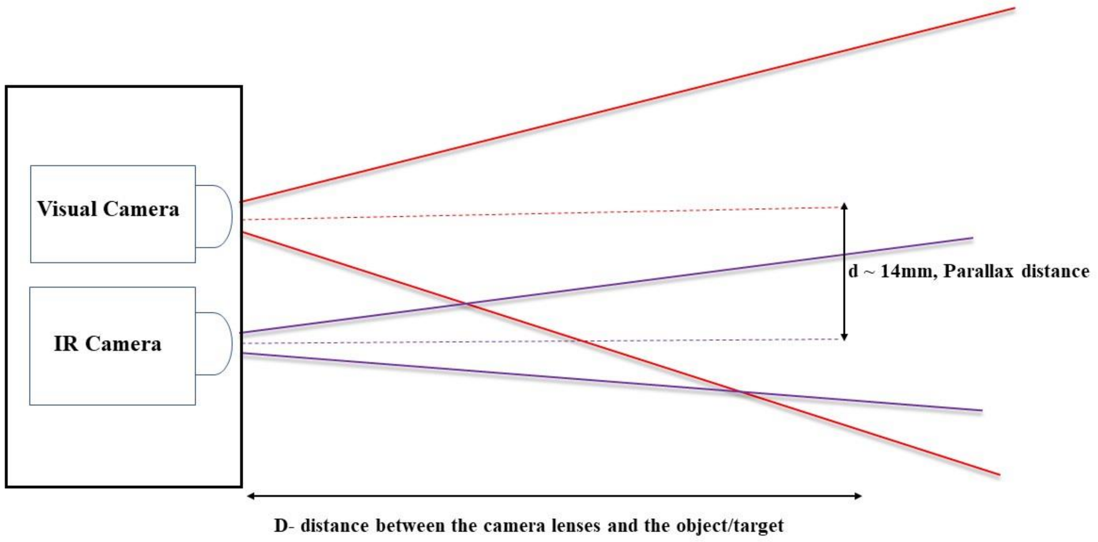

Fig. 1 Illustrates the complete camera system, in this case a C5 with the respective IR and visual camera, the purple lines correspond to the IR- spectra, which is between 1 µm up to 100 µm, (more specifically for C5 it is 8-14 µm) and the red lines illustrates the vision of visual spectra, which is 400 nm up to 700 nm.

2.4 MSX - Multi Spectral Dynamic Imaging

A challenge with the MSX technology is the preciseness between the virtual and the IR image [2] that comes as a consequence of the fact that the two cameras have a finite distance between them (referred to as the parallax distance). Unless taken care of, this deteriorates the quality of the imaging when targets are detected at short distances (for the camera utilized in this work, a few meters or shorter). When the target is further away, the parallax distance is less of a problem.

The basic principles of MSX when a target is addressed at such a distance that the parallax distance is a minor problem is shown in the Figs. 2-3 below:

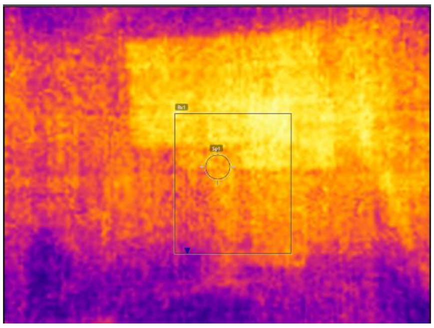

Fig.2 IR image taken by FLIR C5 camera

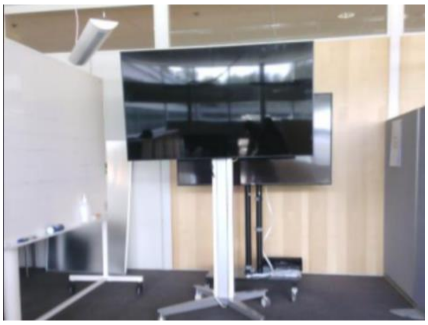

Fig.3 Visual image taken by FLIR C5 camera

The Figs. 2 and 3 illustrate the same object at a distance of larger than 3 meters, which provides a good MSX matching, but taken by different means; one in infrared and the other in visual mode. By adding them, the edges get sharper, and this is the fundamental of MSX, which is shown in Fig 4.

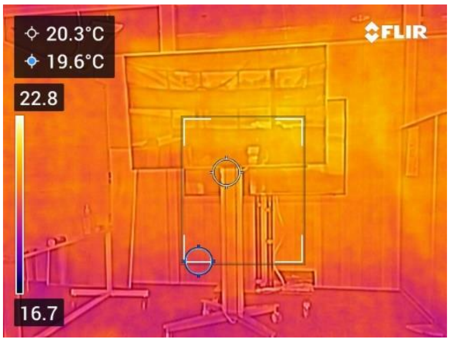

Fig.4 Shows an MSX image, by adding Figs. 2 and 3

The situation is not as advantageous when detecting targets at shorter distances. It has been anticipated that the performance of the MSX technology then can be improved by the addition of a mmWave radar. An example is when the distance to a target is close to the near limit of the MSX matching threshold, which is 0.3 m for the C5 camera and in general let's say that for any distance D around point p, shown in fig.5.

Nevertheless, as shown in fig. 5, in this case, the IR and VIS images does not agree with each other for any target below point p. Point p is defined as the point where, the IR and VIS cameras are overlapping, which means they aim at same targets. In the figure, one can clearly see that the field of view (FOV) for the IR camera and the Visual Camera overlaps only within a fraction of the FOVs of the two cameras, where the lowest point of the overlap region is denoted p.

This is one of the main reasons why we think that the radar might have a good impact for better compensation for targets within the range 0.3-3 meter away from the complete camera system. By the complete camera systems, means the structure where the IR camera and the visual camera are located in i.e., FLIR C5, illustrated in fig.5. The range depends on the camera features. That is, the range 0.3 and 3 meter is specific for C5.

The further the target is, the lower the compensation will be, referring to eq.2. If D goes to infinity the pixel compensation will go to zero. In the case of C5 our start threshold is around 0.3 meter. After 3 meters, the parallax distance d becomes neglectable. Since the range of the complete camera system is between 0.3 and 3 meter, the mmWave radar functioning within the range of 5 meter works fine. In other words, the mmWave radar covers the range required for distance estimation utilized for the compensation of the MSX image quality.

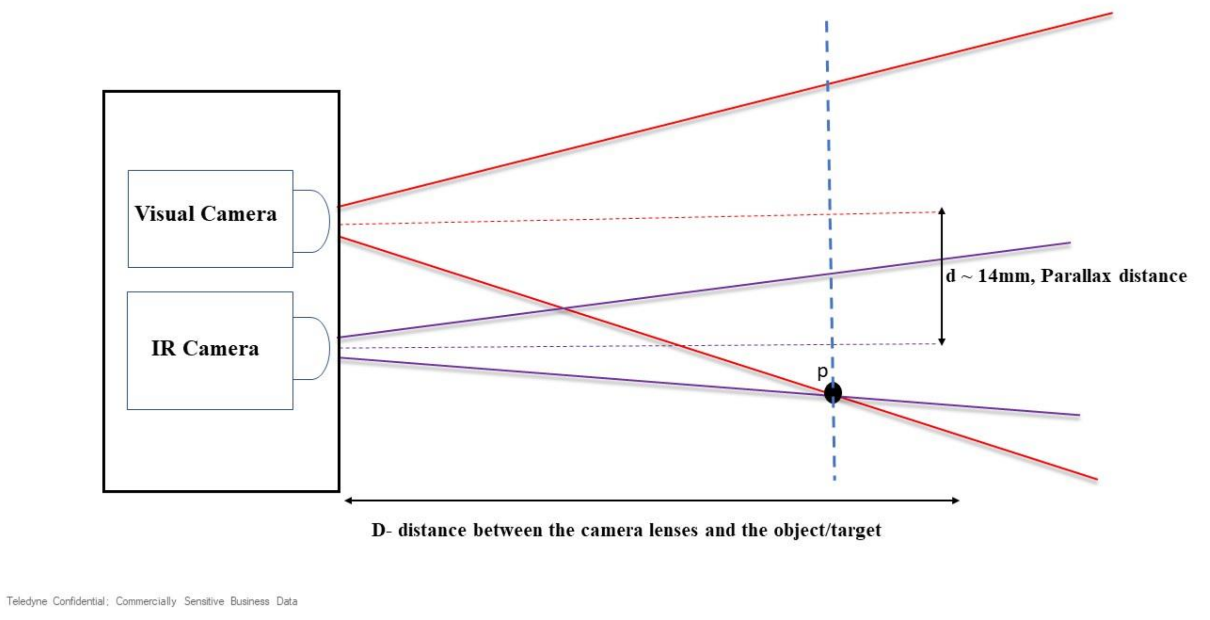

Fig. 5 The figure Shows an illustration of FOV for both the IR lens and the Visual lens, with a parallax distance of 14mm.

The figures 6 to 8 show a hand that is 0.3 meter away from the complete camera system, which means in the area where the IR and Visual camera begins to overlap. In this case, it clearly shows that the edges compensated by the MSX do not match exactly. That's an example where MSX compensation is limited and might need some fulfillments compensating the correct distance to the target, so that the edges match better.

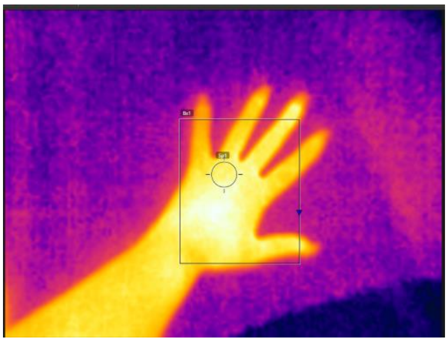

Fig.6 IR image taken by FLIR C5 camera

Fig.7 Visual image taken by FLIR C5 camera

Fig.8 An MSX image based on fig.6 + fig.7

2.5 Low energy radar technologies

There are several ways laser radar technologies can be realized. The ones most relevant to this work are shortly described below.

MIMO - Multiple Input Multiple Output

Multiple Input Multiple Output (MIMO) radars are categorized as low energy radars. They work based on wireless communication between multiple antennas of both the transmitter and the receiver [3] and have therefore a rather complicated realization.

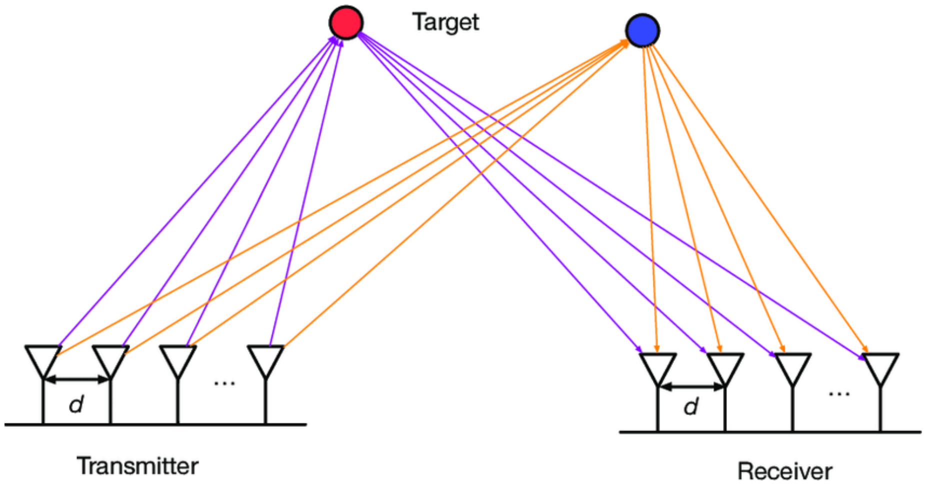

Fig. 9. The picture above shows an illustration of MIMO radar paths between the transmitter and the receiver [4]

The Single Input Single Output (SISO) radar works along the same principle as the MIMO radar, with the main difference being that, instead of having multiple paths between the transmitter and the receiver as shown in Fig. 9, in SISO has only one single input and output.

mmWave radar

The millimeter wave radar has a frequency above 40 GHz. It thus works in the microwave regions. This implies that it has widely useful operation in space, where the attenuation coefficient of the atmosphere is low (it can be approximated as zero). In addition, it is also used for short range application, including the measurement of the distances between objects.

The mmWave radar used in this report consists of an evaluation kit from Acconer, which has a variety of uses, such as detecting breath, tracking target and distances [5].

The benefits of using a mmWave radar is that it is much lower in cost than for example laser-based technology i.e., LIDAR. A mmWave radar is also driven by much less energy taken from the camera's battery and also more accurate for shorter distances. The limitation for a mmWave radar is that it could only estimate target that is within 5 meters distance from the detector surface.

Another benefit of using a mmWave radar as a complement to handheld cameras in particular the C5, is that it will not require any huge hardware design changes, since the shape of the radar lens is flat and fits to the area located close to the VIS and IR camera.

LIDAR- Light detection and ranging

LIDAR stands for light detecting and ranging and is used to measure variable distances between the detector and a target. The principle of LIDAR is to use light pulses, mostly from lasers, that bounce back from a target. By measuring the time delay between the emitted and the returning signal, the LIDAR can estimate the distance to the target.

Some of the main applications of LIDAR technology include autonomous driving assistance systems, remote sensing, navigation, and mapping systems. In all these three different applications the main focus is the distance to the target [6], as shown in Fig 10.

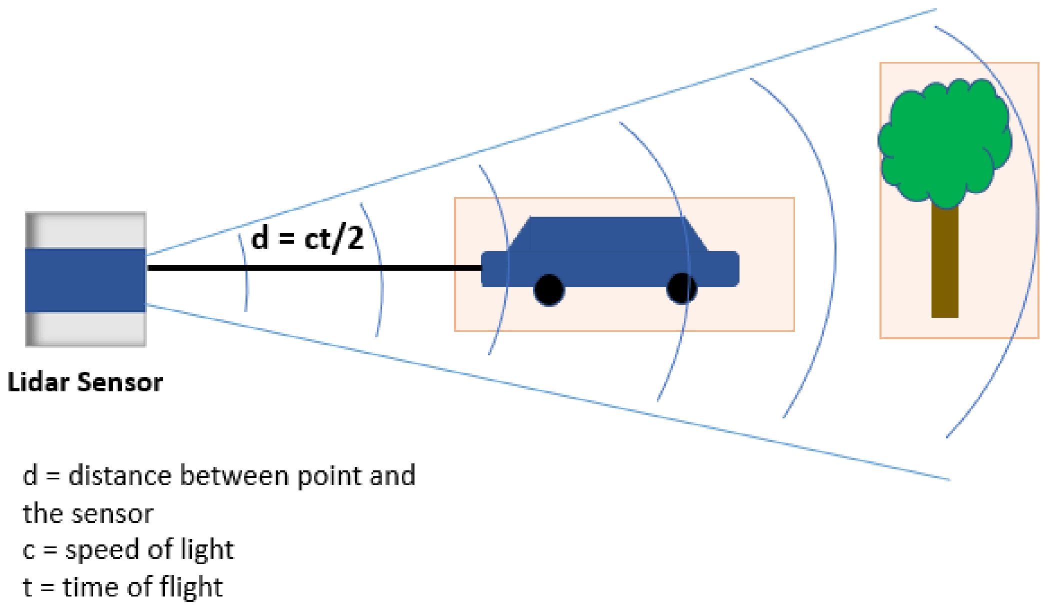

Fig.10 Illustration of LIDAR system taken from [6]

2.6 Why Radar

Radars are widely used due to often low costs, which is advantageous for businesses. The reason that the radar is used as a complement is however that the evaluation kit from Acconer is easy to integrate with the modules used at FLIR.

2.7 mmWave Radar from Acconer

The mmWave radar from Acconer works as a pulsed radar, which means that it gets signals from an object and by bouncing back the signal it can estimate the distance from the object, as shown in the figure below [7].

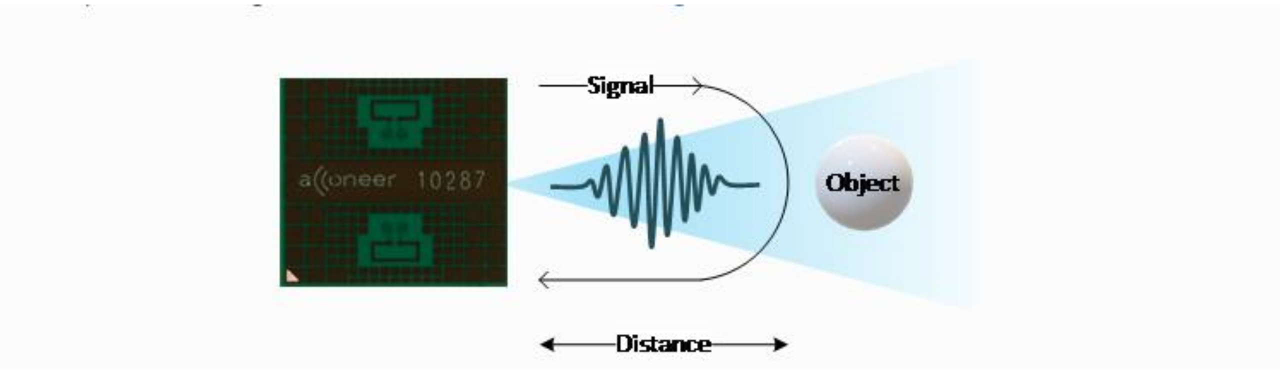

Fig. 11 shows an illustration of a pulsed coherent radar, where the time of flight is used for measuring the distance from an object. The figure is taken from [7].

By knowing the ToF and the speed of the radio waves, which is the same as speed of light (c, which is approx. $3.0 * 10^8$m/s), one can measure the distance by the following formula:

$$D = \frac{ct}{2} \quad (3)$$

where *c* is the speed of light and *t* is the time of flight.

2.8 The FLIR C5 Camera

The FLIR C5 Camera is one of many hand-held cameras that FLIR has built and developed, this camera is categorized as one of their budget cameras. The FLIR C5 is widely used by different end user, some as private customers and other as companies within construction work, industry and within condition monitoring.

The FLIR C5 has a field of view with 55 degrees for the IR lens and a resolution with 160 pixels. The FLIR C5 camera is based on two cameras, one for the visual spectra and the other for the IR spectra. They are both located 14mm away from each other, which means that they have a so-called parallax distance of 14mm. The FLIR C5 has many features, i.e. it has MSX matching, which is as described earlier in this report, the match between the VIS and IR image[8]. This can be manually adjusted for the cases where the MSX match is not properly fitted.

The picture shows a FLIR C5 camera, taken from [8]

3. Methods

3.1 Equipment

The equipment used in this report was a FLIR C5 camera, which is a pocket size camera mostly used within construction work or for private customer needs e.g., for home inspections. The other equipment used was a mmWave radar from Acconer, for distance measurements. To compare the distance measurement between target and detector, a yardstick was used. Hence, the detector implies the complete camera system and the mmWave radar together.

In order to communicate with the camera and the mmWave radar, a laptop/computer where used. The software called Putty was used for communicating with the camera. When it comes to communication with the mmWave radar another software called the "Portable exploration tool from Acconer" was used.

The target used in this report was a water bottle, a hand, a TV, and these targets was randomly chosen at different distances. The other target used was a radiator that was under heating process.

3.2 Experimental set-up

The experiment is based on a FLIR C5 camera and some targets. The target could be anything of interest with a distance of *D* meters from the detector. The detector in this case is defined as both the camera detector and the radar detector. The maximum range or limitation for the distance between the target and the detector must be below or equal to 5 meters, since the radar detector has a limitation of 5 meter and the camera has a threshold for compensating between 0.3 to 3 meter.

The software used for the evaluation kit is called the "Portable Exploration Tool", which comprises the mmWave radar and the lenses from Acconer. Another software used is Putty, which provides possibilities to manually control the FLIR C5 camera from the computer and recorrect the distance from a target. This will be required for filling in the distances, by using the distance given by the mmWave radar. When both the radar and the camera are connected to the computer, measurements can start. This is done by placing a target with a distance *D* from the detector (camera + the radar detector) and taking an MSX image, first without recorrecting the distance and another measurement with adjusted distance based on the information provided by the radar. As a comparison for estimating the distance from the target, a yardstick was used, in order to see how well estimation was made by the radar. Fig. 12 below shows a schematic illustration of the set-up. Further on, fig. 13 shows the complete camera system, a FLIR C5 camera connected with the mmWave radar from Acconer.

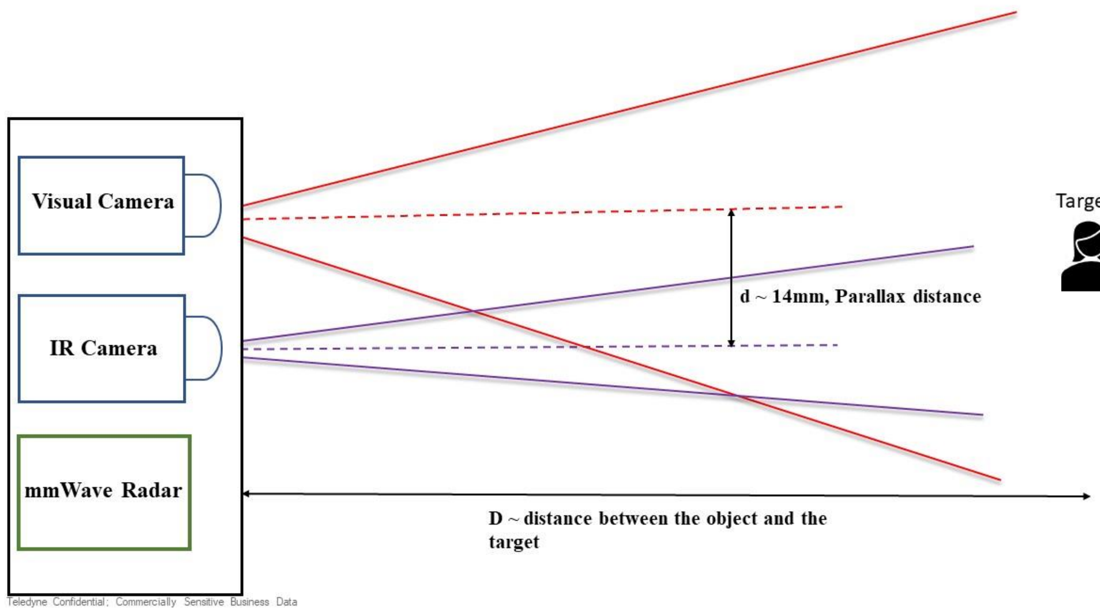

Fig. 12 shows an illustration of the experimental set-up

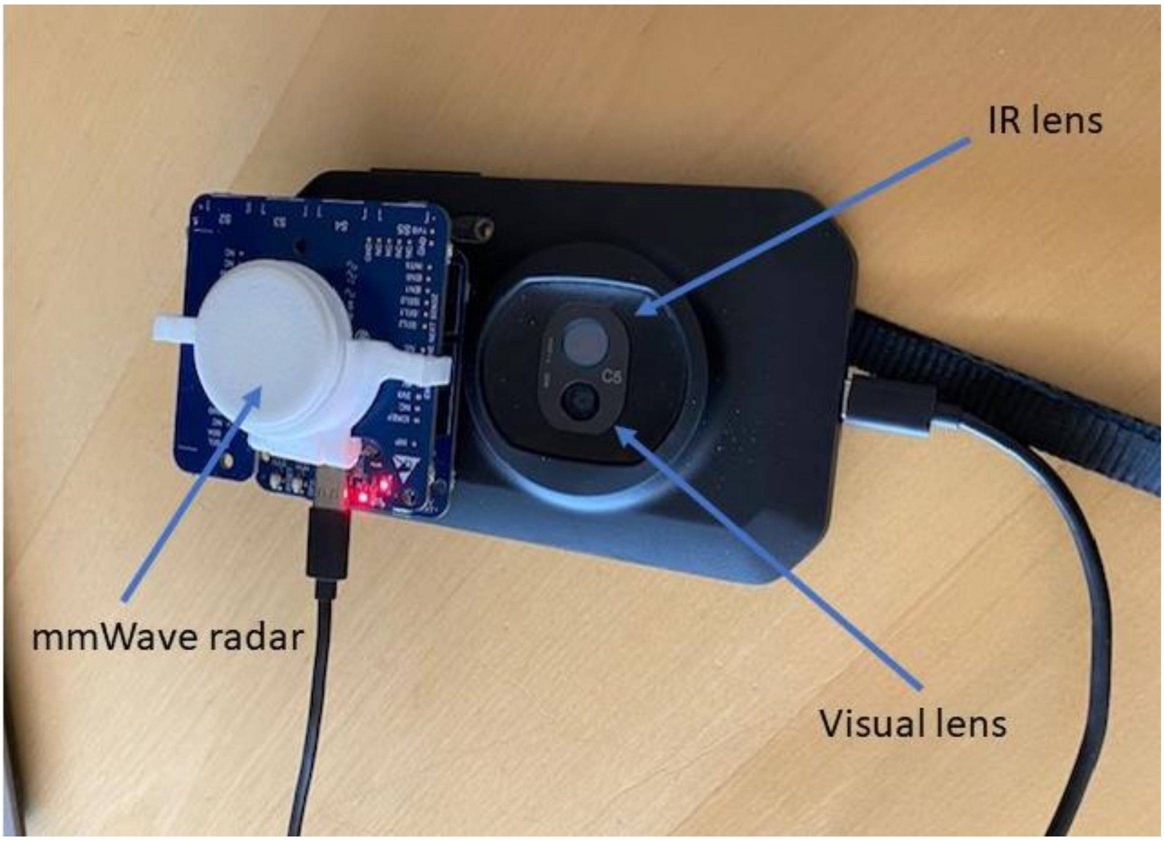

Fig. 13 Shows a FLIR C5 camera, with the mmWave radar used.

4. Results

4.1 Different targets with different distances from the detector

The result was acquired depending on targets and distances from the complete camera system. The first measurement was acquired by the use of the MSX, and the second measurement by adjusted MSX with the help of the mmWave radar, in order to see if it gives any better results or estimation for the alignment of VIS and IR image.

Fig 14 was taken with 0.5 meter between the target and the complete camera system. Fig. 15 is aiming on the same target as fig.14, but with adjusted MSX. The compensated pixels in Fig.15 were around 5 pixels (more precisely 4.67 pixels by computing according to eq.2 given on page 6).

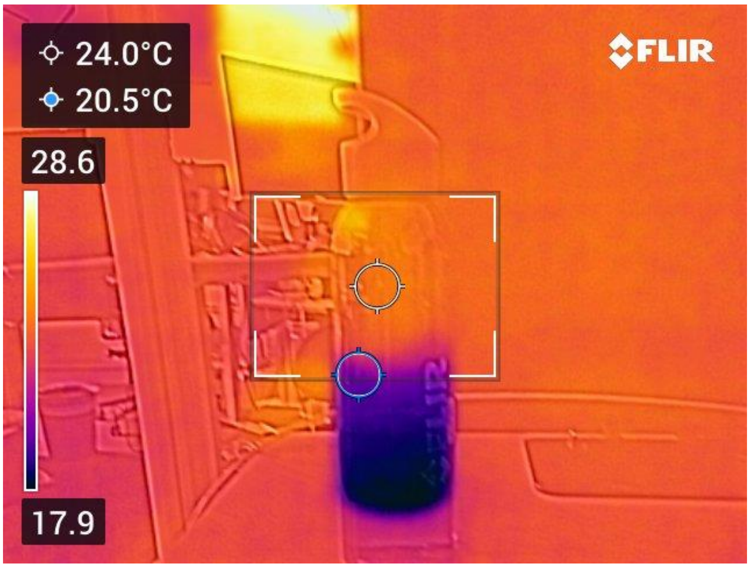

Fig.14 Shows a picture of a bottle as a target, with MSX mode on

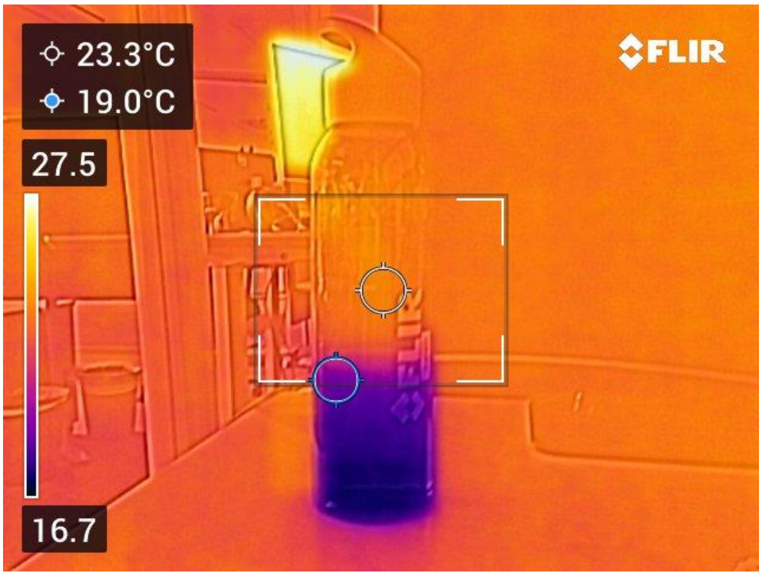

Fig.15 Shows the same target as shown in fig.14 with adjust distance, taken from the radar. Approximated distance from the target was 0.5 meter

The graph shown below is a cloud point of distances based on the target that the mmWave radar has focused on, the target is seen in fig.18 further below in the report. The aiming target is a TV situated approximately 3.31 meter away from the complete system (the complete camera system and the mmWave radar). In the graph shown, the y-axis represents the estimated distance between the target and the mmWave radar, while the x-axis represents the signals bouncing back from a target to the mmWave radar.

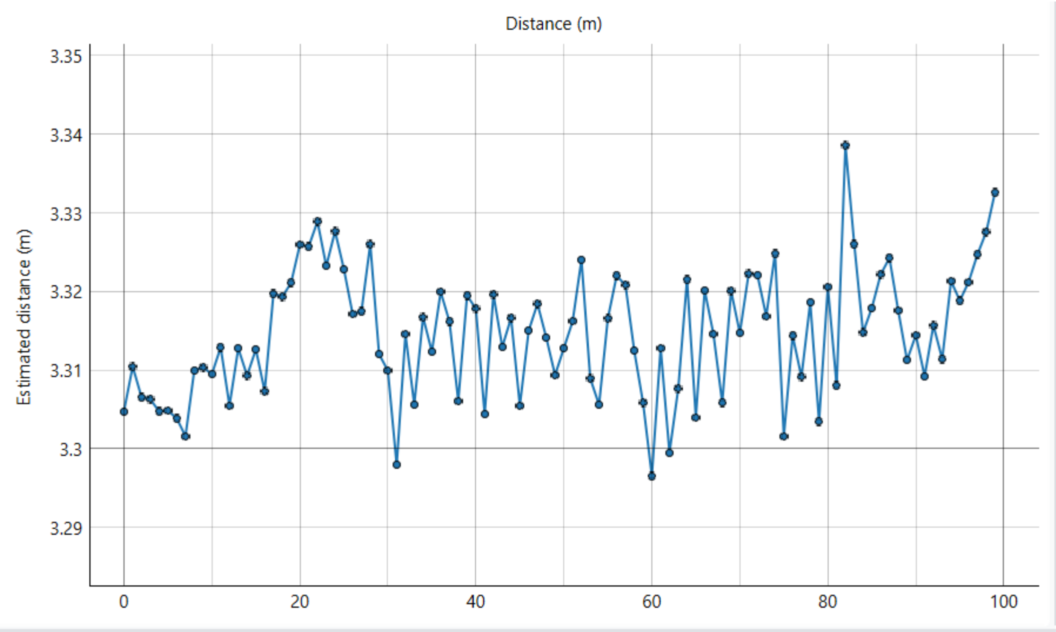

Fig. 16 Shows the cloud point of distances made from the target shown in fig.17 and fig 18

Fig 17 was taken with 3.31 meter between the target and the complete camera system. Fig. 18 is aiming on the same target as in fig.17, but with adjusted MSX. The compensated pixels in fig.18 were around 1 pixel (more precisely 0.71 pixels by computing according to eq.2 given on page 6).

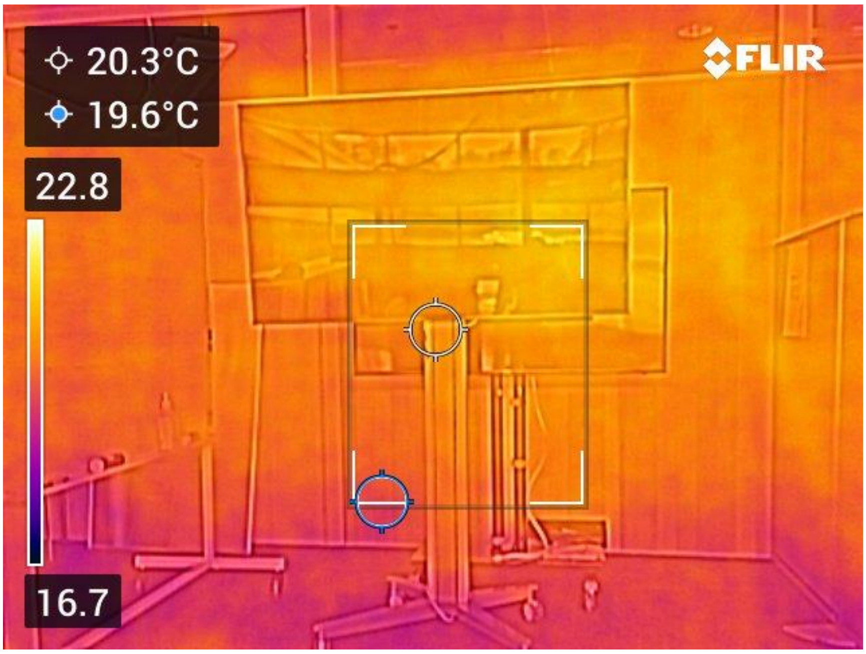

Fig.17 Shows an MSX image, with a TV as a target with 3meter distance away from the detector

Fig. 18 Shows the same target as shown in fig.17 but with adjusted distance evaluated by the radar. The distance according to the radar was 3.31$\pm$0.1m.

The graph shown below is a cloud point of distances based on the target that is in front of the mmWave radar, the target is seen in fig. 21, further below in the report. The aiming target is a hand situated 0.3 meter away from the complete system (the camera system and the radar). In this case the mmWave radar shows a flat graph, which implies that for shorter distance the radar is more focused on the target. The graph below represents, the estimated distance on the y-axis and on the x-axis, the signals bouncing back from a target to the mmWave radar.

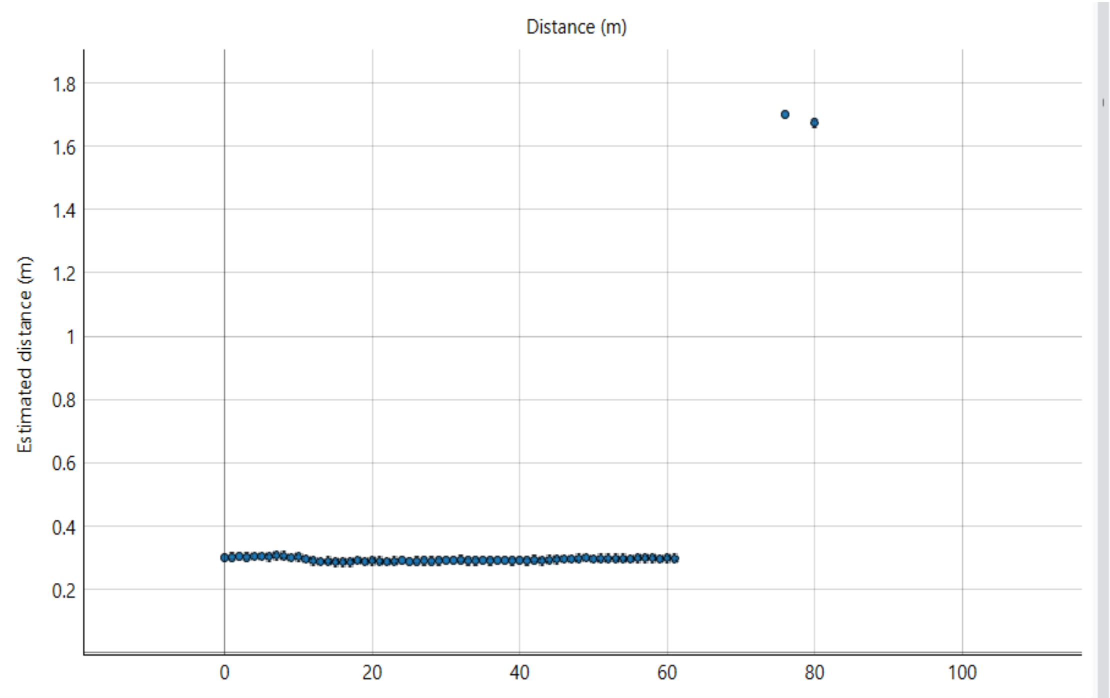

Fig. 19 Shows the cloud point of distances from the target of fig.20 and fig.21

Fig. 20 was taken with 0.3 meter between the target and the complete camera system. The target in this case is a hand. Fig. 21 is aiming on the same target as fig.20, but with adjusted MSX. The compensated pixels in fig.21 were around 8 pixels (more precisely 7.77 pixels by computing according to eq.2 given on page 6).

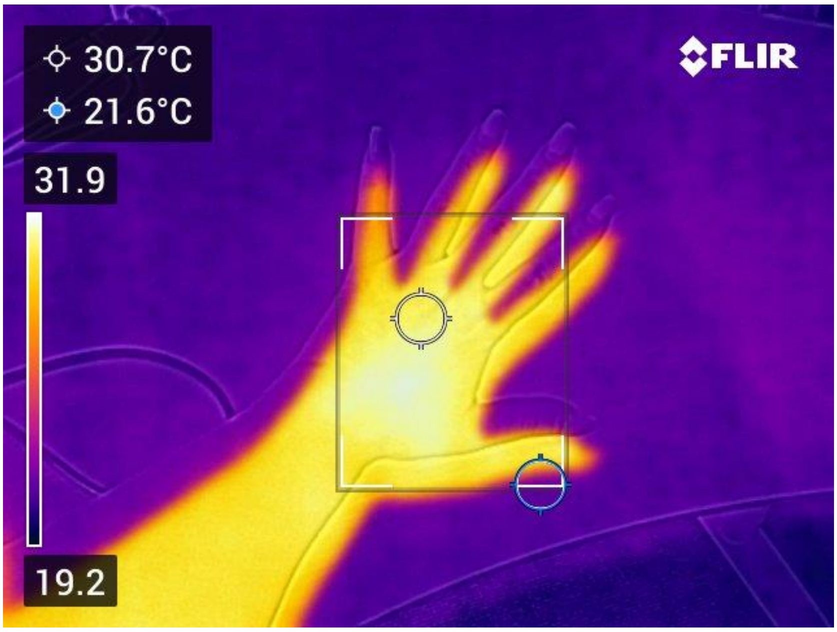

Fig. 20 Shows a hand with MSX applied

Fig. 21 Shows the same target as shown in fig.20 but with inserted distance from the radar, the insert distance was 0.3m.

4.2 One target, different distances

In this section one can see the results of having one target with different distances away from the detector, first measurement was made 1.5 m away, the second with 1.0 m, the third measurement with 0.8 m and the last one was 0.4 m away. For each distance, the results were acquired two times. One with MSX applied and the other with re-correction of the MSX with the help of mmWave radar.

Fig. 22 was taken with 1,5 meters between the target and the complete camera system. The target in this case is radiator. fig. 23 is aiming on the same target as fig.22, but with adjusted MSX. The compensated pixels in fig.21 were around 2 pixels (more precisely 1,55 pixels by computing according to eq.2 given in the beginning of this report).

Fig.22 shows a target, in this case a radiator 1.5m away from the detector, MSX is not re-corrected

Fig.23 Shows the same target as fig.22, with a re-corrected MSX by the help of the mmWave radar, distance from the target was 1.5m

Fig. 24 was taken with 1.0 meter between the target and the complete camera system. The target in this case is the same as for figs.22-23, the difference is that the distance is closer. Fig. 25 is with adjusted MSX. The compensated pixels in fig.25 were around 2 pixels (more precisely 2.33 pixels by computing according to eq.2 given on page 6).

Fig. 24 Shows the radiator 1.0 m away from the detector, with no corrections for the MSX

Fig. 25 Shows the same target as fig 24, with corrections for the MSX

Fig. 26 was taken with 0.8 meter between the target and the complete camera system. The target in this case is still a radiator as for the previous figs.22-25, the difference is that the distance is shorter. Fig. 27 is with adjusted MSX. The compensated pixels in fig.27 were around 3 pixels (more precisely 2.91 pixels by computing according to eq.2 given on page 6).

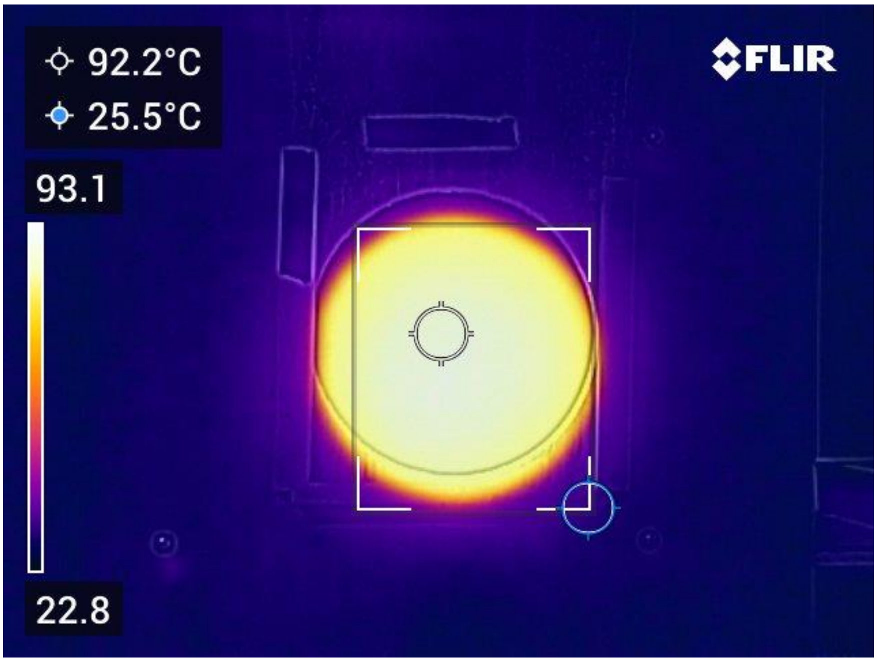

Fig.26 Shows the radiator with a distance 0.8m from the detector, with no correction for MSX

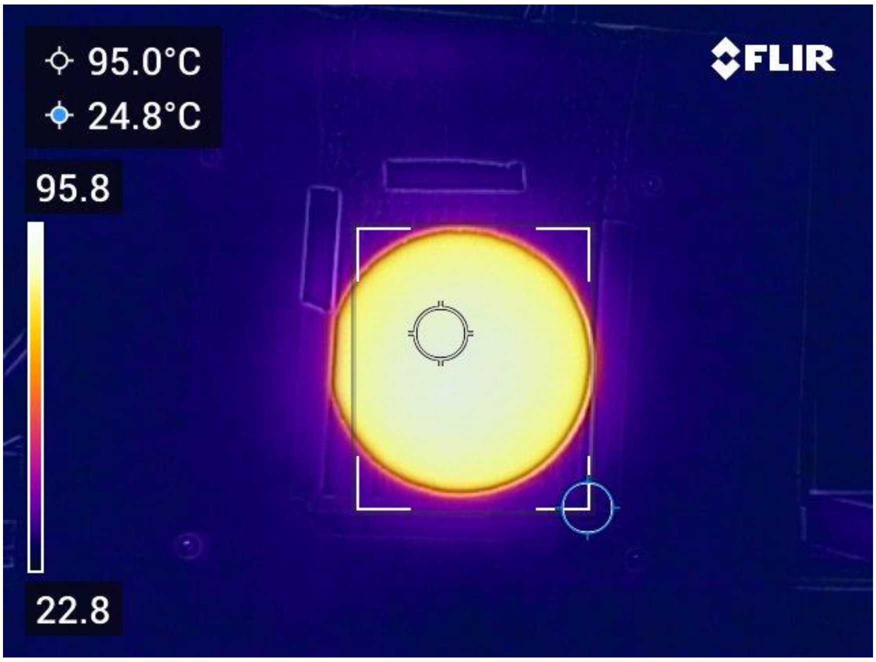

Fig. 27 Shows the radiator with 0.8m from the detector with corrected MSX.

Fig. 28 was taken with 0.4 meter between the target and the complete camera system. The target in this case is still a radiator as for the previous figs.22-27, the difference is that the distance to the target is shorter. Fig. 29 is with adjusted MSX. The compensated pixels in fig.29 were around 6 pixels (more precisely 5.83 pixels by computing according to eq.2 given on page 6).

Fig. 28 Shows the radiator with 0.4m from the detector, with no corrections for MSX

Fig. 29 Shows the radiator with 0.4m from the detector, with corrections for MSX.

The graph shown illustrates the decreasing pixel compensation, based on the Fig. 22-29 the less the distance is the larger the pixel compensation value is, since at short distances the MSX matching is not properly aligned between the IR and the VIS image.

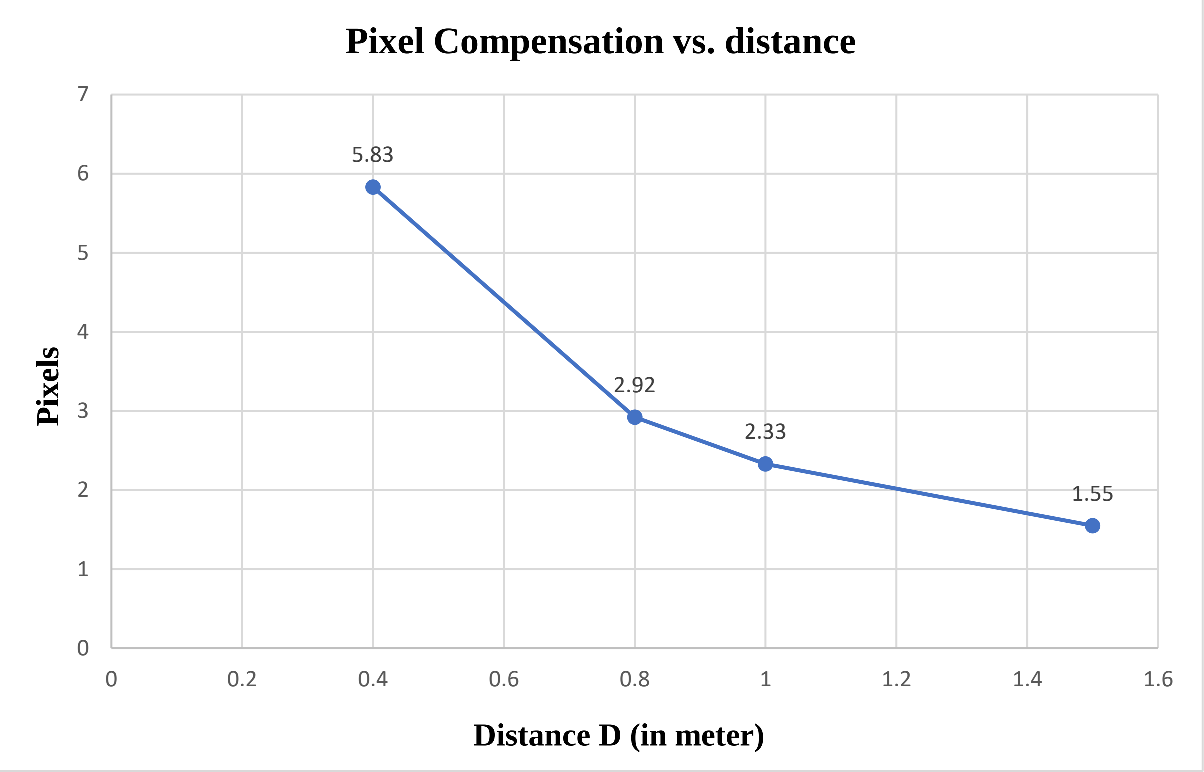

Fig. 30 Shows a graph with number of pixels on the y-axis and the distance D on the x-axis.

5 Discussion & Conclusion

First of all, it is shown that the correction of MSX with the help of mmWave radar is mostly needed for short distances. This confirms that, our original assumption was correct. By adjusting the distance created by the radar, we can clearly see that adjusting the distance will give us a better estimation of MSX-matching.

To begin with, comparing fig. 15 with fig.18, one can see that the pixel compensation value decreases by increasing the distance between target and the complete system, including the complete camera system and the mmWave Radar. In fig.15 the distance to the target, in this case a bottle was 0.5 meter away from the detector, the pixel compensation computed was 5 pixels. While for fig.18 the distance was 3.31 meter and the pixel compensation computed was around 1 pixel. This implies that by increasing the distance the pixel compensation for any target is decreasing, which means that the difference between IR and VIS gets smaller.

By looking at the figs. 20-21, where the distance was settled at 0.3 meter, the compensation was 8 pixels, the same argument for fig. 15 and fig.18 confirms that the pixel compensation increases by decreased distance, and even a larger difference appears when it's around the near threshold for the C5 camera.

For distances nearby 0.3 meter, as exemplified by fig.20, where the distance is 0.3 meter, the image quality with MSX applied is not as competent as it expected. However, by adjusting the distance from the target, according to the value given by the radar, one can clearly notice that the image quality of MSX matching gets better, as shown in fig 21. Now one may wonder why? As mentioned in the beginning of the report, fig.5 illustrates the complexity of having a good MSX match because that the visual lens and the IR lens for any target below than point p, is almost impossible since they are not agreeing with each other. In other words, they are aimed at different things for any target situated below than point p and for any target after the point p, their area of interests overlaps, implying that they indeed are looking at same targets.

However, figs.22-29 shows a target i.e. a radiator one could see that the pixel compensation was increasing for each shorter distance. The measurement was first taken at 1.5 meter distance away from the target, followed by 1.0, 0.8 and 0,4 meter. As a result of those measurements for figs.22-29, the compensation was increasing by decreased distance from the target, and as mentioned before the argument here also satisfies that for further distances the less compensation will be and vice versa.

On the other hand, we know that the further away the target is, the more both visual and IR camera overlaps. That is, the compensation can be negligible. In these kinds of cases 14 mm as a parallax distance could be assumed as zero. Which we clearly can see on the graph (fig.30) shown in the result part. The further the distance is, the less the compensation is required, and vice versa.

However, even though there are benefits of using a radar to compensate the distance, there are also some difficulties. One of them is how to integrate the radar in the hardware design of a handheld camera. For the case of C5 this could be achieved relatively easy, but not every camera has the same design and resolution, so one will need to figure it out.

Another challenge could be, that the mmWave radar has difficulties to focus on one target when the distance is quite large, as in the case of figs. 17-18, where the distance to the target was 3.31 meter. Looking at the graph on Fig.16, one can see that the radar has a cloud point with $\pm$0.1 meter for the target located 3.31 meter away. The reason is that the radar starts to aim at other targets near to the focused one, however, the diff. is not that large that it could cause any problem. Also, one can compensate that diff. by making a code in python so that the radar could concentrate more precisely on the target of interest. By other word, the challenge here is less of a problem since there are tools included in the kit that provides more accuracy if needed when integrating systems together. As a comparison, by looking at the cloud point made from the mmWave radar, shown in fig. 19, the graph shows a flat line for 0.3 meter, means that the radar does not get disturbed by the surrounding target for shorter distances.

In the beginning of this report, we also mentioned that there are some other technologies, such as MIMO, SISO and LIDAR. Those are some other radar technologies, that also can be used for compensating MSX depending on the cameras need. We all know, by now that each camera system has different parallax distance d, but the principle is the same. What I am trying to imply is that using different radar depending on how much compensation is needed is also a way to make a better product. Our aim in this report was only to show that if one type of radar can work as a complement for the camera, there will be other radars that could do the same but for another limitation than the one we used.

The parallax distance shown in fig.5 can differ from one camera to another depending on the complete camera system, but in general, for any parallax distance d between visual and IR camera, there will be a need for compensation, while the parallax distance could vary. Nevertheless, we can conclude that the hypothesis in the beginning of this report is confirmed by the results discussed above.

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