The Analysis of the Requirements Necessary to Visualize Finger Veins With a Finger Vein Swipe Sensor

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***Abstract*—Security within passwords and electronic devices has become more important. Therefore, there is an increasing demand for compact finger vein scanners. This research continues with Alvarez's research on designing a compact finger vein swipe sensor [1]. Since their research managed to visualize the joints within the finger, but failed to distinguish any finger veins, the objective of this research is to discover whether it is possible to visualize finger veins with a similar setup. Several experiments were conducted to test and improve the quality of the images, the dynamic range of the images, the camera and the code. Also a new aperture filter was designed to improve the quality of the images. From the experiments could be could be concluded that with several improvements it is assumably possible to increase the quality of the images sufficiently to identify finger veins. However, the dynamic range of the images is too low. Theoretically this could be improved by increasing the gain or exposure time of the camera, but the current code does not allow these values to be altered. To conclude, the current setup is not able to visualize any finger veins, since the dynamic range of the camera cannot be sufficiently increased, when supported by the current code.**

I. Introduction

A. Social and research Gap

Since the rise of the internet and modern technology, the security of electronic devices and online accounts has become increasingly important. The most common way to protect these devices and account is through the utilization of passwords. Even though passwords have many advantages, there are also many potential problems. Password can, for example, be hacked or forgotten. To increase security, passwords are sometimes replaced by finger print scanners. Although these provide more security than passwords, fingerprints can still be hacked. As Zhang et all. (2012) suggest, a phone can be unlocked by using fingerprints that were left on the screen [2]. Finger vein scanners are even more secure than finger print scanners in protecting devices and identifying individuals in general. Finger vein scanners work by sending infrared light through the finger. Because the hemoglobin in the blood absorbs infrared light, the finger veins can be detected by a camera. By observing the absorption spectrum of the camera, the infrared light intensity, received from different positions of the finger, can be determined. Just like finger prints, finger veins have a unique pattern. For this reason they can, just as effectively as finger prints, be used to distinguish one person from another. Unlike finger prints, however, finger veins leave no visible traces and are therefore significantly harder to spoof [3]. Today there are already some finger vein scan designs present on the market. Most of the currently available scanners are quite big and none of the developed products are small enough to be easily incorporated into modern technology. Therefore, finger vein scanners are the logical next step in the protection of everyday devices.

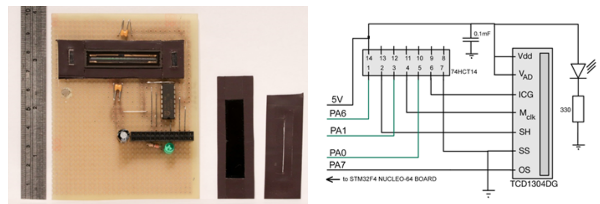

Fig. 1. This figure shows the hardware of the original design. The left image shows the circuit board on the left, the IR filter in the middle and the aperture filter on the right. The right image shows the wiring schematic of the hardware [1].

B. Original Design

This research is based on the work of Alvarez [1]. For this reason, his design was used as a starting point. Because both their software and hardware were partially reused in this research, it is important to describe the current design both to give an impression and to create a frame of reference. Therefore a distinction is made between hardware and software.

1) Hardware: The hardware currently uses a CCD line sensor (TCD1304DG by Toshiba) that is lit up by a single near infrared LED from above. The LEDs used are SFH4550 IR LED's, that transmit light with a wavelength of 850 nm. The This CCD line sensor is an extremely thin camera that is used to capture the incoming light. To ensure that only IR light is captured, an acrylic IR filter is put on top on the camera. This filters out any incoming light with a wavelength below 750 nm. Besides the IR filter, the design also uses a hand crafted aperture filter. This is a narrow optical slit that is used to only let through highly directional light. The aperture filter was created by manually cutting a narrow opening. The sensor is driven by a STM32F4 Nucleo-64 board. Both the circuit and the filters are displayed in figure 1.

2) Software: The current design uses a trio of programs to generate the scans. First of all Keil μvision is used to program the microcontroller and to drive the timers for the inputs of the CCD. Both the code itself and the drivers for the program were created from scratch. Secondly, MATLAB is used to take the output and generate a visible image. Since MATLAB is not in sync with the other programs, the input file that is required needs to be created by a third program, STMStudio. This is used to capture the output of the camera and generate an array of data that can be interpreted by the MATLAB script.

3) Flaws of the Original Design: Although the original design is very innovative, it still requires some improvements. The goal of the scanner is to clearly visualize the veins within the finger. The original design is unfortunately unsuccessful in visualizing the finger veins. First of all, the quality of the original scan is still too blurry to detect any finger veins and therefore needs to be improved. A second problem concerns the image reconstruction. Currently, the size of the scan is dependent on the swiping speed of the finger. If a finger is swiped faster, the created image will be shorter than if it is swiped a little slower. Because of the inconsistent swiping speed, the images can become somewhat deformed. To counteract this problem an image reconstruction method needs to be implemented. Thirdly, the camera sensor currently has a glass coating. This can cause problems because the glass does reflect a part of the incoming light. A last point of improvement would be to let the DMA of the micro controller replace MATLAB in constructing the image. This is an improvement since the MATLAB program was not in sync with the rest of the program. Also, the CPU usage for this method is unknown.

C. Research Questions

This leads to the following research question: "To what extent is it possible to improve the image quality to clearly visualize finger veins using a finger vein swipe sensor lit by NIR light?" To be able to provide an answer to this research question, it needs to be broken down into several sub questions:

- To what extent is the quality of the images sufficiently high to visualize the finger veins?
- To what extent is the CCD sensor capable of visualising finger veins?
- To what extent is the currently used code able to support the technical demands in order to visualize the finger veins?

D. Research Scope

The goal of this research is to improve on the work of Alvarez [[1]]. Concerning the software, no changes will be made in the programs that are used. This means that Keil μvision, MATLAB and STMStudio will be kept to drive the microcontroller and generate images. As for the hardware, only the lighting and the filters fall within the scope of research. No adjustments will be made to the board or circuit that was formerly used.

E. Research Outline

In section II similar products and research will be discussed as well as Alvarez's most relevant results [[1]]. Then, in section III, the experiments will be discussed in chronological order, along with their results. Section IV is the discussion. Here, the results will be discussed along with any possible future research. Finally, Section V is the conclusion, where the research question, along with it's sub questions, will be answered.

Fig. 2. The USB Finger Vein Biometric Scanner by Hitachi [6].

II. Related Work

This section has been divided into two parts. The first part will look into similar products and the second part will focus on Alvarez's most relevant results [[1]].

A. similar products

For quite some time now companies have been working on the development of finger vein scanners. The current leader in the development of finger vein scanners is Hitachi. They have been working on finger vein scanner technology for over fifteen years now. Through the years they have developed several devices already that visualize finger veins. One example is their USB Finger Vein Biometric Scanner [5]. This scanner can be seen in figure 2.

This device sends near infrared light from above trough the finger. Near infrared light was chosen because it passes through the finger while the hemoglobin in the blood reflects the near infrared light. By observing the light level that have passed through the finger, a visual image can be constructed of the finger veins. Another example is the HS100-10 Contactless Hybrid Finger Scanner by NEC. Their design is more open since the NIR light is sent from the sides. This design is a hybrid finger scanner, because it scans both the finger veins and the finger print simultaneously. This scanner can be seen in figure 3

The problem with these designs however is that they are still relatively large. As mentioned in the introduction, this thesis is based on Alvarez's work [1]. Their goal was to create a compact finger vein scanner. Therefore, a thin swipe sensor was selected to observe the light. There are currently already available finger print swipe sensors. An example is the Eikon II Swipe Fingerprint Sensor. By swiping a finger over the sensor, the finger print can be detected. The same principle can be applied for finger vein scanners. Swipe sensors have a smaller size and are therefore more compact. The Eikon II Swipe Fingerprint Sensor is displayed in figure 4.

The dimensions of the swipe sensor Unfrotnunaetly do not allow for the entire finger to be scanned at once, therefore image reconstruction is required. Due to limited development in finger vein swipe sensors, similar products can be observed

Fig. 3. The HS100-10 Contactless Hybrid Finger Scanner by NEC [7].

Fig. 4. The Eikon II Swipe Fingerprint Sensor [8].

to explore the field of swipe sensor image reconstruction. Mardiansyah et al [4] already researched image reconstruction in finger print swipe sensors. They mention several methods through which current reconstruction is done and focusses on how it can be done more efficiently. Through conventional methods blocks of pixels are compared by their light intensity. Based on the level of similarities, it is determined whether two blocks overlap and are therefore a visual representation of the same point. Since a choice was made for a thin swipe sensor, a filter needs to be placed in front of the camera to filter incoming light. First of all, there will be a filter that only passes through the desired infrared wavelength. Secondly, to increase the quality of the image an aperture filter or optical slit will be added to remove luminous noise. Aperture filters are already common in photography. For this project a slit will be used as long as the camera itself. Since the finger vein scanner design prioritizes compactness, it is important to consider the direction of the lighting. Originally finger vein scanners used lighting from above. However, a recent study has shown that the direction of the light source has become redundant, since the bone inside the finger acts as a reflector in all directions. This means that the intensity of the light received at the camera, is not influenced by the incoming direction of the light source. Therefore, the location of the light source can be decided freely. Since the flatness of the design is important to keep everything compact, the light sources are ideally placed besides the camera itself.

B. *Main Findings of Other Research*

Since this research is based on the work of Alvarez [[1]], it is important to discuss the results of their research that influenced this research. First of all they did an experiment to test the image quality of their finger vein swipe sensor. For this experiment a ruler was swiped over the CCD line sensor in a linear motion. This experiment as done in both natural lighting as well as with a LED 6cm above the sensor. The results of this experiment are displayed in figures 5 and 6. From these results they concluded that when comparing the images, although the aperture filter is not perfect, it proves that an aperture filter is needed to increase the image quality. Another interesting result occurred when both an actual finger and a phantom finger were scanned to see the results. These are displayed in figure 7. Two notable things were interpreted from these results. First of all, the quality of the scans when using the phantom finger is greater compared to when a human finger was used. The dynamic range of the images where the phantom finger was used is greater than for the human finger. Secondly, the quality of the image was discussed. Although they were able to visualise the joints in the finger (the lighter areas in figure 7), the finger veins cannot be detected. This leaves space for future research and is the main reason for this research.

III. Experiments and Results

In this section of the report all the experiments that were conducted will be listed, along with their results. Since the results of some experiments were the reason for others, all experiments will be discussed chronologically.

A. *Experiment 1: Improvement of the Aperture Filter*

One of the major focuses of this research is to see if the quality of the images can be improved. Since the original aperture filter was created by manually cutting a small slit into the material. The problem with this method is that the edges of the slit become very rough, which results in inconsistencies in the observed light.Due to these inaccuracies, a new aperture filter was created. See figure 8. Instead of manually cutting a hole in the material, a highly accurate laser cutter was used to create the new filter. The size of the slit is equal to the image sensing element of the camera. This means that all directional light from above is let through, while any sideways

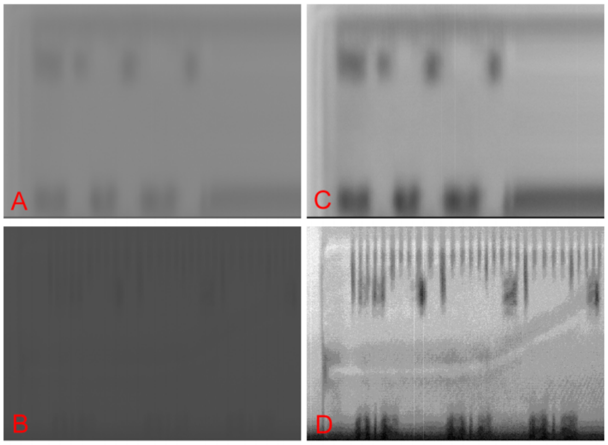

Fig. 5. mage showing a) Ruler swipe under natural light. b) Ruler swipe under natural light with aperture filter. c) Increased contrast version of A for comparison purposes. d) Increased contrast version of B for comparison purposes [1].

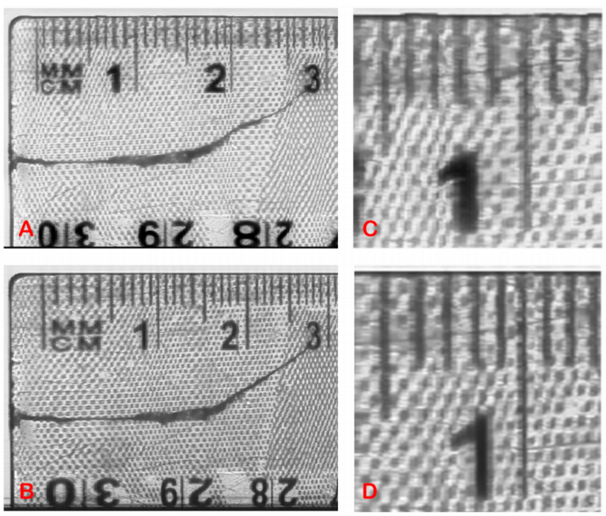

Fig. 6. Image showing: a) Increased contrast version of the ruler swipe under LED light. b) Increased contrast version of the ruler swipe under LED light with aperture filter. c) Partial magnification of A. d) Partial magnification from B [1].

lighting is filtered out. To test the quality the aperture filter, Alvarez's ruler experiment needs to be repeated [1]. For this experiment, a ruler was scanned under natural lighting. The ruler was manually pulled over the sensor while the aperture filter is applied. The swipe happens in a linear motion with a constant velocity. Since the aperture filter blocks out a lot of light, another version of this experiment was done where a white light source is added 6 cm above the line sensor to increase the luminosity. The results of this experiment can be found in figure 9. Because the an external light source was used in one of the scans, a magnified version of that particular scan is also compared a magnified version of Alvarez's scan taken where an external light source was used [[1]]. These results can be seen in figure 10.

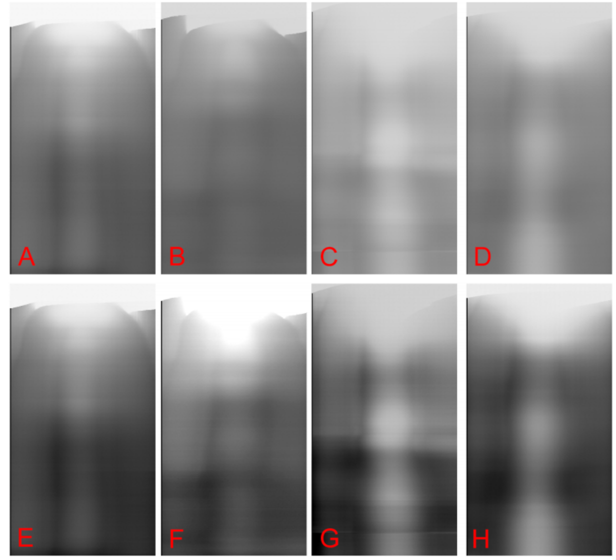

Fig. 7. Different scans of the same finger. Raw images are shown in A, B, C, D and higher contrast images, respectively E, F, G, H [1].

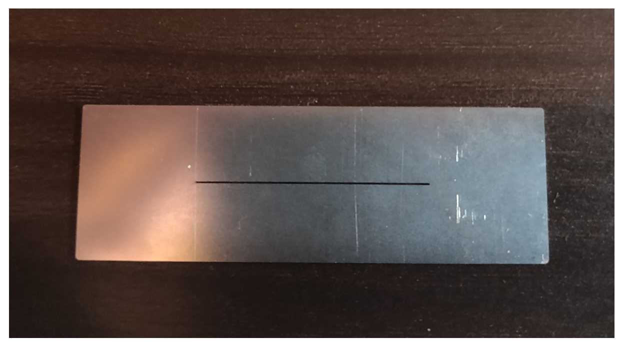

Fig. 8. The new aperture filter.

1) Results Experiment 1: As mentioned previously, the original design of the finger vein swipe sensor has a few flaws. One of these flaws concerns the quality of the scans. A new aperture filter was designed and tested in experiment 1. The results of this experiment can be seen in figure 9 and figure 10. The first thing that stands out is figure 9C in comparison to figure 9A. The difference between the two images is that an external light source was used during the scan resulting in figure 9A. The result of the additional light source are apparent. Under only natural lighting, without the use of the extra light source, The ruler cannot be detected. This means that the new aperture filter needs a light source to visualize items. With the original aperture filter this was not the case. This can be seen in figure 9D. This the case because the size of the optical slit has been reduced in the new filter. As a result of this less light is let through the slit. Therefore, to scan items such as a transparent ruler, a directional light source needs to be placed above the scanner. When comparing the quality between the images in figure 9A and 9D, however, there is a clear improvement in quality. Although the quality has been improved, one could argue that it is caused by the external

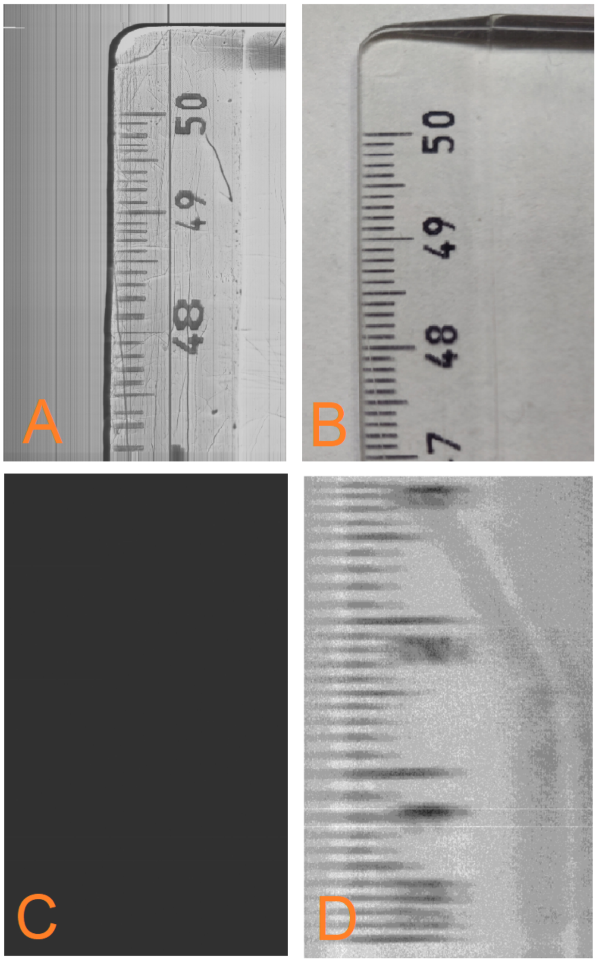

Fig. 9. A: The result of the ruler experiment using the new aperture filter with the additional light source. B: An image of the ruler used for the ruler experiment C: The result of the ruler experiment using the new aperture filter under natural light. D: The result of the ruler experiment using the original filter performed by Alvarez [1].

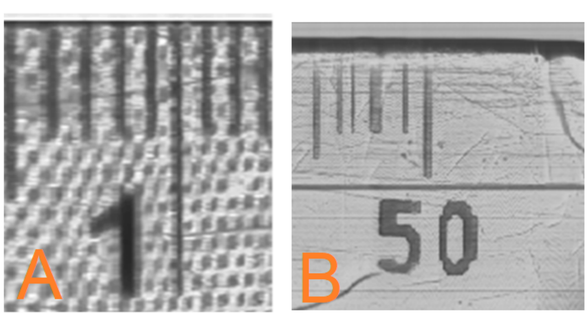

Fig. 10. A: A magnified version of Alvarez's experiment where the original aperture filter was used to scan a ruler using a LED light source. [1] B: A magnified version of the result of the ruler experiment using the new aperture filter with the additional light source.

Fig. 11. This figure displays the phantom finger that is used in all experiments. The finger contains artificial bones, joints and finger veins, which are surrounded by silicon tissue.

light source. Therefore, a magnified version of the ruler scan with the extra light source is compared to a magnified version of Alvarez's scan, where a light source was used as well [[1]]. Although the difference in quality decreases, there is still a quality difference. Figure 10B has, in comparison to figure 10A, has a higher quality. This can be observed because the image in figure 10A is blurrier overall. Also, at points of high contrast, the transitions in figure 10B clearly show a high contrast, whereas in figure 10A, the transitions are a lot more indistinct.

B. Experiment 2: Influence of the Different Filters

In experiment 1 a new aperture filter was introduced. The results are displayed in figure 9. There can be seen that the new aperture filter requires more light than the previous one. To test the capabilities of the filters a new experiment has been conducted. In this experiment multiple scans were made with different conditions. In all scans a phantom finger is swiped over the scanner. The phantom finger can be observed in figure 11. The finger contains artificial bones, joints and finger veins, which are surrounded by silicon tissue. The choice was made for a phantom finger rather than a human finger based on two reasons. First of all in Alvarez's research it was proven that phant fingers give a better result when scanned [1]. Secondly, using a phantom finger is more reproducible in any future works. The only lighting is provided by highly directional LEDs driven by the maximum current. The LEDs are positioned 5 mm above the phantom finger. The number of LEDs used is dependent on the scan. The filters that are used during the scans also differ per scan. The goal of the experiment is to observe the visibility of the finger joints using a different combination of the aperture filter and the IR filter. The results when using only a single LED are shown in figure 12 and the results using two LEDs are shown in figure 13. Finally, a single scan has been made with only the aperture filter applied, lit by 4 parallel LEDs. This scan is displayed in figure 14.

1) Results Experiment 2: There are a few things that were tested during experiment 2. These are the effect of the aperture filter, the effect of the IR filter and the effect of increasing the

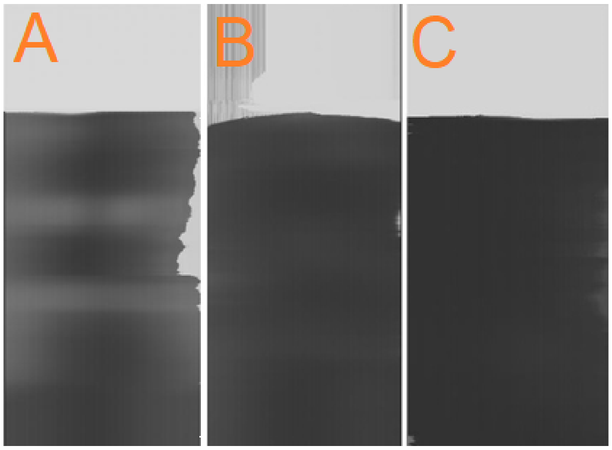

Fig. 12. This figure contains the results of experiment 2 where only one LED has been used. A: The result of experiment 2 using one LED and no filters. B:The result of experiment 2 using one LED and only the IR filter. C: The result of experiment 2 using one LED and only the aperture filter.

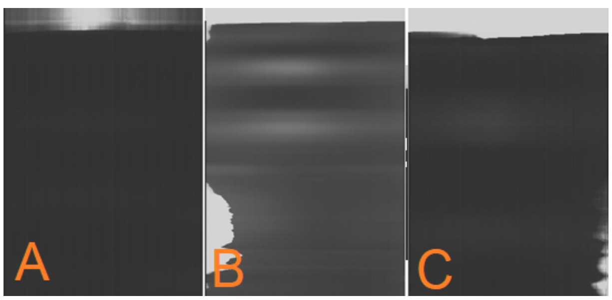

Fig. 13. This figure contains the results of experiment 2 where two LEDs have been used. A: The result of experiment 2 using two LEDs and both the IR filter and the aperture filter. B:The result of experiment 2 using two LEDs and only the IR filter. C: The result of experiment 2 using two LEDs and only the aperture filter.

Fig. 14. The results of experiment two when using only the aperture filter, illuminated by 4 adjacent LEDs.

luminosity. The results of this experiment can be seen in figure 12, figure 13 and figure TOEVOEGEN. Figure 12 and figure 13 show the effect of both the IR filter and the aperture filter on the brightness of the scan. In figure 12A, A scan can be seen where only one LED is used along with no filters. In the lighter parts of the figure, both the finger joints can be detected, although they are blurry. When adding the IR filter to this setup like in figure 12B or adding the aperture filter like in figure 12C, the visibility of the finger joints decreases significantly. In both cases this can be explained by analyzing the purpose of the filters. Both of the filters have a function to filter out incoming light. First of all, in case of the of the IR filter, it concerns light that is below the wavelength of 750 nm. The disadvantage of this is, however, that this filter is not perfect. This means that the filter does not completely remove all the wavelengths above 750 nm and nothing below 750 nm, but there is a gradual drop off. Also, since the filter is not perfect a smaller suppression also occurs in wavelengths below 750 nm. The reduction of the luminosity by the IR filter results in a lower brightness. This effect can be observed when comparing figure 12A and 12B. Similarly to the IR filter, the aperture filter also has a purpose to filter light. In this case, the purpose is to filter out any non-directional light. Even though this increases the quality of the image, this results in a reduced brightness. This reduction can be observed when comparing figure 12A and figure 12C. When comparing figure 12B and 12C, the effects of both filters can be compared. Since the brightness in figure 12C is lower than in 12B, the drop-off in brightness caused by the aperture filter must be stronger than for the IR filter.

One of the ways to counteract the drop in brightness is to increase the lighting luminosity. Since the LED is already driven by the maximum current, the luminosity can be increased by adding additional LEDs to the setup. Figure 13 shows scans where two adjacent LEDs were used, both at max current. The effects of adding multiple LEDs can be observed when comparing figure 12 to figure 13. In both figure 12B and figure 13B a scan was made using applying only the IR filter to the setup. Similarly, figure 12C and 13C only use the aperture filter. Except for the amount of LEDs, the conditions during the previously mentioned figures were similar. When comparing figure 12 and 13, an increase in brightness can be detected when using multiple LEDs. When looking at figure 13A, however, where both the IR filter and the aperture filter are applied, the brightness is still insufficient to detect the finger joints.

Figure 14 shows an image where the amount of LEDs have been increased even further. In this particular case four parallel LEDs were used. The results in figure 14 are not as expected. This is because the camera got overexposed. When using too many LEDs, the lighting setup grows to a point where the light can directly see the camera going around the phantom finger. A disadvantage of the camera, discovered during this experiment, is that when a certain spot on the camera gets overexposed, the entire camera becomes saturated. As a result of this phenomenon, no sensible output can be detected.

C. *Experiment 3: External Finger Vein Detection*

Even though the phantom finger used in the first 2 experiments contains artificial finger veins, they have not been visualized so far. Therefore an experiment was conducted to test whether external finger veins can be detected. For this experiment a static scan was made of a thin piece of black tape. The scan is static since nothing was swiped over the sensor. The thin piece of black tape is placed on the scanner to resemble an external blood vessel. The black tape was covered with toilet paper to resemble the finger tissue. For this scan a single LED light was used at maximum current 2 cm above the scanner. As for the previously discussed filters, only the new aperture filter was applied here. A total of 8 scans were made. For the first scan only a single layer of toilet paper was used to cover the scanner and the tape. This experiment was repeated 8 times, where an extra layer of paper was added every scan. The results are displayed in figure 15. For comparison, another scan was made, where instead of toilet paper, a phantom finger was used to represent the tissue. This image can be found in figure 16.

1) Results Experiment 3: Experiment 3 was conducted to test the possibility of visualising external finger veins. The veins were depicted by a thin piece of black tape. To imitate the finger tissue multiple layers of toilet paper were used. The results of this experiment are depicted in figure 15. The increment in the amount of used paper is clearly visible. The more layers are added, the darker the images become. This is the case because a thicker layer of paper lets through less light, resulting in a darker image. The piece of tape, that represents a finger vein is also visible in the image. The tape blocks out almost all of the light and therefore it's color remains the same, independent of the amount of paper. The contrast between the vein and the tissue, however, does become smaller when more tissue is added. This results in a lower contrast between the vein and the tissue. Figure 16 shows the experiment where, instead of toilet paper, a phantom finger was used to simulate the finger tissue. Again the piece of tape is visible, however, there is a very small contrast between the tape and the finger tissue. The scan where 8 layers of paper were used, most closely resembles the phantom finger scan in figure 16A.

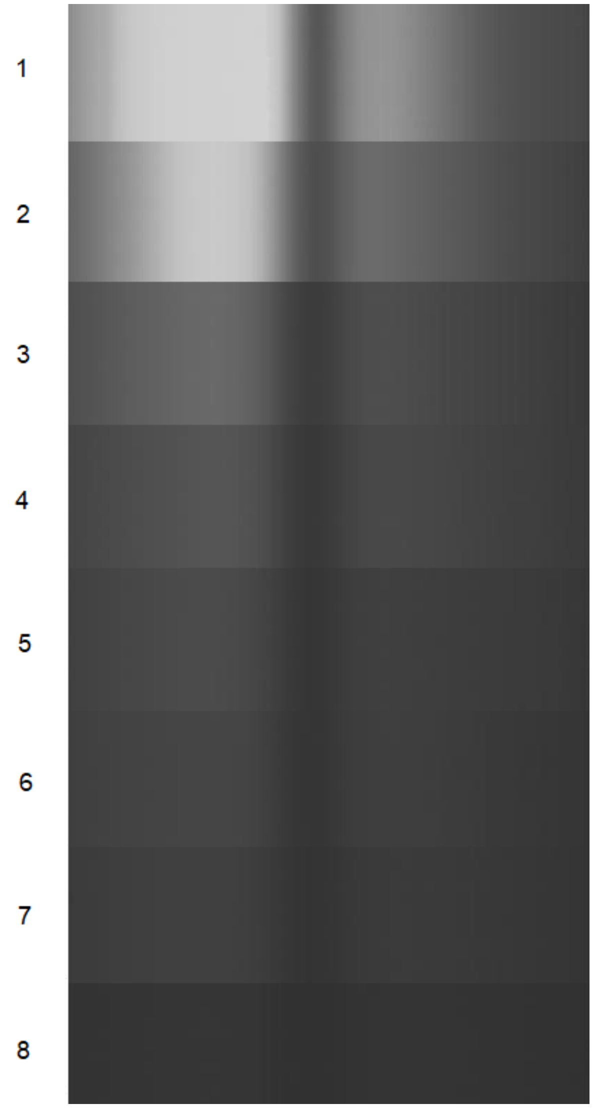

Fig. 15. This figure shows 8 scans where a piece of black tape was scanned while covered in multiple layers of toilet paper. All 8 scans have been displayed stacked on top of each other. The number to the left represents the amount of layers of paper used during the scan. The horizontal axis represents the width of the scanner. The vertical axis is time. Since all scans are static, no changes on the vertical axis can be observed.

D. *Experiment 4: Fine Tuning the Exposure Time of the Sensor*

In the previous experiments was discovered that the dynamic range, within the images, is too small. A new experiment will be done to increase the dynamic range in order to visualise the finger veins. For this experiment a static scan will be made of a phantom finger with internal artificial finger veins. One LED, 5 mm above the phantom finger, will be used as lighting. The new aperture will also be used to filter out any non-directional light. A scan under these conditions will be performed several times. Each time the exposure time of the sensor will be increased starting from 10 microseconds. The goal of this experiment is to find an exposure time with a dynamic range where the finger veins in the phantom finger become clearly visible.

1) Results Experiment 4: Unfortunately, with the current scanning conditions, it is not possible to either change the exposure time, nor the gain of the sensor. The problem is that the currently used program, written in Keil μvision, using custom designed drivers, is riddled with bugs. For this reason, with the current program files, the exposure time cannot to be altered.

IV. Discussion

Looking at all the results of the experiments a few things can be observed. The first experiment introduced a new aperture filter in order to increase the image quality. From figures 9 and 10 could be concluded that the quality of the images has indeed been improved by the new aperture filter. There is,

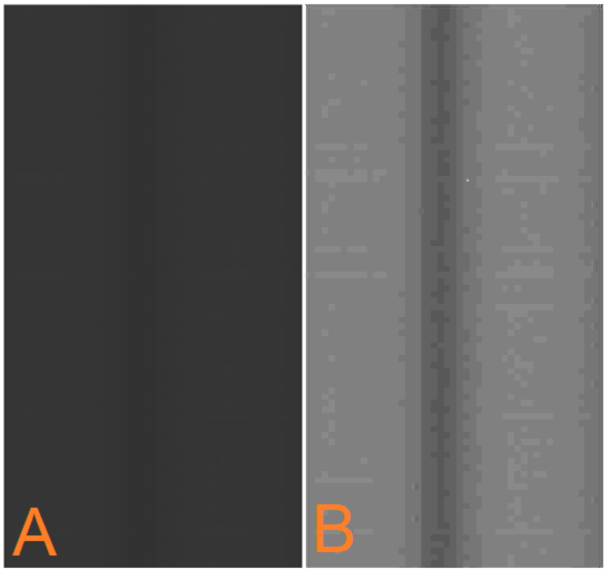

Fig. 16. In this figure a piece of black tape was scanned while covered by a phantom finger. In A the original version is displayed, while B shows a higher contrasted version of this scan.

however, also a side effect when using the new aperture filter. The slit sized has been reduced to match the camera size. The smaller slit size locks out more light than a bigger one would. From figure 9 could be concluded that, in order to observe something, more input light is required. This effect could also be observed during the second experiment. When the aperture filter was applied less light was recorded by the camera, than when the aperture filter was not present. The same thing could be said for the IR filter. When the IR filter was used the brightness of the scan decreased. Regarding the IR filter another discovery was made. The purpose of the IR filter is to filter out any natural light from the surroundings and only let through the IR light from the LEDs. However, in figure 9 could be observed that the aperture filter already fulfilled this same task. The scan in figure 9C was made with only the aperture filter applied in natural light. From the image nothing can be observed. Therefore, it can be concluded that the aperture filter already filters out the majority of natural light and therefore the new aperture filter can be used to replace both the old aperture filter and the IR filter altogether. Besides testing the filters, experiment 2 also experimented with using multiple LEDs in parallel. From figure 12 and 13 can be concluded that the brightness of the images is indeed increased when two LEDs are used, rather than one. The image in figure 13C, however, shows that when using the aperture filter and two LEDs, the image still lacks brightness. A logical response is to increase the amount of LEDs even further. Unfortunately, a problem was encountered when even more LEDs were used. This can be seen in figure 14. Here the light from the LEDs, due to the larger setup, directly contacts the camera, which gets overexposed and fails to output any results. In theory a design could be created where the ends of the camera are covered so the camera does not get saturated. To achieve the desired brightness by only increasing the LEDs, a lot more LEDs are needed. This also causes some new problems of its own. First of all, for the light to be let through the filter, it needs to be highly directional. Therefore, it is important to accurately position all the LEDs. Secondly, because of the small size and the required directness, there is not a lot of space for the LEDs. Lastly, the design of the finger vein swipe sensor is especially focused on compactness. Ideally, fewer LEDs are used in the design. Since the original design was not able to detect any internal finger veins, experiment 3 was conducted to test if it is able to detect any external finger veins with the current design. From the results of this experiment, in figures 15 and 16, could be concluded that the external finger vein could indeed be detected. However the contrast between the veins and the tissue is very low. The gray values of the tissue and the vein are currently too close to each other to make clear distinctions. Ideally, to visualise any external or internal finger veins, the dynamic range of the sensor should be increased. There are several ways this could be done. First of all, the light input could be increased. This has already been discussed and is probably not the optimal way. The currently used LEDs are already very directional and bright. Increasing the number of LEDs would not be difficult due to lack of space and would counteract the desired compactness of the design. Secondly, the dynamic range could be increased by using a higher quality camera. If a camera can detect a higher range of gray values, the range of values between the veins and the tissue would also increase. Lastly, to increase the dynamic range the gain or the exposure time of the CCD could be increased. While increasing the latter, it is important to realise that a longer exposure time also could reduce the quality of the scans, due to the motion of swipe. During experiment 4 an attempt was made to increase these variables, however the currently used code did not allow it. To fix the flaws within the program a few actions could be taken. Since the current code has many problems and uncertainties, the most obvious solution would be to completely rewrite all the code. This way a more solid base could be created that allows for easier improvements. A second option would be to start over all together, using a different micro controller and different programs. This solution would require even more work than the previous one, but may be more user friendly. Besides these improvements there are also other areas of possible improvement if the finger veins were ever visualised. First of all, the lighting angle could be changed for more compactness. Currently the LEDs are positioned directly above the sensor. It would, however, increase the compactness of the sensor if the LEDs could be moved to the side of the sensor, resulting in a more compact setup. Secondly, some image processing should be applied after making the scan. Currently the swiping image length is dependent on time and therefore the swiping speed. This means that if a fast swipe was made, a finger would appear shorter on the scan, since it costs less time to scan the finger. Using image reconstruction, it would be ideal if the scans were made independent of the swiping time and speed.

V. Conclusion

In the end it is important to decide whether the research question: "To what extent is it possible to improve the image quality to clearly visualize finger veins using a finger vein swipe sensor lit by NIR light?" has been answered. The short answer is that it is not possible to visualise any finger veins, because during the research, no internal finger veins have been visualised. To substantiate the answer, the sub questions need to be answered. The first subquestion is: "To what extent is the quality of the images sufficiently high to visualize the finger veins?" Since no finger veins have been visualised it is difficult to decide on a clear answer for this question. However, based on the experiments, a speculation can be made. In experiment 1 was shown that, with the new aperture filter, the quality of the scans has clearly improved. To support this, the scan results were very clear. For this reason it is safe to assume that the quality of the images generated by the current setup is sufficiently high to visualize the finger veins. The second sub question is: "To what extent is the CCD sensor capable of visualising finger veins?" Again only a speculation can be made, because no veins have been visualized. The second an third experiment showed that the dynamic range of the CCD sensor is currently too low. Theoretically, however, this problem could be solved by increasing the gain or the exposure CCD sensor. However, this conflicts with the third sub question: "To what extent is the currently used code able to support the technical demands in order to visualize the finger veins?" Although theoretically the exposure time and gain of the sensor should be improvable, practically the software is not capable of supporting these changes due to bugs. Due to the collision between these problems, the research question has to be answered with a no. The quality of the images are insufficient, because with the current software, the dynamic range of the camera cannot be increased enough to visualise finger veins.

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