TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Electrical Power Engineering and Mechatronics

MACHINE VISION SYSTEM FOR SCRATCH DETECTION OF CELL PHONE DISPLAYS

MASINNÄGEMISSÜSTEEM MOBIILTELEFONI EKARAANIDE KRIIMUSTUSTE AVASTAMISEKS

MASTER THESIS

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Tallinn 2023

AUTHOR’S DECLARATION

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ABSTRACT

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Abstract:

The quality of a cell phone's display can significantly impact its user experience and value. Scratches on the screen can interfere with the user experience and make the phone less desirable to potential buyers. Therefore, accurately grading the condition of a phone's display is an essential task in the mobile phone industry, particularly when it comes to buying and selling used phones.

Manual inspection is a time-consuming and inefficient method prone to human error, making it necessary to implement an automated solution. A machine vision system consisting of a specialized camera and image processing software can provide a fast, accurate, and reliable method for detecting scratches on cell phone displays. The current grading process for used phones based on the severity of display scratches relies on manual methods. This procedure is laborious, prone to low accuracy and efficiency, and requires skilled graders. Automated or semi-automated inspection techniques can decrease the possibility of human error, improve accuracy and reliability, and reduce the time and expense needed to grade phones.

This thesis proposes a novel approach for grading cell phones using machine vision based on the number of scratches on their displays. The goal is to increase accuracy and efficiency by automating the scratch detection and counting process. The study demonstrates the feasibility of using machine vision to accurately grade cell phones based on the number of scratches on their displays. A machine vision model will be developed and evaluated for this task, and its performance will be compared to that of manual methods. The goal is to demonstrate the potential benefits of using such a method for grading cell phones in the mobile phone industry, leading to increased customer satisfaction and loyalty.

Keywords: Machine vision, Image processing, Automation, Grading, Cell phone displays, Increasing efficiency, Increasing accuracy.

LÕPUTÖÖ LÜHIKOKKUVÕTE

Autor: Tharindu Dilshan Bopage	*Lõputöö liik:* Magistritöö
Töö pealkiri: Masinnägemissüsteem mobiiltelefoni ekraanide kriimustuste avastamiseks	
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Ülikool: Tallinna Tehnikaülikool *Teaduskond:* Inseneriteaduskond *Instituut:* Elektroenergeetika ja mehhatroonika instituut	
Töö juhendaja(d): Daniil Valme, Algusjärgus teadur *Töö konsultant (konsultandid):* NA	

Sisu kirjeldus:

Mobiiltelefoni ekraani kvaliteet võib märkimisväärselt mõjutada selle kasutajakogemust ja väärtust. Kriimud ekraanil võivad segada kasutajakogemust ja muuta telefoni vähem atraktiivseks potentsiaalsetele ostjatele. Seetõttu on telefoni ekraani seisukorra täpne hindamine mobiiltelefonitööstuses oluline ülesanne, eriti kasutatud telefonide ostu ja müügi korral.

Käsitsi kontrollimine on ajakulukas ja ebaefektiivne meetod, mille puhul esineb inimlikke vigu, seega on vaja rakendada automatiseeritud lahendusi. Spetsialiseeritud kaamera ja pilditöötlustarkvara abil loodud masinõppe süsteem võib pakkuda kiiret, täpset ja usaldusväärset meetodit kriimude avastamiseks mobiiltelefoni ekraanidel. Kasutatud telefonide hindamine vastavalt ekraanikriimude raskusastmele tugineb praegu käsitsi meetoditel. See protseduur on töömahukas, altid vähesele täpsusele ja efektiivsusele ning nõuab oskustega hindajaid. Automatiseeritud või poolautomaatse kontrollitehnika kasutamine võib vähendada inimlike vigade võimalust, parandada täpsust ja usaldusväärsust ning vähendada vajalikku aega ja kulusid telefonide hindamiseks.

Käesolev lõputöö pakub välja uudse lähenemisviisi mobiiltelefonide hindamiseks masinõppe põhjal, tuginedes kriimude arvule ekraanidel. Eesmärk on suurendada täpsust ja efektiivsust, automatiseerides kriimude avastamise ja loendamise protsessi. Uuring demonstreerib masinõppe kasutamise võimalikkust mobiiltelefonide hindamisel vastavalt kriimude arvule ekraanidel. Loodakse masinõppe mudel, mis hinnatakse selle ülesande täitmisel ja selle tulemusi võrreldakse käsitsi meetoditega. Eesmärk on tõestada sellise meetodi potentsiaalseid eeliseid mobiiltelefonide hindamisel, mis viib kliendi rahulolu ja lojaalsuse suurenemiseni.

Märksõnad: Masinnägemine, Pilditöötlus, Automaatika, Hinne, Mobiiltelefoni ekraanid, Tõhususe suurendamine, Täpsuse suurendamine

THESIS TASK

Thesis title in English:	**Machine vision system for scratch detection of cell phone displays**
Thesis title in Estonian:	**Masinnägemissüsteem mobiiltelefoni ekraanide kriimustuste avastamiseks**
Student:	**Tharindu Dilshan Bopage, 215382MAHM**
Program:	**Master of Science in Mechatronics**
Type of the work:	**Master Thesis**
Supervisor of the thesis:	**Daniil Valme, Early Stage Researcher**
Co-supervisor of the thesis:	**-**
(Company, position, and contact)	2022/2023 2022/2023 Spring
The validity period of the thesis task:	
Submission deadline of the thesis:	**18.05.2023**

Supervisor (signature) Student (signature) Head of program (signature)

Co-supervisor (signature)

1. Reasons for choosing the topic.

Currently, the majority of companies use manual methods to grade used phones based on the number of scratches on their displays. This process can be time-consuming and prone to low accuracy and efficiency, as it relies on human inspection and manual counting of the scratches. In some cases, this process is carried out in companies located in Estonia as well. They have separate departments and skilled graders for the grading. These departments are completely operated manually. On average, a skilled grader will take 2 to 4 minutes to grade a phone with the naked eye.

There are several drawbacks to manual scratch detection including,

- **Time-consuming and inefficient:** Thoroughly examining and inspecting each phone manually for scratches and other defects is a time-consuming process that requires significant time and effort. As the number of devices to inspect increases, the time required for manual inspection also rises, leading to a bottleneck in the process and limiting scalability. Moreover, manual inspection is labor-intensive and challenging to scale up, resulting in delays and increased error likelihood, especially when graders become overwhelmed. The inefficiency of a manual inspection lies in the high labor costs and slow production processes it causes, particularly for companies that need to inspect large volumes of products. Additionally, the uniform nature of manual inspection can result in employee dissatisfaction and burnout, leading to high turnover rates and difficulty in maintaining an experienced workforce. To address these challenges, companies should consider adopting automated or semi-automated inspection methods, providing consistent and accurate results while improving employee job satisfaction.
- **Limited accuracy:** Limited accuracy refers to the potential for human error to occur during the manual inspection process, which can result in missed scratches or false reports of scratches. This can lead to inaccurate quality control and can result in costly losses for the company due to rejected products or returns. Furthermore, manual inspection is prone to errors due to the monotonous nature of the task, and graders may become tired or lose attention to detail over time. This can further reduce the accuracy of the process and increase the possibility of errors. As such, implementing automated or semi-automated inspection methods can help to reduce the potential for human error and improve the overall accuracy and reliability of the inspection process, ensuring consistent and accurate results.

This thesis aims to address these challenges and propose a new solution for grading cell phones based on the number of scratches on their displays using machine vision. By automating the scratch detection and counting process, the aim is to improve the accuracy, and efficiency as well as develop a proper methodology for cell phone grading. Accelerating the condition-assessing process has the potential to significantly reduce the time and cost required for grading phones, while also increasing the reliability and consistency of the results.

2. Thesis objectives

The main goal of the thesis is to optimize the smartphone display condition grading procedure by creating a custom machine vision-based setup. Sub-objectives of the task are as follows,

- Optimize the efficiency of the grading.
  The efficiency will be measured by the number of phones graded per hour in particular companies that specialized in grading. In manual grading, the average efficiency is 20 phones per hour. But this automation process can grade 100+ phones per hour. It depends on the speed of the operator because there should be an operator who always gives a phone to the system to grade. The methodology followed to optimize the efficiency of grading will be discussed in the chapters.
- Optimize the accuracy of the grading.
  In manual grading, accuracy depends on the skill of the grader. If the grader is tired after working for a long time, he may miss the details to some extent and the results will be inaccurate. But with this automation process, the system can count each scratch and maintain the accuracy uniformly of the grading process. Will discuss more in the chapters.
- Maintain a consistent speed of grading.
  In manual grading, nobody can estimate the speed for counting the scratches on a phone display. Mostly it depends on the number of scratches and the tiredness of the operator. For example, if a phone has 2 scratches, a person can count those within five seconds but if a phone has more than 20 scratches, the person will take around 60 seconds or more to count them all. Automation of the process will count any number of scratches within the same time frame. In the thesis, the calculations will explain how long it takes to grade a phone.

3. List of sub-questions:

- What are the appropriate techniques for the system?
  The thesis report will discuss what are the techniques presently used in the industry, what are the drawbacks of them and what is the best technique for this system. There will be an analysis to find better software tools to develop a methodology for a scratch detection system.

- What software tools should be used to manipulate the setup?
  There are various software tools used in the industry for the scratch or defect detection process. Some of the software tools are very old and they still use in the industry while some companies use modern software tools. This study will analyze what is the appropriate software tool to manipulate this setup.

- Which criteria should be considered to design the setup?
  - lighting system, lighting angles, and required distance to install lights.
    Lighting is responsible for illuminating the object and highlighting its distinct features to be viewed by the camera. It is one of the critical aspects of machine vision systems; the camera cannot inspect objects that it cannot see. Therefore, lighting parameters such as the distance of the light source from the camera and object, angle, intensity, brightness, shape, size, and color of lighting must be optimized to highlight the features being inspected. In addition, the object must be seen clearly by the camera when it is struck by light; hence, the object's surface properties must also be considered during lighting optimization.

  - Selecting the appropriate optics for better detection.
    Using cameras, lenses, sensors, and filters, a machine vision system can capture information relevant to a task that will be carried out by a computer. Many tasks can potentially be tackled with proper optics such as the detection of the phone, identifying the edges of the phone, and counting the scratches on the display.

4. Basic data:

To write this thesis, the author will use previous academic knowledge in machine vision, working experience in a similar industry, and its requirements to improve productivity. The following sources of materials will be used as basic data in this thesis.

1. "Machine Vision Handbook", Bruce G, Batchelor, Springer, 2012
2. "Digital Image Processing", fourth edition, Rafael C, Gonzalez, 2017
3. "Automatic surface defect detection for mobile phone screen glass based on machine vision", Chuanxia Jian, Jian Gao, Yinhui Ao, 2016

5. Research methods

Study and use previous research papers which is regarding this subject and its findings to guide toward some of the objectives and will use formulas that are given by the product handbooks or data sheets to get better results. Also, will use TalTech labs to build the prototype, test the prototype, identify the changes and corrections, and analyze the test solutions.

6. Graphical materials

The thesis report will consist of flow charts, tables, diagrams, drawings, and figures. Most of the graphical elements will be available in the main report whereas some diagrams and flow charts will be included in the appendixes.

7. Thesis structure

The thesis report comprises the introduction, literature review, key ideas, organizing principles, summary, and conclusion chapters. Additionally, the main chapters are further divided into sections and subsections.

For example,

1 Introduction
  - 1.1. Background and the Motivation for the Research
  - 1.2. Problem states and research aims.

2 Literature review
  - 2.1. Background of the scratch detection system
  - 2.2. Industries that recently used scratch detection system
  - 2.3. The appropriate technique for the solution

8. References

For references, the author will use books, research articles, and reports related to machine vision systems, digital image processing, and scratch detection systems. Some of them are as follows,

1. "Machine Vision Handbook", Bruce G, Batchelor, Springer, 2012
2. "Digital Image Processing", fourth edition, Rafael C, Gonzalez, 2017
3. "Automatic surface defect detection for mobile phone screen glass based on machine vision", Chuanxia Jian, Jian Gao, Yinhui Ao, 2016
4. "Image-based surface scratch detection on architectural glass panels using deep learning approach", Zhufeng Pan, Jian Yang, Xing-er Wang, Feiliang Wang, Iftikhar Azim, Chenyu Wang, 2021
5. "Lighting design for machine vision application", Sunil Kumar, Kopparappu, 2006

Also, the author will use the following sources for the references and gather information for this thesis.

- IEEE Xplore and TalTech library
- Google Scholar to find related articles which have been published.
- Relevant websites
    - https://www.springer.com/gp
    - https://www.sciencedirect.com/
    - https://www.mdpi.com/
- Specific datasheets from the manufactures

9. Thesis consultants

N/A

10. Work stages and schedule

No	Activity description	Expected completion date
1.	Review research papers and prepare a literature review	26.01.23
2.	Start writing the literature review	30.01.23
3.	Comparisons and analysis	15.02.23
4.	Submit thesis topic sheet	21.02.23
5.	Start writing chapters 4,5, and 6	01.03.23
6.	Building a prototype	20.03.23
7.	Testing the prototype	01.04.23
8.	Sending the first draft to the supervisor	17.04.23
9.	Final version for the revision	08.05.23
10.	Thesis submission for plagiarism	18.05.23
11.	Submission of thesis document	26.05.23
12.	Thesis defense	03.06.23

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PREFACE

Cell phone displays are an important component of smartphones, and their quality can significantly impact the user experience. One issue that can affect the quality of a cell phone display is the presence of scratches, which can degrade its appearance and functionality. To ensure that only high-quality displays are shipped to customers, manufacturers must implement efficient and reliable methods for detecting scratches on the surface of the display.

Manual inspection is time-consuming and subject to human error, so an automated solution is needed. A machine vision system can provide a fast, accurate, and reliable method for detecting scratches on cell phone displays. Such a system consists of a specialized camera and image processing software that is designed specifically for this application. The camera captures images of the display, and the image processing software analyses the images to detect scratches.

Various image processing techniques can be used for scratch detection, including thresholding, edge detection, and pattern matching. The choice of technique will depend on the specific characteristics of the scratches and the display surface. By carefully designing and tuning the machine vision system, it is possible to achieve high levels of accuracy and reliability in detecting scratches on cell phone displays.

Once implemented, a machine vision system for scratch detection can be integrated into the production line, allowing manufacturers to inspect each display quickly and accurately as it is produced. This can help to ensure that only high-quality products are shipped to customers, leading to increased customer satisfaction and loyalty.

LIST OF ABBREVIATIONS

3D	-	3 Dimensional
CSK	-	Countersunk
CNN	-	Convolutional Neural Network
DOF	-	Depth of Field
FOV	-	Field of View
GUI	-	Graphical User Interface
HDF	-	High-Density Fiber
LED	-	Light Emitting Diode
nos	-	Numbers
ROI	-	Region of Interest
RGB	-	Red Green and Blue
SW	-	Short Wave
USB	-	Universal Serial Bus
VI	-	Virtual Instrument
vs	-	Versus

1 INTRODUCTION

In today's ever-evolving society, a significant shift towards the circular economy is taking place. As we strive to reduce waste, minimize resource consumption, and promote sustainability, the concept of prolonging the lifespan of products has gained immense importance. This paradigm shift necessitates a thorough evaluation of the condition of various items, providing essential information regarding their state. By embracing this approach, we can simplify the reuse of existing resources and expedite crucial processes within the circular economy.

One particular area where this evaluation becomes crucial is in the context of cell phone displays. With the widespread usage of mobile devices and the constant advancements in technology, the disposal of these devices has become a pressing concern. Recognizing the value of extending the lifespan of cell phones, there is a growing need to develop efficient systems that can assess their condition and identify potential issues.

The condition of a cell phone's display can have a significant impact on its value and usability. Scratches on the screen can interfere with the user experience and make the phone less desirable to potential buyers. Therefore, accurately grading the condition of a phone's display is an important task in the electronics industry, particularly when it comes to buying and selling used phones.

Currently, the majority of businesses rely on manual methods to grade used phones based on the severity of display scratches. However, this manual inspection process has several drawbacks, including limited accuracy and time-consuming inefficiency. Human error, fatigue, and scalability issues can affect the reliability and productivity of the grading process. To address these challenges, there is a need to implement automated or semi-automated inspection techniques that can improve accuracy, efficiency, and scalability.

This thesis focuses on the development of a machine vision system for scratch detection on cell phone displays, aiming to overcome the limitations of manual inspection methods. By harnessing the power of advanced image processing techniques, cutting-edge algorithms, and state-of-the-art machine vision technology, this research seeks to develop a novel approach for grading cell phones based on the number of scratches on their displays.

The objective is to increase accuracy, efficiency, and scalability in the grading process, ultimately contributing to the principles of the circular economy. By automating the scratch detection and counting process, the time and cost involved in grading phones can be significantly reduced, while ensuring consistent and reliable results.

This thesis will propose a proper methodology for grading cell phones using machine vision, compare the performance of the developed system with manual methods, and demonstrate the feasibility of using machine vision for accurate scratch detection. The study will showcase the potential benefits of implementing such a system in the electronics industry, highlighting improved accuracy, efficiency, and consistency in grading cell phones.

Through this research, the author aims to pave the way for enhanced circular economy initiatives, promoting the reuse of resources, reducing waste, and contributing to a more sustainable future in the electronics industry. By leveraging the capabilities of machine vision technology, can revolutionize the process of assessing cell phone displays and make significant strides toward a more efficient, accurate, and sustainable approach to grading and reusing electronic devices.

2 LITERATURE REVIEW

2.1 Background of scratch detection systems and the industries that use them

In many different industries, including electronics, automotive, manufacturing, and construction, scratch detection systems are widely used to evaluate the condition of surfaces and materials. These systems come in both manual and automated varieties. Visual inspection [1], measurement tools [2], and testing techniques [2] are used in manual scratch detection methods. Visual inspection involves looking for scratches with the naked eye or with the aid of magnifying devices like microscopes. The depth and length of scratches can be measured using measuring tools like calipers, micrometers, and other measuring tools. Scratches can be found using testing techniques like scratch hardness testers and scratch adhesion testers.

Automated scratch detection systems examine images or videos of the surface being examined using computer vision or machine vision techniques. Machine vision models [3], which are used to automatically detect and categorize scratches in new images, can be a part of these systems. These models are trained on sizable datasets of images with annotated scratches. To analyze images and extract features like edges, textures, and patterns that might point to the presence of scratches, image processing algorithms [4] can be used. To inspect large or complex surfaces, robotics can also be used to integrate automated scratch detection systems with robotics platforms [5]. The application-specific requirements and limitations, such as the size and complexity of the surface being inspected, the type and severity of the scratches, and the desired accuracy and speed of the detection process, all influence the scratch detection system that is selected.

Scratch detection is frequently used in the electronics sector to evaluate the state of displays, lenses, and other parts of gadgets like laptops, tablets, and smartphones. Scratch detection is a technique used in the automotive industry to check the surfaces of car bodies, windows, and mirrors for scratches and other flaws. Scratch detection is a technique used in manufacturing to examine the surfaces of many different products, including medical devices, appliances, and automotive parts. Scratch detection is a technique used in the construction industry to examine the surfaces of different building materials like concrete, steel, and wood.

Overall, the use of scratch detection systems can enhance the performance and safety of products and structures while ensuring the quality of surfaces and materials in a variety of industries. scratch detection systems will give an accurate output while improving the productivity of an organization than manual inspecting for scratches by a human with naked eyes.

2.2 Image processing techniques

The appropriate technique for a scratches detection system depends on various factors such as the type of surface being inspected, the type of scratches to be detected, the environment in which the inspection takes place, and the desired accuracy and speed of the system [6]. However, there are a few common techniques that are often used for scratches detection systems. These include image processing, machine learning, and robotic systems.

Image processing involves analyzing an image of the surface to detect scratches. Techniques such as thresholding, morphological operations, and edge detection can be used to highlight scratches in the image. The image can be acquired using a camera or a scanner, and processed using software algorithms to detect scratches. This approach can be relatively cheap and easy to implement compared to a full-fledged robot system and machine learning [6].

Machine learning techniques, such as deep learning, can also be used to detect scratches in images. Convolutional Neural Networks (CNNs) can be trained on a large dataset of images with and without scratches to learn to detect scratches automatically. This approach requires a significant amount of data and computational power to train the model but can result in high accuracy [6].

Robotic systems can be designed to inspect surfaces for scratches automatically. The system may include a robot arm with a mounted camera or other sensors to acquire images of the surface, and software algorithms to process the images and detect scratches. This approach is more complex and expensive than image processing or machine learning but can be used in harsh environments or for high-speed inspection [6].

The choice of solution will depend on the specific requirements of the system and the trade-off between accuracy, speed, cost, and other factors. Because of the cost-effectiveness and ease of implementation, image processing techniques will be considered as an appropriate technique for this task. However, image processing can be divided into two major sections: image processing based on computer vision and image processing based on machine vision.

In conclusion, it is important to evaluate the advantages and disadvantages of each technique before deciding on a scratches detection system. Image processing based on computer vision can be useful when the surface is relatively simple and the scratches are easily detectable. On the other hand, machine vision can be used when the surface is complex and the scratches are difficult to detect. Ultimately, the choice of technique will depend on the specific requirements of the system and the desired level of accuracy and efficiency.

2.2.1 Computer vision vs machine vision

When developing a scratch detection system, it is essential to consider the advantages and disadvantages of both computer vision and machine vision systems. Several reasons suggest that machine vision is preferred over computer vision for this purpose. One such reason is the robustness of machine vision systems in real-world environments. These systems are better equipped to handle changes in lighting, camera angles, and other factors that may affect the appearance of scratches on a surface.

Another significant advantage of machine vision systems is their speed. They use specialized hardware and algorithms designed for real-time image analysis, making them faster than computer vision systems. This feature is especially important for production line applications where speed and efficiency are critical to the overall process. Machine vision systems can also be easily integrated with other equipment, such as conveyors or inspection cameras. This feature ensures seamless operation in a production line environment and eliminates the need for additional processing and handling of the data.

Cost-effectiveness is another reason why machine vision systems are preferred over computer vision systems. They can be designed to meet specific requirements and optimized for cost and performance, making them more cost-effective than computer vision systems. Machine vision is a well-established field with a long history of development and application. Many experts and companies specialize in this area, making it easier to find the right resources and expertise to develop and deploy a machine vision–based scratch detection system.

Table 2.1 Advantages and disadvantages of a machine vision system [2]

Machine vision system	
Advantages	**Disadvantages**
Robustness to environmental changes	Limited to specific tasks
Speed	May not be as flexible as computer vision
Integration with other systems	Can be limited in terms of accuracy and scalability
cost-effectiveness	dependent on specialized hardware
Expertise in the field	

Table 2.2 Advantages and disadvantages of a computer vision system [2]

Computer vision system	
Advantages	**Disadvantages**
Flexibility and adaptability to different tasks	Processing time can be slow for large datasets
High accuracy and scalability	Can be computationally intensive
A large and growing community of experts	May require a large amount of training data
Access to a wide range of algorithms and techniques	Can be more complex and challenging to implement
Potential for innovation and exploration of new approaches	Dependent on the availability of computing resources

In conclusion, considering the possible advantages and reasons discussed above, it is evident that image processing based on machine vision techniques is the most appropriate method for developing a scratch detection system. The robustness, speed, integration capabilities, cost-effectiveness, and expertise available in machine vision make it the best choice for this task. A machine vision setup generally consists of an object-feeding mechanism such as a conveyor belt, dedicated lighting, optics, an image sensor (machine vision camera), a product information database, a data processing unit, and a mechanism for rejecting faulty products. For the machine vision setup of this study, the author dedicated lighting, optics, and image sensors to capture high-quality images of the scratches and software for image processing.

2.3 Analysis of the existing software tools

Scratches detection systems have become increasingly important in modern industries due to the need for high-quality products and efficient manufacturing processes. With the advancements in technology, various software programs have been developed to detect defects on different surfaces, including wood, metal, plastic, and even on highly reflective surfaces like glass or mobile phone displays. These software programs use advanced image processing techniques and machine learning algorithms to detect even the smallest defects such as scratches, dents, or discoloration on the surface. By implementing these defect detection systems, manufacturers can reduce waste, improve production efficiency, and ensure that their products meet the highest quality standards. MATLAB, Cognex software, LabView, and OpenCV are all popular software platforms used in image processing. Each platform has its strengths and weaknesses, and the choice of platform often depends on the specific task at hand.

MATLAB is a widely used platform for image processing due to its ease of use and versatility. It provides a range of tools for image filtering, segmentation, and analysis. Additionally, MATLAB has a vast library of pre-built functions and toolboxes for image processing. However, MATLAB is a coding and matrix-based software and it can be slow when it comes to large-scale image processing tasks and is generally not suited for real-time applications [7].

OpenCV is a popular open-source platform for computer vision and image processing. It provides a range of algorithms and tools for image filtering, segmentation, and feature detection. OpenCV is highly optimized for real-time applications and has excellent support for hardware acceleration. However, it can be difficult to learn for beginners and lacks the pre-built functions and toolboxes of MATLAB [6].

Cognex software is a widely used platform in the field of machine vision and image processing. It offers a comprehensive suite of tools and libraries specifically designed for industrial inspection and automation applications [8]. Cognex software provides advanced algorithms and capabilities for tasks such as pattern recognition, defect detection, and measurement. It offers a user-friendly interface and intuitive tools for setting up and configuring machine vision systems. Cognex software is known for its robust performance, high-speed image processing, and reliable inspection capabilities, making it a popular choice for quality control and inspection tasks in various industries.

On the other hand, LabView is a graphical programming platform developed by National Instruments (now part of Keysight Technologies). It is widely used in scientific and engineering applications, including image processing and machine vision. LabView utilizes a visual programming approach where users can create applications by connecting icons or blocks graphically, known as Virtual Instruments (VIs). LabView offers a wide range of modules and toolkits for acquiring, analyzing, and processing images, making it suitable for developing complex vision systems [9]. It also provides integration with various hardware devices and offers extensive libraries and functions for rapid development.

When it comes to selecting LabView for a particular scratch detection task, the best reason is its graphical programming environment. LabView's visual approach enables intuitive programming, especially for users who are more comfortable with a graphical representation of code. For complex systems like scratch detection, LabView's graphical programming environment simplifies the development process and enhances the system's maintainability. It allows developers to easily design and configure the vision system by connecting visual elements, making it easier to understand and modify the elements when necessary. This visual representation can be particularly beneficial for scratch detection systems, where complex algorithms and image processing techniques are involved.

Moreover, LabView's versatility and integration capabilities make it a strong choice for scratch detection. It supports seamless integration with various sensors, cameras, and industrial equipment, allowing for easy interfacing and communication between different components of the scratch detection system. LabView's extensive libraries and toolkits for image processing and machine vision provide ready-to-use functions and modules for tasks such as image acquisition, preprocessing, feature extraction, and analysis. These pre-built components can significantly reduce development time and effort, enabling faster implementation of the scratch detection algorithm.

In summary, the best reason for selecting LabView for a particular scratch detection task is its graphical programming environment, which offers an intuitive and visually appealing approach to system development. This, combined with LabView's versatility, integration capabilities, and extensive libraries, makes it a strong choice for developing efficient and effective scratch-detection systems.

2.4 Analysis of the appropriate lighting system

For a scratch detection system to accurately record the visual details of the scratches, an appropriate lighting system is essential [3]. In addition to being adjustable to accommodate various lighting scenarios and surface types, the lighting system should offer enough illumination to record the depth and width of the scratches. The ideal lighting intensity should be bright, even, and free of glare or shadows.

Another crucial aspect to take into account is the color temperature of the lighting system. The perceived color of the surface and scratches depends on the color temperature. Scratch detection systems typically prefer neutral white light with a color temperature of between 5000 and 6000K [3]. The angle and direction of the lighting system are also important aspects that have an impact on the visibility of the scratches. To avoid hiding or obscuring the scratches, the lighting system should be positioned to reduce shadows and specular reflections. The surface's texture, curvature, and reflectivity all affect the ideal lighting angle and direction.

The lighting system should also be controllable and synchronized with the camera system to ensure consistent illumination and avoid flicker or distortion [3]. This control and synchronization can be achieved through hardware or software interfaces. Additionally, the lighting system should be cost-effective and easy to maintain, with replaceable bulbs or LED arrays. The lighting system should also be robust and durable to withstand frequent use and environmental conditions.

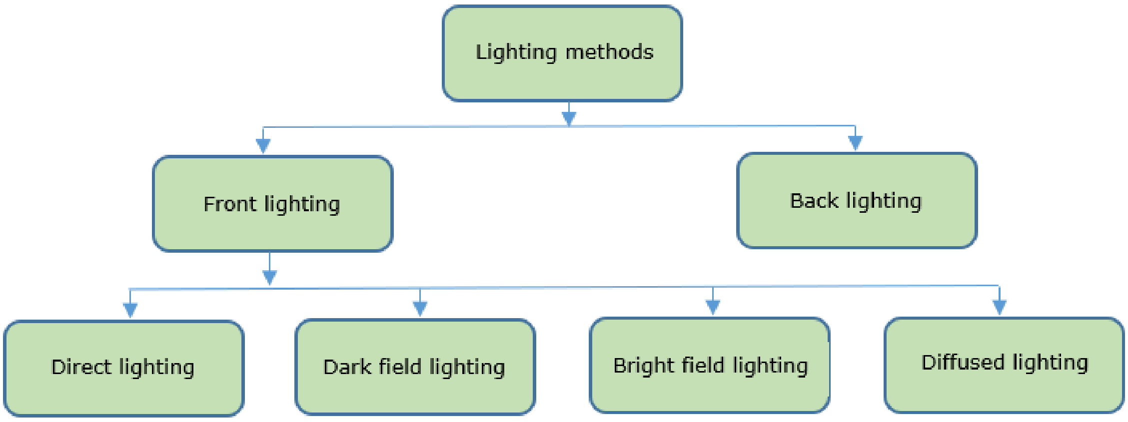

Figure 2.1 Variety of lighting methods

In the context of a scratch detection system, front light and backlight refer to different types of illumination sources that are used to illuminate the surface of a material or object. The front light is typically a light source that is positioned in front of the object and directed toward the surface to be inspected [3]. It provides direct illumination of the object's surface and highlights any raised features or irregularities in the material.

However, it may not be as effective in highlighting scratches or defects that are parallel to the direction of illumination.

Backlight, on the other hand, is a light source that is positioned behind the object and directed toward the surface. It illuminates the object from the opposite side, creating a contrast between the surface and any defects or scratches present in the material [2]. Backlighting is particularly effective in detecting scratches or other surface defects that are parallel to the illumination direction.

In a scratch detection system, both front light and backlight can be used in combination to provide a more complete analysis of the material's surface. The front light can provide information about the material's texture and surface features, while the backlight can reveal any scratches or defects that may be present. But in this study, the author focused to detect scratches on mobile phone displays. So backlights will be ignored since it does not affect smartphone displays though it works on transparent materials.

Darkfield lighting is a technique used in scratch detection systems to create contrast between surface defects and the surrounding material [3]. This technique works by illuminating the material at a steep angle so that the light reflects off the surface at an oblique angle rather than being directly reflected toward the camera or sensor. Darkfield lighting creates a contrast between the scratches or defects on the surface of the material and the surrounding area, making it easier to detect even very small or subtle defects. This technique is particularly useful for detecting scratches or other surface defects on shiny or reflective materials, where other lighting techniques such as front lighting may not be as effective.

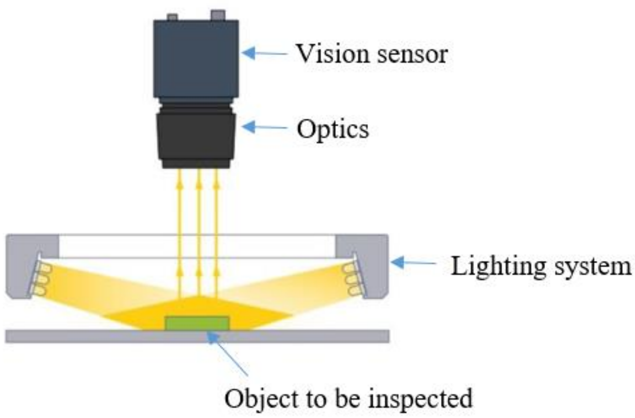

Figure 2.2 Dark field illumination [10]

To achieve darkfield lighting, LED diffused lights are used, which direct the light toward the material at a steep angle. The light is typically collimated, meaning that it is focused into a narrow, parallel beam, to ensure that it is directed toward the material at the desired angle. The camera or sensor is positioned in such a way that it can capture the oblique reflection of the light off the surface of the material.

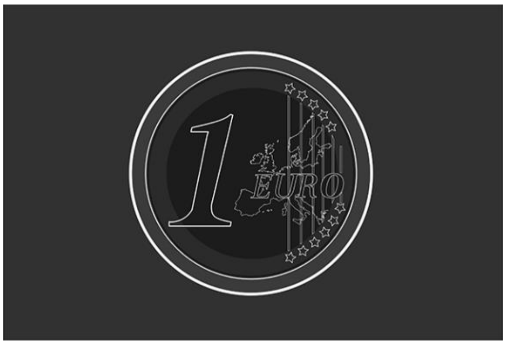

Figure 2.3 How edges emphasize through darkfield [11]

2.5 Analysis of the appropriate optics and sensors for the system

When selecting appropriate optics and sensors for a scratch detection system, several factors need to be considered. One of the most important considerations is magnification [12], which determines the level of detail that can be captured by the system. A higher magnification is generally required for detecting smaller scratches, while a lower magnification can be sufficient for larger scratches. However, higher magnification often comes with a trade-off of a smaller Field Of View (FOV) [13] and a shallower Depth Of Field (DOF) [14].

The FOV refers to the area of the object that can be captured by the camera. A larger FOV can be useful for detecting scratches over a wider area, but it may also result in lower resolution. The DOF, on the other hand, refers to the range of distances over which the object appears in focus. A shallower DOF can be problematic if the object being inspected has varying depths or if scratches are located in different planes.

Another critical factor to consider when selecting optics and sensors is resolution. Higher resolution can provide more detail and accuracy in detecting scratches, but it may also require more processing power and storage. Cost is also an important consideration when selecting optics and sensors, as higher-end lenses and cameras can be more expensive.

Given these considerations, the JAI GOX-3201M-USB [15] machine vision camera with Computar M2514-SW lens [16] is a suitable choice for the scratch detection system. The JAI GOX-3201M-USB offers a high resolution of 3200 x 2400 pixels, which is necessary for capturing small scratches with accuracy. The camera also has a fast frame rate of up to 55 fps, which is useful for real-time inspection applications.

The Computar M2514-SW lens provides a magnification of 0.25x, which is appropriate for capturing scratches of varying sizes. The lens also has a large FOV of 17.6 x 13.2 mm and a DOF of 7.5 mm, allowing for the detection of scratches on objects with varying depths. Additionally, this lens is cost-effective compared to other high-end lenses, making it an excellent choice for cost-sensitive applications.

In summary, the selection of the JAI GOX-3201M-USB machine vision camera with Computar M2514-SW lens is based on the consideration of magnification, FOV, DOF, resolution, and cost. The combination of high resolution, fast frame rate, appropriate magnification, large FOV, and shallow DOF make this system an excellent choice for accurate and real-time detection of scratches on a variety of surfaces. The cost-effectiveness of the selected optics also makes it a practical choice for industrial applications.

2.6 Literature review conclusion

After analysis and consideration of various factors, utilizing a machine vision-based system for scratch detection is strongly recommended. This comprehensive system offers accurate and efficient detection of scratches while minimizing the risk of false positives or missed defects. To achieve optimal results, the following components are highly recommended:

Firstly, LabView is the preferred choice for programming the scratch detection system. Its graphical programming environment provides an intuitive and visually appealing approach to system development. LabView's user-friendly interface allows for the creation of complex systems by connecting graphical elements, enhancing the system's maintainability, and enabling efficient development of the scratch detection algorithm. In addition, diffused lights employing the dark field technique should be utilized for scratch detection. This lighting method enhances contrast and effectively highlights surface defects, such as scratches. By employing diffused lighting, the system can capture high-quality images that improve the visibility of scratches, resulting in more accurate and reliable detection. To ensure optimal image acquisition, the JAI GoX 3021M USB machine vision camera with the M2514-SW Computar lens is highly recommended. This camera offers high resolution and reliable performance, enabling detailed and accurate image capture. The M2514-SW Computar lens complements the camera by providing suitable focal length and optical characteristics specifically designed for machine vision applications.

Considering these facts, the proposed system is expected to deliver excellent results in scratch-detection applications. It provides accurate and efficient detection of scratches while minimizing the risk of false positives or missed defects. By utilizing LabView for programming, implementing diffused lights with the dark field technique, and utilizing the JAI GoX 3021M USB camera with the M2514-SW Computar lens, the system ensures optimal performance and reliable scratch detection capabilities. Regarding the system's requirements and specifications, it should be designed to work without external lighting conditions. An intuitive user interface should be implemented to facilitate easy configuration of parameters such as the number of scratches to be detected and the classification of the device (for example, Grade A, B, C, or D). The system should also prioritize serviceability, allowing for modifications and updates as needed. Lastly, it should be designed with appropriate sizes and dimensions to fit comfortably on the available table space, ensuring a compact and practical solution for scratch detection.

3 DESIGN OF THE SYSTEM

3.1 Optics and vision sensors

The system must be capable of capturing high-resolution images with sufficient clarity and detail to detect small scratches accurately. The requirements are that the camera should have a high pixel count and a lens with low distortion and high resolving power to ensure precise imaging. Additionally, the optics should provide adequate depth of field to capture both surface and subsurface scratches, and the camera should have adjustable focus settings for capturing images at different distances.

To establish an efficient and accurate scratch detection system, the author has chosen to utilize the JAI GoX 3021M USB camera with the M2514-SW Computar lens as the optics and vision sensors. To ensure proper setup, it is crucial to determine the correct height for locating the camera in the system relative to the workpiece. Considering the desired FOV for the raw image, which is satisfied as 150 mm x 200 mm, and the fact that the vision sensor is 1/1.8″ type, can now proceed with the calculation of the height of the system. It is important to consider the characteristics of the lens and the vision sensor type to accurately determine the height for optimal positioning.

JAI GoX 3021M USB camera is specifically designed to complement a 1/1.8″ type sensor (in another way 7.2 mm x 5.4 mm), which has its predetermined size. The sensor size plays a significant role in determining the magnification and subsequently affects the resulting field of view. With this information in hand, we can proceed with the calculation of the required height.

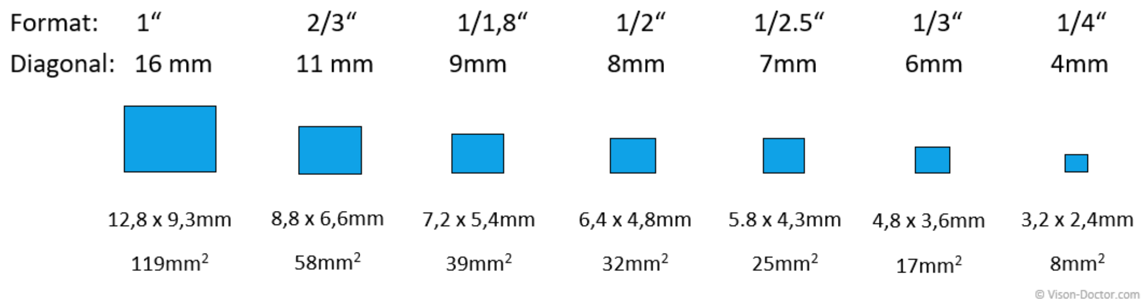

Figure 3.1 Typical sensor sizes of industrial cameras [17]

By applying the concept of similar triangles, can establish a relationship between the known sensor size and the desired field of view. This relationship is then equated to the ratio between the distance from the sensor (working distance + height) and the calculated height itself. With the focal length, sensor height, and field of view, can derive the following equation to solve for the working distance.

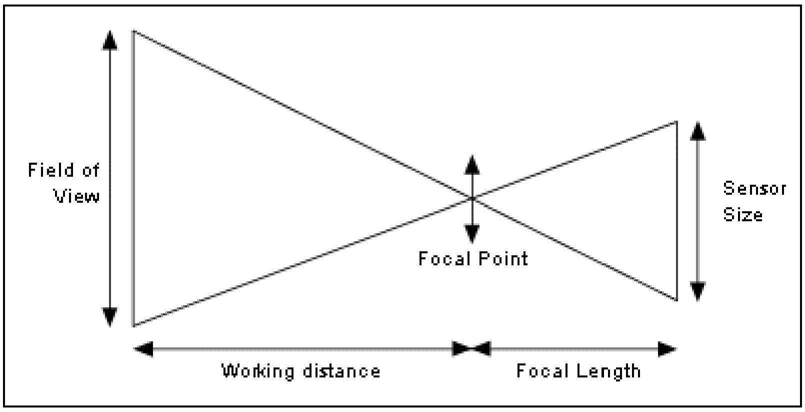

Figure 3.2 Working distance and the field of view diagram. [18]

$$\frac{Focal\ length}{Working\ distance} = \frac{Sensor\ height}{Height\ of\ FOV} \tag{3.1}$$

So, based on Equation 3.1, the working distance for the JAI GoX 3021M USB camera is:

$$Working\ distance = \frac{Height\ of\ FOV\ \times Focal\ length}{Sensor\ height}$$

$$Working\ distance = \frac{5000\ \text{mm}}{7.2\ mm} = 694.45\ mm$$

The working distance between the sensor and the workpiece has been calculated as 694.45mm, taking into account the specifications of the JAI GoX 3021M USB camera. This working distance serves as a crucial factor in the overall setup, as it impacts the field of view and image capture. Once the height is accurately calculated, it represents the precise distance between the sensor and the workpiece necessary to achieve the desired field of view. Ensuring that the camera is positioned at this calculated height, then can capture images that encompass the intended area and facilitate precise and reliable scratch detection.

In conclusion, based on the known working distance of the JAI GoX 3021M USB camera, the desired field of view, and the specific sensor size, calculated the height for locating the camera. This calculated height guarantees optimal positioning, enabling the camera to capture images within the specified field of view. By meticulously adhering to this determined height, the user can maximize the performance and accuracy of your scratch detection system, allowing for meticulous analysis and detection of scratches on the workpiece.

3.2 Controlling the background lights

Based on the literature review results, the LED diffused lights with dark field techniques were selected to illuminate the setup. To integrate it into the system it was important to consider how to control the ambient lights, what the height LED lights should be placed, and the angle of the light rays. For controlling the ambient light of the setup, The scratch detection system will be installed inside a fully covered enclosure measuring 400x400x850mm. This enclosure will help control the background lighting, ensuring the system operates optimally. The enclosure will be constructed using 30x30mm aluminum extrusions for the frame, providing a sturdy and robust structure for the system. Additionally, 3mm thick HDF sheets will be used to cover the enclosure, ensuring that the system is fully enclosed and protected from external lights.

For determining the height of the light source, the author used trigonometry, and for the lighting angle, 67.5^0 of satisfied angle which the light reflection and contrast are not affected by the image acquired by the camera. To determine the height of the light source, the author used the following trigonometry equation.

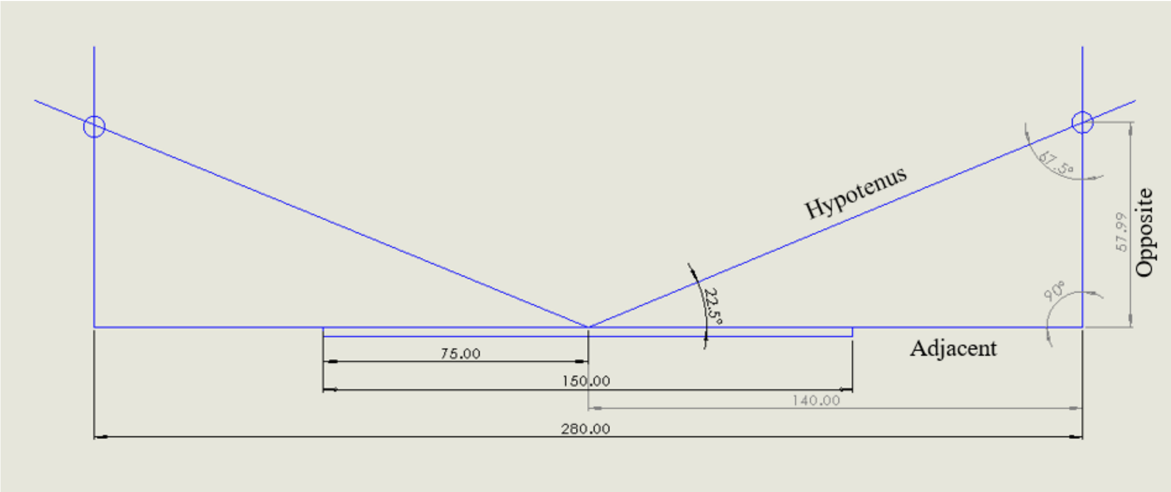

Figure 3.3 The height for fixing the LED diffused lights

$$tan\,\theta = \frac{Opposite}{Adjacent} \tag{3.2}$$

$$Opposite \;=\; 140\;mm\,.\tan 22.5\,°$$

$$Opposite \;=\; 57.99\;mm$$

Where $Opposite$ - side of the triangle that is opposite to the angle θ, mm,

$Adjacent$ - side of the triangle that is adjacent to the angle θ, mm.

By the equation, the author determined the height of 58 mm to place the LED diffused light source. The use of diffused lights in the scratch detection system offers several advantages. These lights evenly illuminate the workpiece, ensuring that every corner receives adequate lighting while effectively highlighting scratches or defects on the display. Importantly, the angle of the diffused lights does not impact the reflection or contrast captured by the camera. This means that the lights can be positioned at various angles without compromising the quality of the captured images. Overall, the diffused lights provide consistent and optimal lighting conditions for scratch detection, resulting in accurate and reliable results. Process and calculations.

3.3 Image capturing

Firstly, the user will need to open the Functions palette in LabView and locate the "IMAQdx" functions. This library provides support for acquiring images from industrial cameras. The user can then drag and drop the "IMAQdx Open Camera" function onto the block diagram. This function will open a connection to the camera. After opening the camera, the user will need to configure the camera settings using the "IMAQdx Configure Grab" function. This function allows the user to set the image format, resolution, and other properties according to the user's preferences.

Once configured the camera settings, the user can start acquiring images from the camera using the "IMAQdx Start Acquisition" function. This function will start the image acquisition process. After starting image acquisition, the "IMAQdx Grab" function can be used to retrieve the acquired images. This function retrieves a single image from the camera. Then display the image using the appropriate display function, such as the "IMAQ Display Image" function.

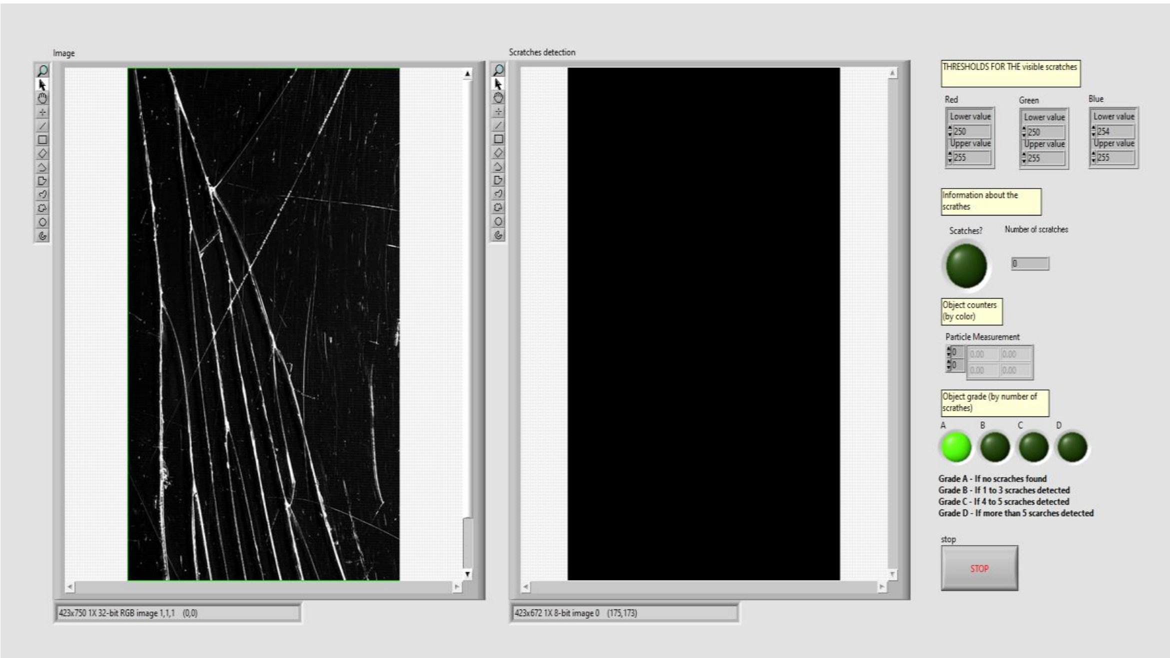

Figure 3.4 Sample image recognition by the pre-saved image.

3.4 Create LabView block diagram.

In the LabView block diagram, the author used "Vision acquisition" VI since there is a JAI GoX 3201M USB machine vision camera used in this system. The "Vision Acquisition" VI in LabVIEW is used to acquire image data from different types of cameras. It provides a variety of functions and settings to control camera properties such as exposure time, gain, and image format. The VI also allows users to configure camera triggering and acquisition modes. Once the image data is acquired, it can be processed and analyzed using other LabVIEW functions and tools, such as the Vision Development Module. The Vision Acquisition VI supports various image formats and interfaces, including USB, GigE, Camera Link, and IEEE 1394. It is a powerful tool for industrial and scientific applications that require high-speed and high-resolution image acquisition.

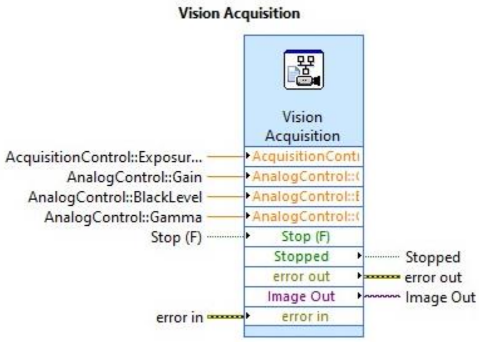

Figure 3.5 Vision Acquisition VI [9]

A couple of "IMAQ create" VIs. IMAQ Create is a LabVIEW VI (virtual instrument) used for creating image acquisition sessions. It allows users to create an acquisition session, specify the image format and size, and configure the acquisition properties. The VI can also be used to set up trigger and frame rates, set up regions of interest (ROIs), and configure other acquisition parameters. Once the image acquisition session is created using "IMAQ Create", it can be used in other LabVIEW VIs or applications to acquire and process images in real-time or batch mode.

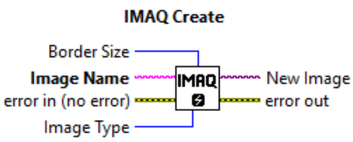

Figure 3.6 IMAQ create VI [9]

Then there are two special VIs called "ROI descriptor" and "IMAQ control rectangle to ROI". In LabVIEW's Image and Vision palette, "ROI descriptor" and "IMAQ convert the rectangle to ROI" functions are used for defining regions of interest (ROIs) on an image. The "ROI descriptor" function is used to create an ROI object that describes a rectangular or polygonal region of interest on an image. The ROI object can then be passed to other LabVIEW functions for further processing. The "IMAQ convert the rectangle to ROI" function is used to convert a rectangular region of interest to an ROI object. This function takes the coordinates of the rectangle (top, left, bottom, right) and converts them into an ROI object. Both of these functions are useful for identifying and processing specific regions of interest within an image, such as a particular object or feature. They are commonly used in applications such as image analysis, machine vision, and object tracking.

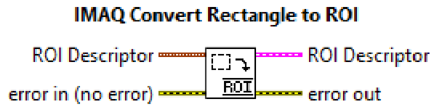

Figure 3.7 IMAQ converts rectangle to ROI VI [9]

Thereafter "IMAQ Overlay ROI" was used, and it is a function in LabVIEW used for highlighting and manipulating regions of interest in an image. It allows the user to define rectangular or elliptical ROIs, which can be moved, resized, or rotated. The ROI can be overlayed on the image and the user can manipulate it in real-time. This is useful for various image processing tasks, such as object detection, tracking, and measurement. The overlay ROI can also be used to visualize the effect of various image processing algorithms on specific regions of interest in the image. And then The "IMAQ ROIToMask 2" VI is used to convert an ROI to a mask image. The mask image is a binary image that is used to identify the pixels within the ROI. The function allows the user to specify the size of the output mask and whether the mask should be inverted. The inverted mask will highlight the pixels outside of the ROI. The output of this function can be used for further image processing or analysis.

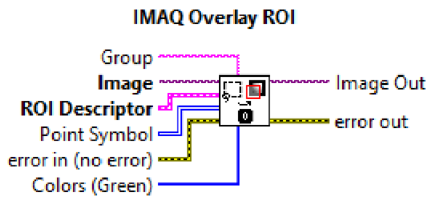

Figure 3.8 IMAQ overlay ROI [9]

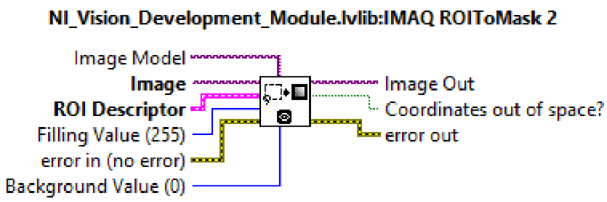

Figure 3.9 IMAQ ROI To Mask 2 [9]

"IMAQ Mask" is a function in LabVIEW's IMAQ Vision module that allows users to create a binary image from an input image by specifying the threshold values. The output binary image is a black-and-white image where the white pixels represent the pixels in the input image that fall within the specified threshold values and the black pixels represent the pixels that fall outside the threshold values. This function is often used in image processing applications for segmentation, object detection, and image analysis. The "IMAQ Extract 2" is used to extract pixel values from an ROI in an image. It takes an input image and an ROI as inputs and outputs a new image that contains only the pixels within the ROI. The function allows users to extract specific features or objects from an image for further processing or analysis. For example, if the user wants to extract only the face of a person in an image, they can draw an ROI around the face and use the "IMAQ Extract 2" function to obtain a new image that contains only the pixels within the ROI, which in this case would be the face.

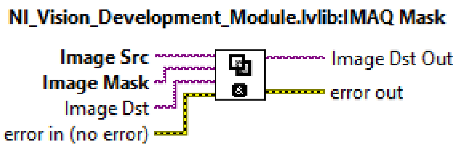

Figure 3.10 IMAQ Mask VI [9]

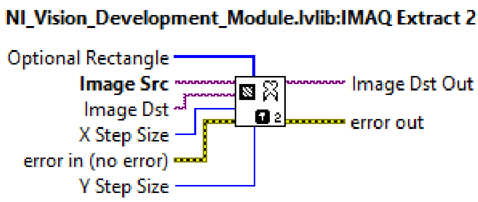

Figure 3.11 IMAQ Extract 2 VI [9]

The next special VI is "IMAQ Cast Image 2". Since JAI GoX 3201M USB produces a gray image by default and for controlling the thresholds, the image should be in RGB format. Therefore, the user needs to convert the gray image an into RGB image. The "IMAQ Cast Image VI" is used to convert one image type to another image type in the LabVIEW environment. It is a part of the LabVIEW Vision Development Module, which is used for image processing applications. This VI can cast images to different data types such as unsigned integers, signed integers, floating points, or complex. By using this VI, users can ensure that the image type matches the data type required by other image processing VIs in their application. This can help to prevent errors and ensure that the processing is performed correctly.

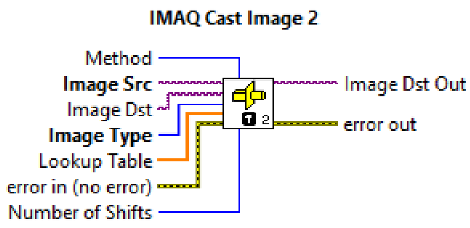

Figure 3.12 IMAQ Cast Image 2 VI [9]

For controlling the thresholds of ROI images and getting a better detection of scratches, the "IMAQ Color Threshold" VI is used in image processing to segment an image into regions of interest based on pixel intensity. It takes an input image and applies a threshold value to each pixel, classifying them as either foreground or background based on whether their intensity is above or below the threshold value. The result is a binary image where foreground pixels are typically set to white and background pixels to black, although this can be inverted. The threshold value can be set manually or calculated automatically based on various methods such as Otsu's method or the mean intensity of the image. The output of the threshold VI can then be further processed using other image-processing VIs to extract features or perform analysis on the segmented regions of interest.

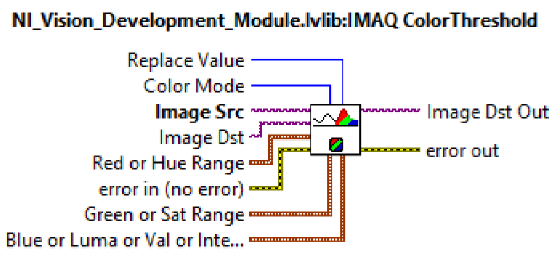

Figure 3.13 IMAQ Color Threshold VI [9]

"IMAQ Remove Particle" VI is used in LabVIEW's Image Processing palette that removes particles from a binary image. The function takes in a binary image and a particle size range as input and returns a new binary image with particles of the specified size range removed. This function is useful in applications such as object detection, image segmentation, and particle analysis. It can be used to remove noise or unwanted objects from an image, allowing for more accurate analysis and detection of objects of interest.

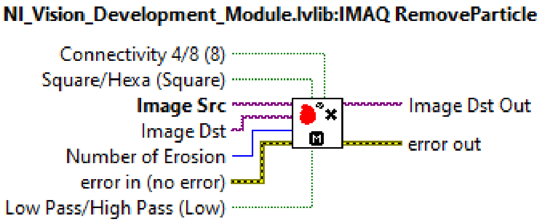

Figure 3.14 IMAQ Remove Particle VI [9]

The last special VI is "In Range VI". The In Range (Expression VI) is a LabVIEW VI that is used to check if a given value lies within a specified range. This VI returns a Boolean value that indicates whether the input value is within the specified range or not. The In Range VI takes two inputs: a value to be checked and a range. The range is specified as two input values, representing the lower and upper bounds of the range, respectively. The VI compares the input value to the specified range and returns a Boolean value of "True" if the value lies within the range, or "False" if it does not.

In Range VI can be used in a wide range of applications. For example, it can be used to validate user input by ensuring that a value entered by the user falls within a specified range of acceptable values. It can also be used to control the behavior of a LabVIEW program by triggering specific actions based on whether a value falls within a certain range. Overall, the In Range (Expression VI) is a useful tool for performing conditional checks in LabVIEW and can be applied to a variety of programming scenarios.

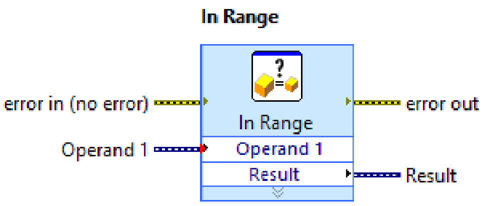

Figure 3.15 In Range VI [9]

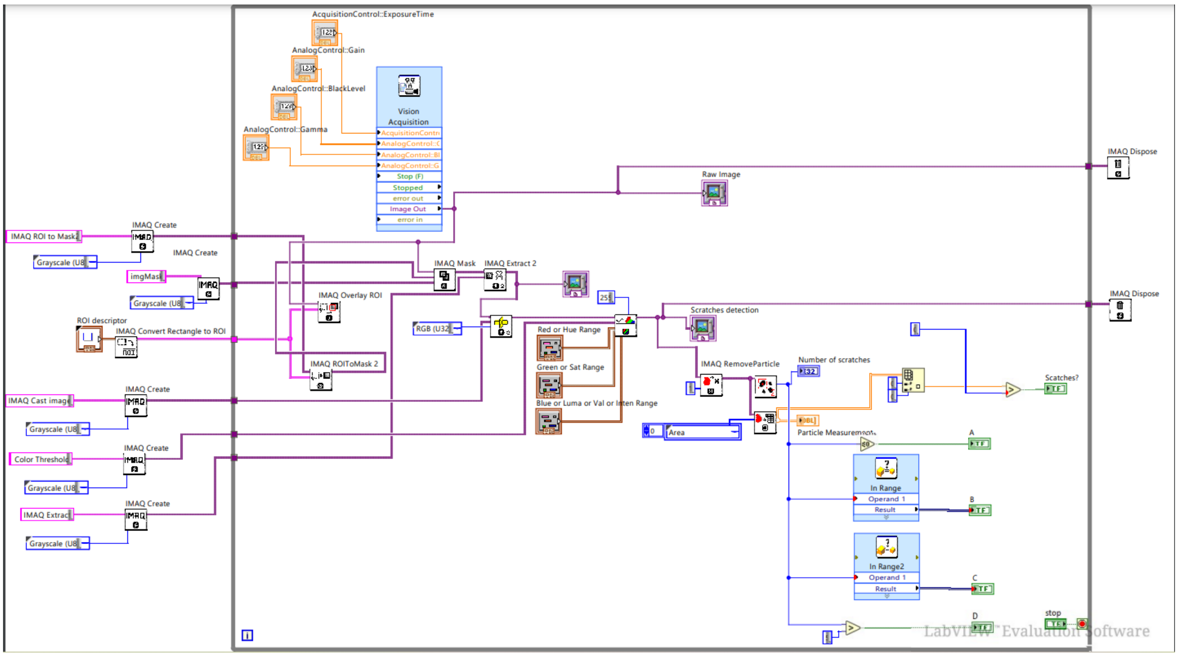

Figure 3.16 Complete block diagram for the scratch detection system

3.5 Image processing

The first step in the scratch detection program is to capture the original image which is produced by JAI GoX 3201M USB camera using the "Vision Acquisition" function. This function allows the program to interface with a camera or any other imaging device to obtain the image. The image is then displayed in the first of the three image viewers that have been created for this purpose. Next, the user defines the ROI on the displayed image using the "IMAQ create" VI and the "ROI descriptor" VI. The "IMAQ Convert Rectangle to ROI" VI will convert the rectangle into an ROI object, which can be used for further analysis.

Once the ROI has been defined and connected, it is overlaid on the original image using the "IMAQ overlay ROI" VI. This step helps the user visualize the area that will be processed for scratches detection. The next step is to convert the rectangular ROI to a mask using the "IMAQ ROI To Mask 2" VI. This conversion creates a binary image with the same dimensions as the ROI, where the pixels inside the ROI are set to 1 and the pixels outside are set to 0.

The "IMAQ Mask VI" is then used to apply the mask to the original image. This step isolates the pixels inside the ROI, which are the only pixels that will be processed for scratches detection. The "IMAQ Extract 2" VI is then used to convert the masked image to grayscale. This step simplifies the image by reducing it to a single-color channel, making it easier to identify scratches and the image will be displayed in the second image viewer.

The "IMAQ Cast Image 2" VI is used to convert a grayscale image to an RGB image. This is necessary if the user wants to apply color-specific image processing functions to the image, such as identifying regions of a certain color. The grayscale image is first duplicated three times to create three identical channels in the RGB image. This is because color images are made up of three channels: red, green, and blue. In a grayscale image, all the pixel values are the same, so only one channel is needed.

Once the grayscale image has been converted to an RGB image using the "IMAQ Cast Image 2" VI, the "IMAQ Threshold" VI can be used to convert the image to a binary format. This is useful for separating regions of the image that meet a certain brightness or color threshold from the rest of the image. The "IMAQ Threshold" VI works by specifying upper and lower bounds for the pixel values that will be considered part of the object of interest. Pixel values above the upper bound or below the lower bound will be considered background.

The "IMAQ Remove Particle" VI is used to remove any small particles or blobs in the binary image that are not scratches. This step further helps to reduce noise and ensure that only actual scratches are detected. Finally, the "In Range Expression" VI is used to compare whether the detected number of scratches is in the expected range or not. If the value is in the given range, VI sends the signal as true and gives a signal to the indicator to indicate the result. Else, it passes to the next In Range Expression VI.

If the user identifies any abnormal condition or wants to stop the program, they can simply click the stop button in the bottom right corner of the interface, which will immediately stop the program and keep the last displayed image in the second image viewer.

4 THE DESIGN OF THE PROTOTYPE

4.1 Graphical User Interface Design

The author of the project developed a graphical interface using LabVIEW to ensure a user-friendly and high-quality experience. The GUI's purpose was to enhance the user's interaction with the software and enable easy comprehension of the system's output. Through thoughtful design and intuitive features, the GUI was created to facilitate seamless user interaction. Its user-friendly layout and intuitive controls make it simple for users to navigate and operate the software. Additionally, the GUI presents the output clearly and understandably, enabling users to interpret the information effortlessly. By focusing on usability and clarity, the author aimed to deliver a graphical interface that enhances the overall user experience.

The graphical interface consists of three image viewers. The first image viewer is responsible for displaying the original row image, and it also indicates the region of interest selected by the user. This feature allows the user to view the selected portion of the image with greater detail and precision. The second image viewer displays the ROI image, which is segmented by the first viewer. The ROI image is created by extracting the region of interest chosen by the user from the original row image. This image viewer allows the user to view the segmented ROI image with greater clarity and focus. The third and final image viewer highlights the scratches detected by the software. The scratches are marked with white color, making them easily identifiable to the user. This feature allows the user to quickly identify the scratches detected by the software and take appropriate action to address them.

In addition to the image viewers, the GUI also includes four control boxes located in the left middle, which allow the user to adjust camera attributes. These control boxes are designed to provide the user with greater flexibility in controlling the camera and achieving better image quality. The first control box, called the "Acquisition control," allows the user to control the exposure time of the camera by adjusting the values. Even if the lens is fully open, the user can still control the lighting by decreasing the exposure time. The highest value of this controller is 17729, while the lowest value is 0. The second control box, called the "Analog control," enables the user to manipulate the black level of the image. The highest value of this controller is 255, which corresponds to the white color, while the lowest value is 0, corresponding to black. The third controller, called the "Gain control," allows the user to adjust the gain of the image. Increasing this controller's value up to 126 will result in a more contrasted image while decreasing it to 0 will produce a darker image. The last control box is called the "Gamma control" and is responsible for controlling the gamma level of the image. By adjusting this controller's value between 0.45 and 1, the user can obtain a clear and sharp image.

In addition to the control boxes for camera attributes, the GUI in LabView also features a special controller in the bottom left corner called "ROI Descriptor." This control box enables the user to define the Region of Interest (ROI) by specifying values for Left, Top, Bottom, and Right. By entering values for these four corners, the program can identify the exact ROI to display in the second image viewer. The second image viewer will then show the cropped image from the original image based on the ROI values set by the user. This feature allows the user to precisely define the area of the image they want to focus on and obtain more accurate results. The ROI Descriptor is a powerful tool that can be used in a wide range of image processing applications and makes the GUI in LabView even more versatile and user-friendly.

The GUI in LabView also features controllers for controlling the thresholds located in the top right corner. There are three controllers called "Red or Hue Range," "Green or Sat Range," and "Blue or Luma or Val or Intern Range." The "Red or Hue Range" controller allows the user to control the red or hue range of the ROI image. The maximum value for this controller is 255, which corresponds to white, while the lowest value is 0, corresponding to black.

Similarly, the "Green or Sat range" and "Blue or Luma or Val or Intern Range" controllers are used to control the green or saturation range and the blue or luma or Val or intern range, respectively. The highest and lowest values for all these controllers are 255 and 0, respectively. By adjusting these thresholds, the user can obtain a sharp and detailed picture of scratches, which will be displayed in the third image viewer. This feature allows the user to detect even the smallest scratches and blemishes on the surface of the object being inspected, making it an invaluable tool for quality control and inspection applications.

Right below the threshold controllers, there is a green color indicator designed to show if the program detects a single scratch on the display. When the program detects a single scratch, the indicator will turn green and light up to notify the user that there are scratches on the display. If there are no scratches detected, the indicator will remain off. Beside the green indicator, there is a text box that shows the number of scratches found by the program. If the indicator is glowing green, the user can see how many scratches there are by checking the numbers in this text box. If the indicator is in idle mode or not glowing, the text box will remain at 0, indicating that no single scratch has been found on the display. This feature allows the user to detect the presence of scratches and blemishes quickly and easily on the display, making it easier to monitor the quality of the display and identify any potential issues or defects. By providing real-time feedback, the GUI makes it easier for the user to identify and address any problems that may arise, ensuring that the display meets the necessary quality standards.

Located below the scratch detection indicator, there is another box specifically designed for indicating particle measurements. The number of particles in each scratch will be displayed in this box, allowing the user to estimate the size and severity of each scratch. To check the detected particles in a specific scratch, the user can simply click the up or down buttons, and the number of particles in that scratch will be displayed. This feature provides the user with a quick and easy way to estimate the size of each scratch, with a higher particle count indicating a longer or deeper scratch, and a lower particle count indicating a thinner or shorter scratch. By providing this level of detail and granularity, the particle counter allows the user to accurately assess the quality of the display and identify any areas that may require further attention or maintenance. This helps to ensure that the display continues to meet the necessary standards and that any issues are addressed promptly and effectively.

In the right bottom corner, there are four special indicators that the user can use to identify the grade of the display. The LabVIEW program is designed to grade displays according to the number of scratches detected on the display. The user can simply identify whether the display is grade A, B, C, or D by these indicators. There are parameters to grade the display according to the number of scratches. If there are no scratches detected on the display and the scratches indicator is off, the A indicator will glow in green color, indicating that the display is graded as grade A. If the system detects one to three scratches, the second indicator will glow in green color, indicating that the display is graded as grade B. Similarly, if the display has four to five scratches on it, the third indicator will glow in green color and indicate that the display is graded as grade C. Finally, if the display has more than five visible scratches, and the system detects all of them, the last indicator will glow in green, indicating that the display has more than five visible scratches, and it will be graded as a grade D display.

In the right-most bottom corner, there is a stop button that allows the user to stop the program immediately in any case. If the user identifies any abnormal condition or scratches on the display that is not detected by the system, the user can click the stop button, and the second image viewer will keep the picture as it is when the stop button is pressed, while all other image viewers and indicators are in idle mode.

In conclusion, the LabVIEW program is a useful tool for detecting scratches on a display. The program provides various tools such as image viewers, threshold controllers, particle counters, and grading indicators to help the user identify and analyze the scratches. The user can define a region of interest, adjust the thresholds to get a clearer picture, and identify the number of particles in each scratch to determine its size. The grading indicators help the user determine the grade of the display based on the number of scratches detected. Overall, the program is a comprehensive solution for detecting and analyzing scratches on a display, and it can help users determine the quality of their displays.

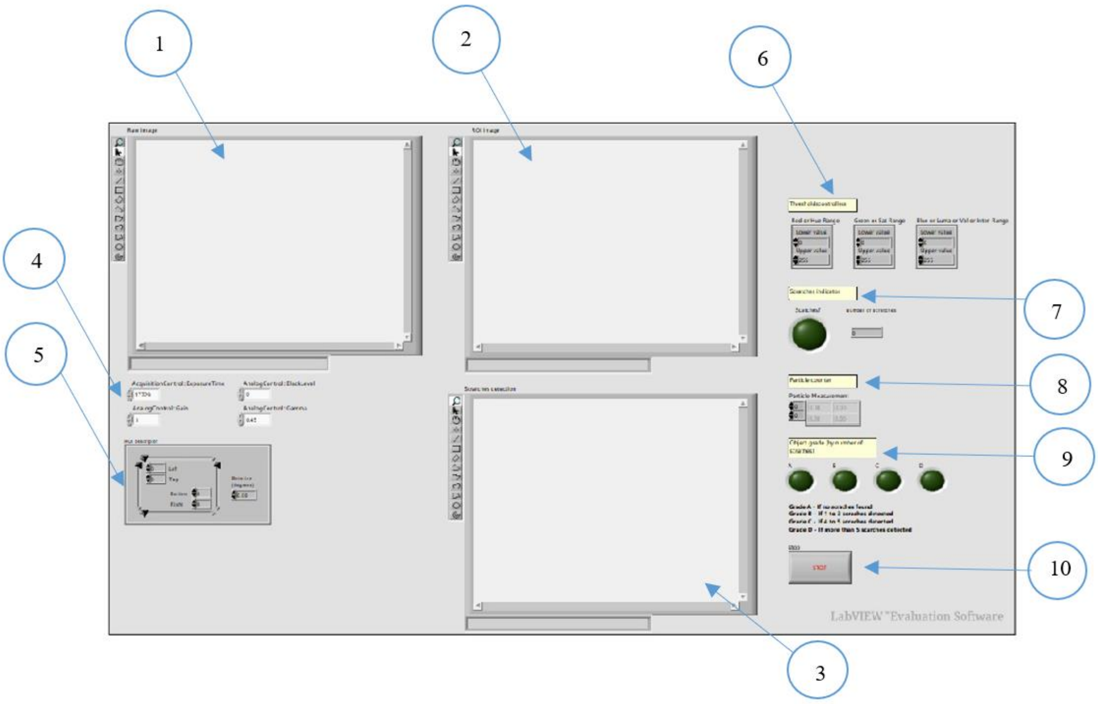

Figure 4.1 The complete GUI of the scratches detection system:

1 – Image viewer for the original image, 2 – Image viewer for the ROI image, 3 – Image viewer for displaying detected scratches, 4 – Camera attributes controllers, 5 – ROI descriptor, 6 – Thresholds controllers, 7 – Scratches indicator and scratch counter, 8 – Particle counter, 9 – Grade indicators, 10 – Stop button

4.2 Frame design

The prototype frame was first equipped with 31x31mm wooden sticks, 3mm thick High-Density Fiber (HDF) boards for side covers, and M4x45mm self-tapping CSK screws for fastening the frame. There were 4 numbers of 843mm long 31x31mm wooden sticks as main vertical columns in four corners while 8 numbers of 340mm long 31x31mm wooden sticks as horizontal columns mounted to make the structure rigid and robust. All the wooden sticks were connected by M4x45mm self-tapping CSK screws. Apart from that, there were 3 numbers of 400mm long 31x31mm wooden sticks in the upper part of the frame as a mounting support of the camera whereas another 2 numbers of 400mm long 31x31mm wooden sticks were mounted in the bottom part of the frame as a mounting support of the lights.

For the covering of the wooden frame, the author used pre-sized 3mm thick HDF boards. There was a 400mm x 849mm x 3mm HDF board as per the back cover while 2 numbers of 403mm x 849mm x 3mm HDF boards as side covers. There is a 406mm x 849mm x 3mm HDF board with a special opening at the bottom as the front cover. This special opening will be used for inserting and ejecting the phones which are needed to check for scratches and grades. For covering the top and bottom of the frame there were 2 numbers of 400mm x 400mm x 3mm HDF boards. Moreover, there will be one more specially designed 400mm x 400mm x 3mm HDF board with an open in the middle to visible only the required area for the camera while covering the rest of the unnecessary background. Finally, four numbers of HDF strips are 361mm x 20mm x 3mm, 361mm, 30mm x 3mm, 179mm x 20mm x 3mm, 179mm x 30mm x 3mm respectively, and a 139mm x 391mm x 3mm HDF board used for making smooth movement while inserting and ejecting the phones.

After installing the components and testing the system with the primary frame which is designed with wooden sticks, the author transferred all the components and the covers to a new frame which is built with aluminum profiles. And then there on used the new structure for testing further steps of the scratch detection system. For the new structure, the author used 30x30mm aluminum profiles [19] all the lengths are similar to wooden sticks used in the primary design, mounting angle 30 GD-Z [20], ISO 7380 - M6 x 10 - 10N screws, and square nut M03H with position fixing for properly mounting of aluminum profiles. All the covering plates are used for the new structure from the previous primary design also the sizes, and the designs of the boards were not changed. Apart from these materials, the author used 4 numbers of 3D-printed bottom nobs to adjust and balance the enclosure and 3D-printed hinges to easily open the front cover when the system needs adjustments or repairs.

Figure 4.2 Enclosure assembly with aluminum profiles:

1 – 30x30 mm aluminum profiles as a horizontal column, 2 – 30x30mm aluminum profiles as camera mounting support, 3 – mounting angles 30 GD-Z [19], 4 – 30x30mm aluminum profiles as vertical column, 5 – 30x30mm aluminum profiles as lights mounting supports, 6 – 3D printed bottom supports, 7 – 3D printed hinges, 8 – magnet [19]

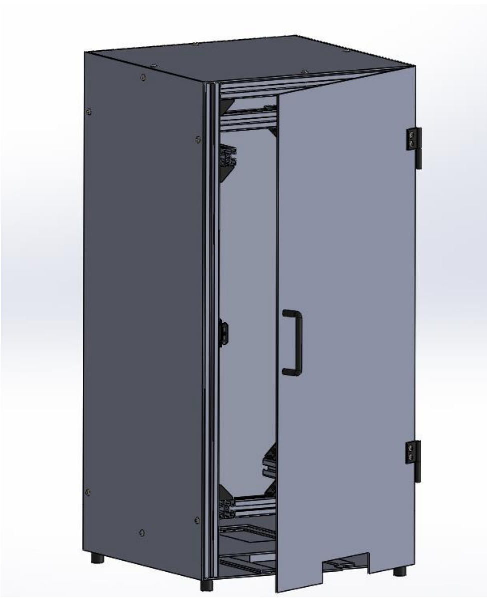

Figure 4.3 3D image of the completed enclosure

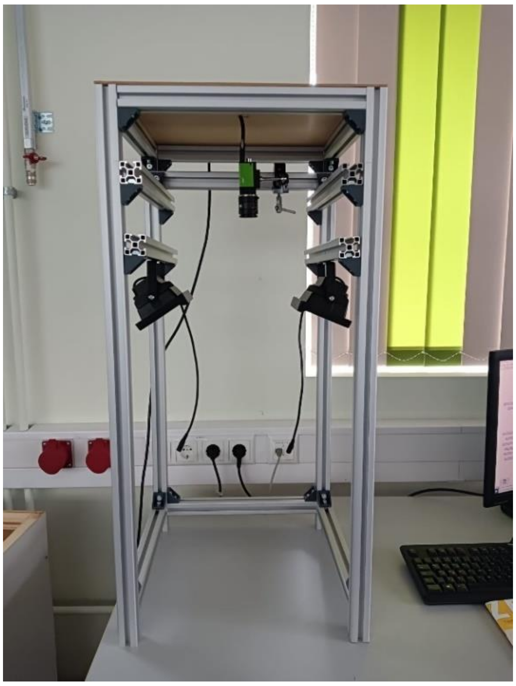

Figure 4.4 The frame after assembling

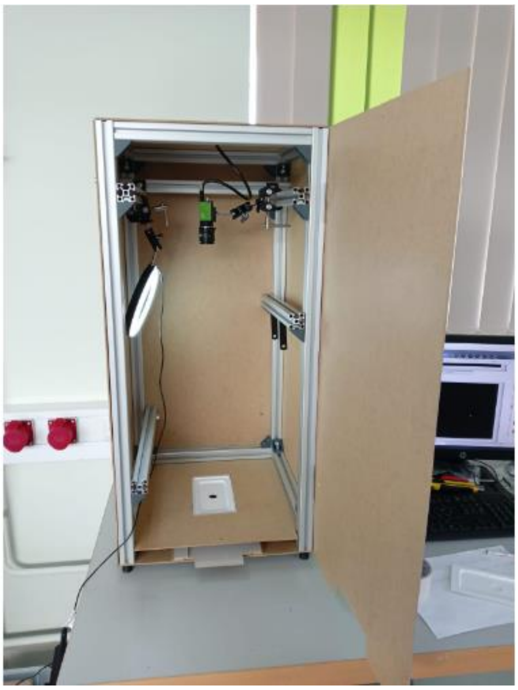

Figure 4.5 The completed enclosure for testing

5 TESTING OF THE PROTOTYPE

5.1 Preliminary test results

For testing the LabView program, the author used the pre-saved image as an original image instead of grabbing an image from the machine vision camera. With the pre-saved image, the author tested the program by adjusting the thresholds to get better detection by the program. Also, the program was tested for receiving the correct grade for the particular image by testing each indicator that stands for indicates the grade of the mobile phone display in this system. The LabView program was programmed to grade a display consequently to the number of scratches detected on it. The tuned parameters are as follows.

Table 5.1 parameters for grading the displays according to the number of scratches

Nr.	Grade	Number of scratches
1	A	0
2	B	1 - 3
3	C	4 – 5
4	D	More than 5

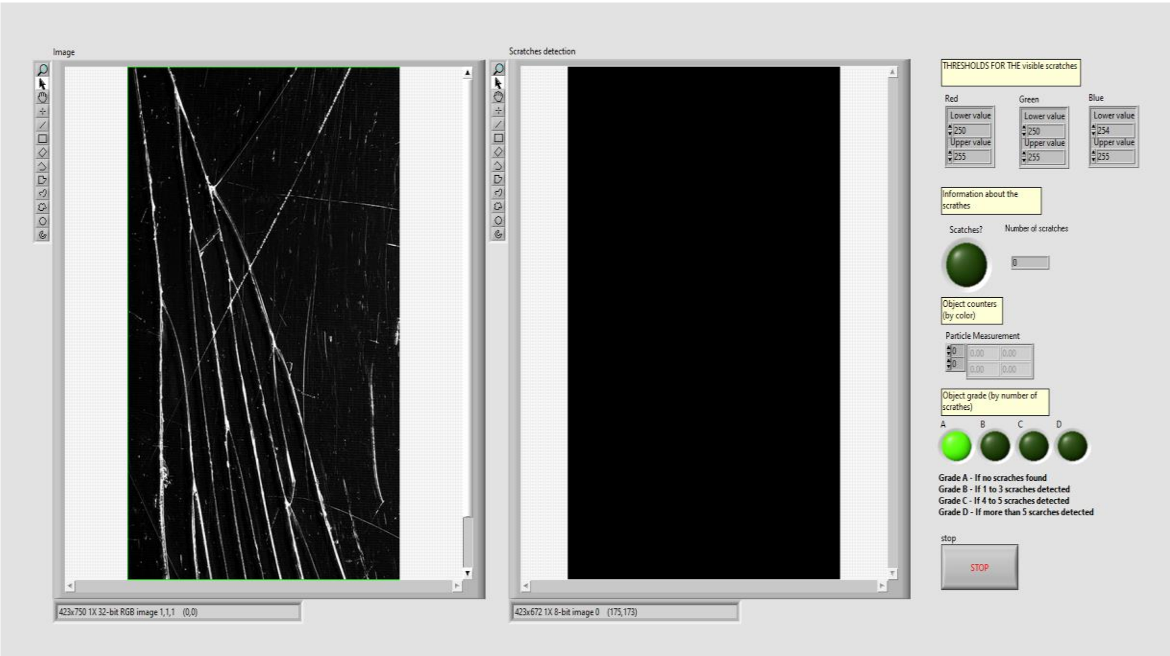

Figure 5.1 The system indicates A grade display (Thresholds values were Red lower 250: Red upper 255, Green lower 250: Green upper 255, and Blue lower 254: Blue upper 255. These threshold values were not affected to detect any scratches of the sample image. So, it shows the grade of the sample picture as A grade)

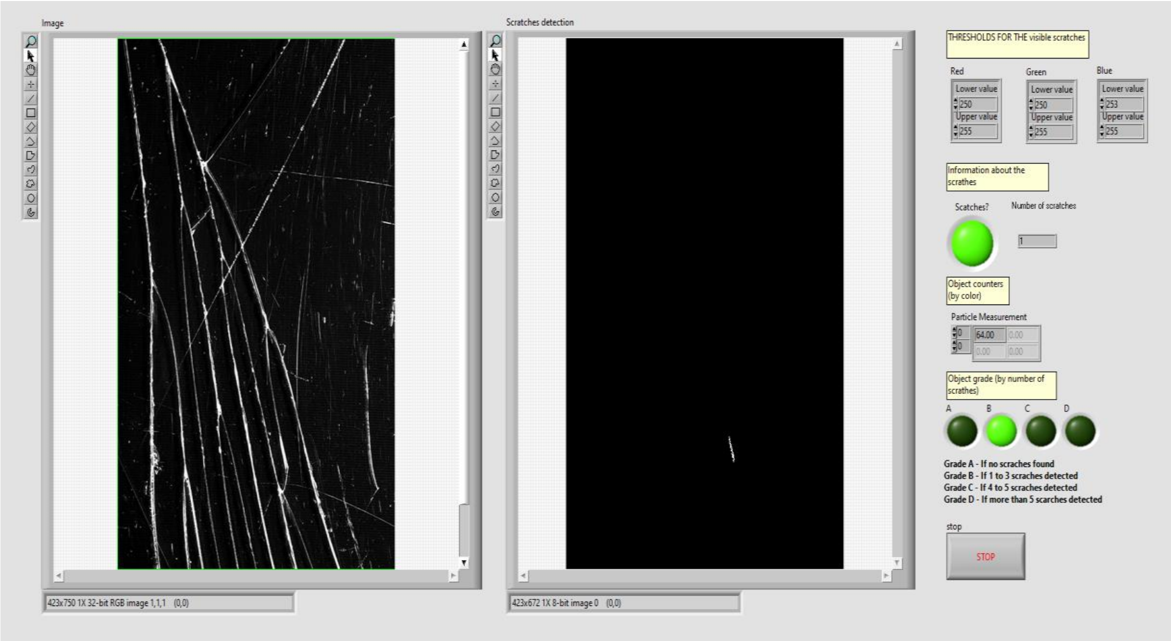

Figure 5.2 The system indicates B grade display (Thresholds values were Red lower 250: Red upper 255, Green lower 250: Green upper 255, and Blue lower 253: Blue upper 255. These threshold values were affected to detect a scratch on the sample image. So, it shows the grade of the sample picture as B grade)

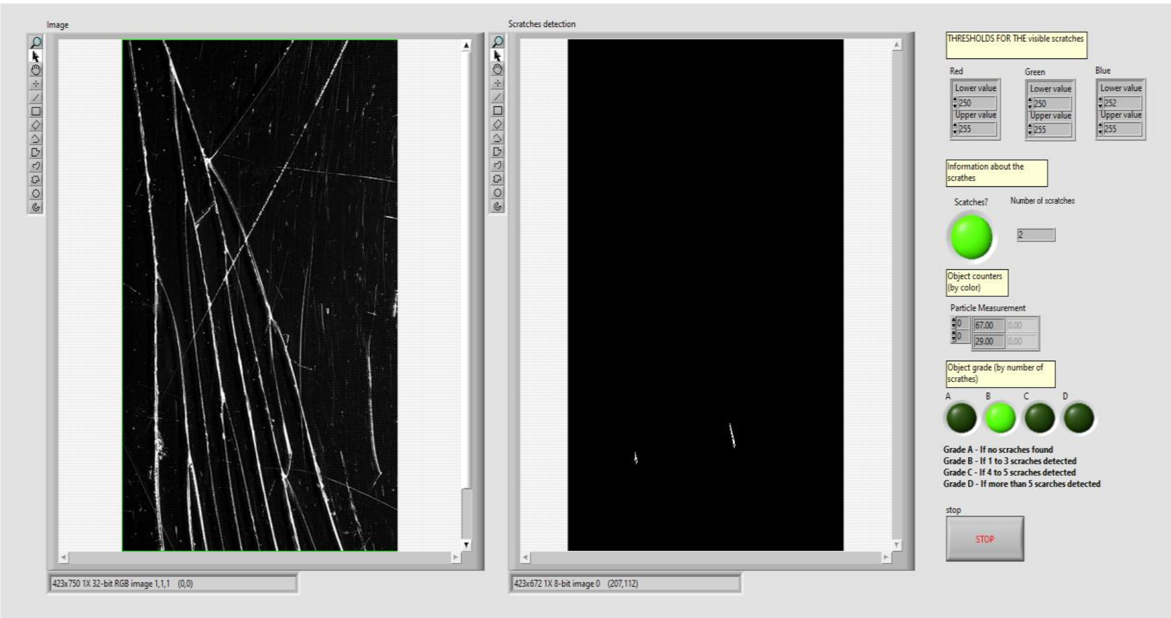

Figure 5.3 The system indicates B grade display (Thresholds values were Red lower 250: Red upper 255, Green lower 250: Green upper 255, and Blue lower 252: Blue upper 255. These threshold values were affected to detect two scratches on the sample image. So, it still shows the grade of the sample picture as B grade)

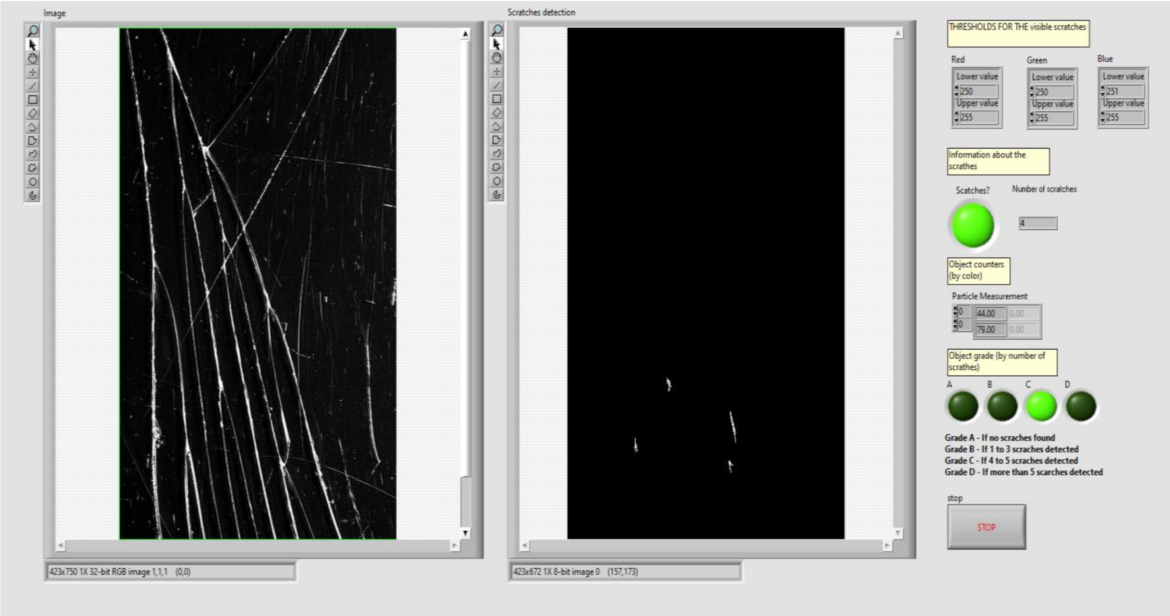

Figure 5.4 The system indicates C grade display (Thresholds values were Red lower 250: Red upper 255, Green lower 250: Green upper 255, and Blue lower 251: Blue upper 255. These threshold values were affected to detect four scratches on the sample image. So, it shows the grade of the sample picture as C grade)

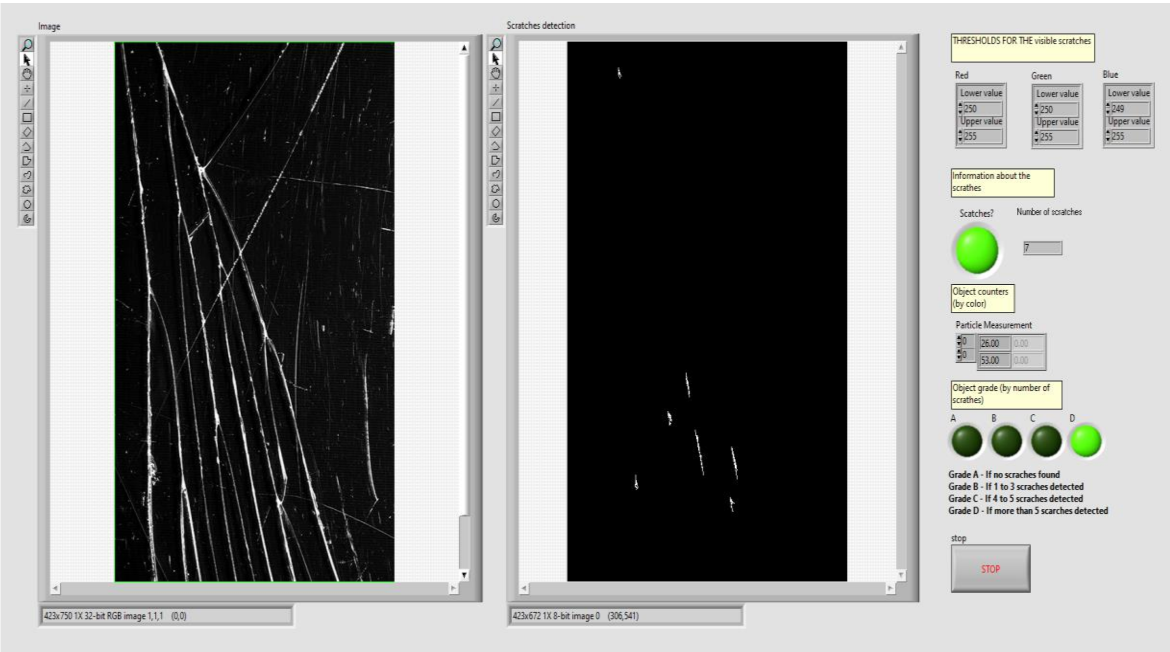

Figure 5.5 The system indicates C grade display (Thresholds values were Red lower 250: Red upper 255, Green lower 250: Green upper 255, and Blue lower 249: Blue upper 255. These threshold values were affected to detect seven scratches on the sample image. So, it shows the grade of the sample picture as a D grade)

5.2 Final test results

for the final test, the author used 3 different mobile phones (2 different iPhone 8 and an iPhone XS). All 3 phones have different numbers of scratches, and the author used them to test the setup after setting up all the settings of the setup. Apart from that, the author used 16000 for exposure time, 0 for black level, 4 for gain, and 0.46 for the gamma of camera attributes controllers for all the phones during the test. For threshold controllers, the lower values for red, green, and blue were 35 while the upper value is 70 for red, green, and blue controllers for all the phones during the test. Before feeding the phone to the system, the display surface must be cleaned and there will be not any single dust particles. If the system finds any dust particles or fingerprints on the display, the system will count those as scratches if those are highlighted under LED diffused lights and their color match with RGB values in the threshold controllers.

Test 1. In test one, the author selected an iPhone 8 model phone with a pristine, scratch-free display. This deliberate choice aimed to evaluate the system's response to a device without any visible scratches. By utilizing this test phone, the author sought to assess the software's performance and ensure its compatibility with devices in optimal condition. This rigorous testing approach helps to guarantee that the GUI functions flawlessly and delivers an exceptional user experience across various devices with different display conditions.

Figure 5.6 iPhone 8 model phone without any scratches on its display

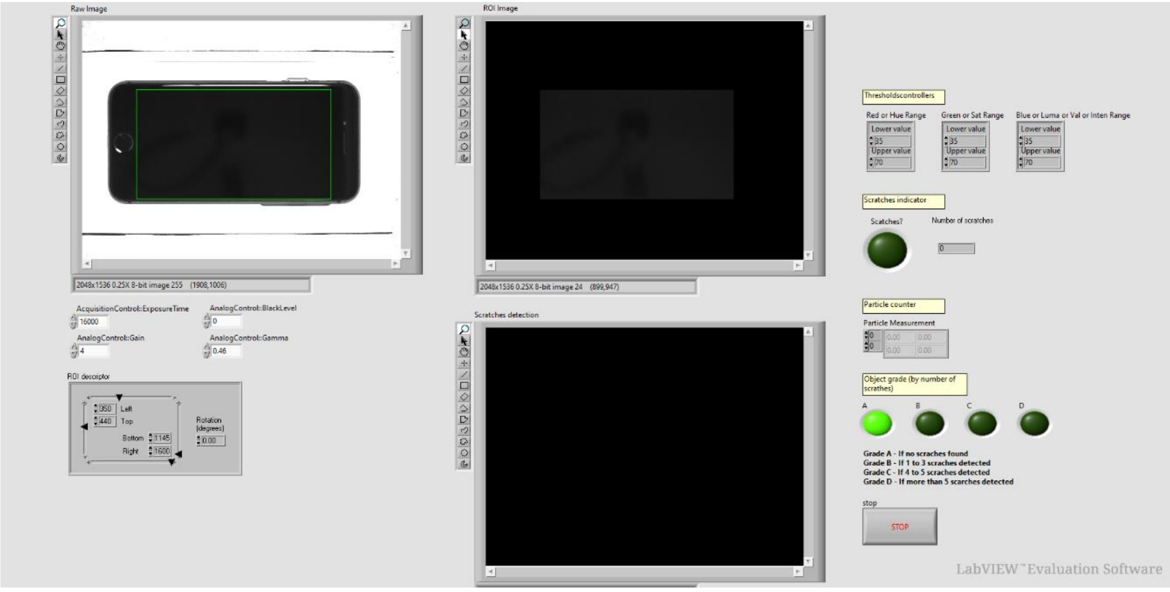

Figure 5.7 Screenshot from the software when the program grade the display as grade A

According to the first test display, the LabView program determined it as a grade-A display. Since the display does not have any scratches on it, the program did not identify any of the defects on the display. A new user will take approximately 8 seconds to feed a phone to the system. It depends on the speed of the operator's ability to open the slider of the setup, place the phone in the correct position and then close the slider. In this test the author spent 8 seconds opening, placing the phone, and closing the slider. Right away the slider is closed, and the system will check the phone and give the results to the reader in milliseconds.

Test 2. In the second test, the author used another iPhone 8 model phone which has 2 numbers of scratches on its display. With ambient lights, there will be some difficulties identifying the scratches on the mobile phone without changing the holding position and angle of the human being. This is the most time-consuming activity when counting scratches manually by a person.

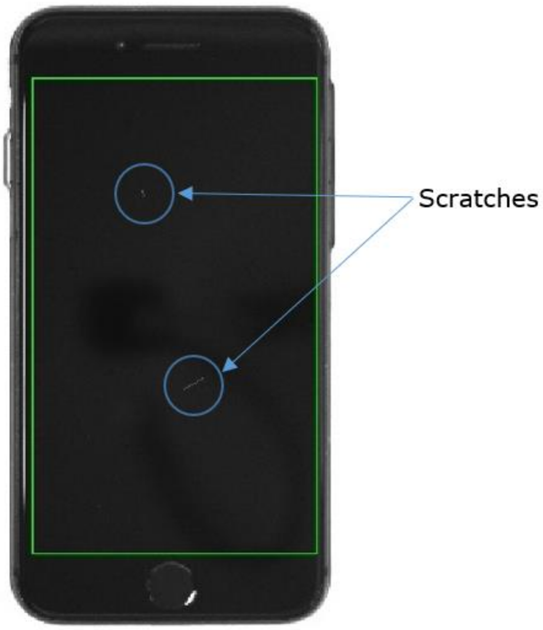

Figure 5.8 iPhone 8 model phone with two scratches on its display

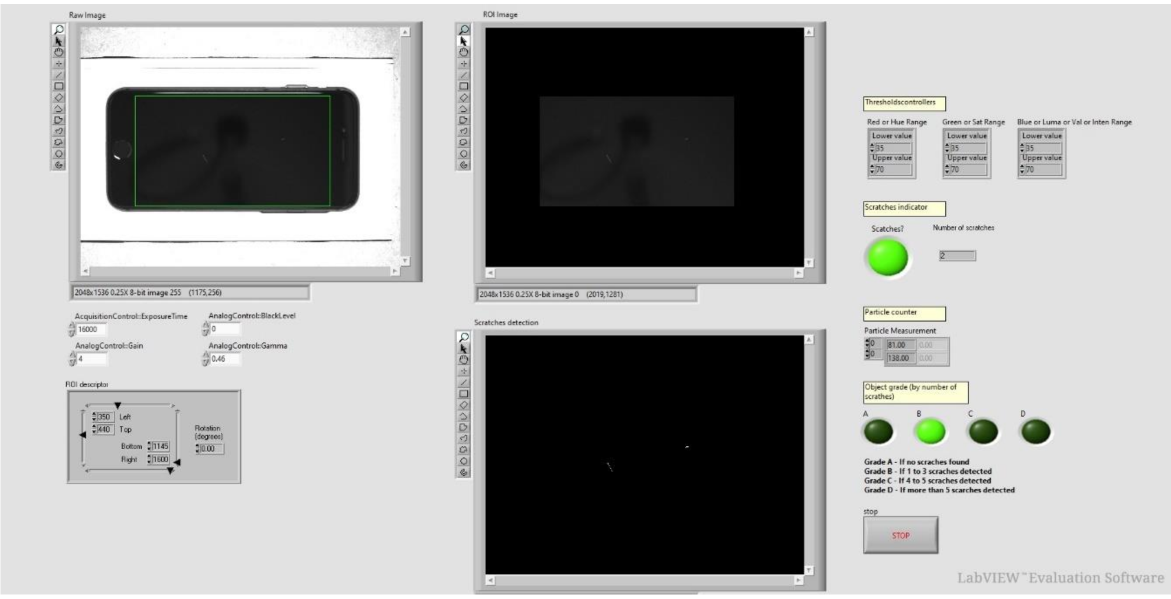

Figure 5.9 Screenshot from the software when the program grade the display as grade B

According to the second test display, the LabView program determined it as a grade B display. Since the display has 2 visible scratches on it, the system recognizes two scratches immediately after feeding the phone to the system. In this test, the author spent 9 seconds feeding the phone in the same way as the previous test. But in this test, there was an additional task to do that is removing the previous phone from the feeder. It took a second, but it is still faster than manual counting since the system counts the scratches in milliseconds right after feeding the phone to the system and the system gives the user a result in GUI thereafter.

Test 3. In the third test, the author utilized an iPhone XS model display that exhibited a total of five noticeable scratches across its surface. These scratches varied in length, and position, representing a challenging scenario for the system to accurately detect and analyze. The purpose of this test was to evaluate the program's ability to effectively identify and assess multiple scratches simultaneously. By introducing a range of scratches, the author aimed to simulate real-world conditions where displays may undergo wear and tear. This test aimed to validate the system's capability to handle complex scratch patterns and provide accurate feedback to the user. By subjecting the GUI to this rigorous testing scenario, the author aimed to ensure that the system could reliably and efficiently detect and classify scratches, enhancing the overall usability and effectiveness of the graphical interface.

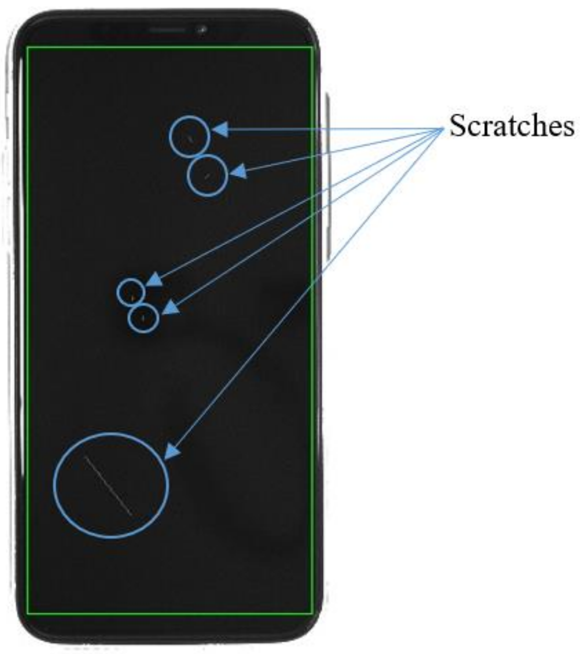

Figure 5.10 iPhone XS model phone with 5 scratches on its display

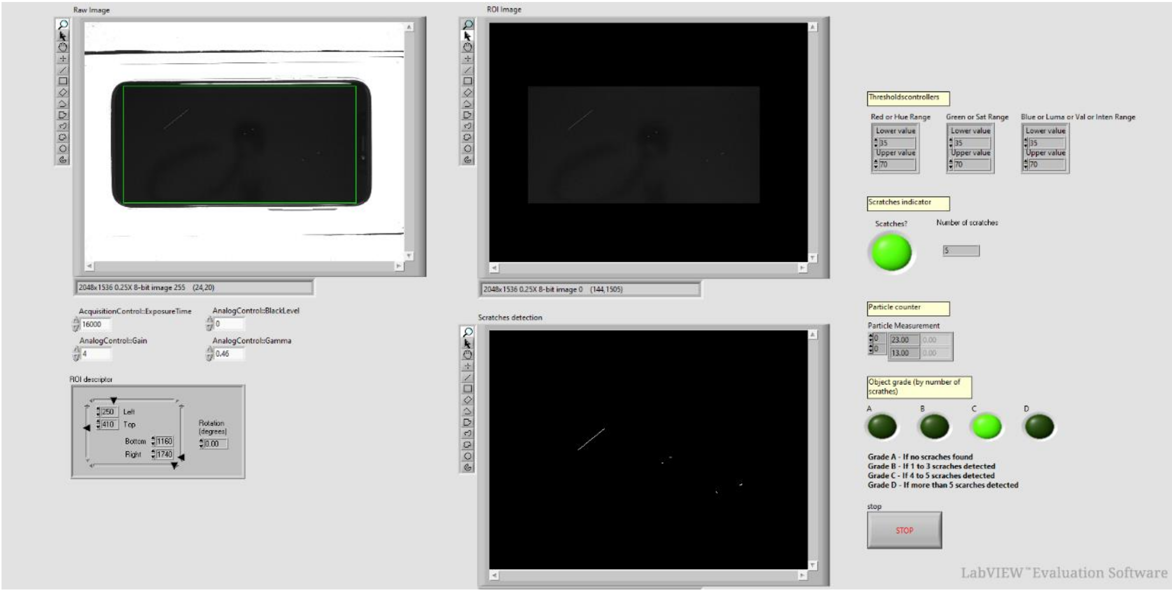

Figure 5.11 Screenshot from the software when the program grade the display as grade C

In the third test, the author used an iPhone XS model display that had 5 scratches on it. On this display, except for only one scratch, all the other scratches are quite small and even hard to recognize by the human eye without changing its holding position and lighting angles. But as in the previous test, the system detected all the large and tiny scratches in a millisecond right after feeding the phone to the system. In this test, the author spent only 8 seconds feeding the phone to the system which means over time, an operator will adapt to the system process and the operator's ability and speed to feed the phone to the system will be considerably increased. There is nothing changed in the setup control settings except the ROI. Since this test phone is a bit bigger than previously used iPhone 8 models, the operator has to change the ROI accordingly to the size of the display. After adjusting the ROI, all other settings were kept the same as in the previous tests.

Test 4. The fourth test aimed to assess the system's response to dust particles and other marks on the display that are not scratched. Using the same display as in the first test, the author intentionally introduced additional dust particles onto the surface. By doing so, the author aimed to evaluate the system's ability to differentiate between scratches and other types of imperfections accurately.

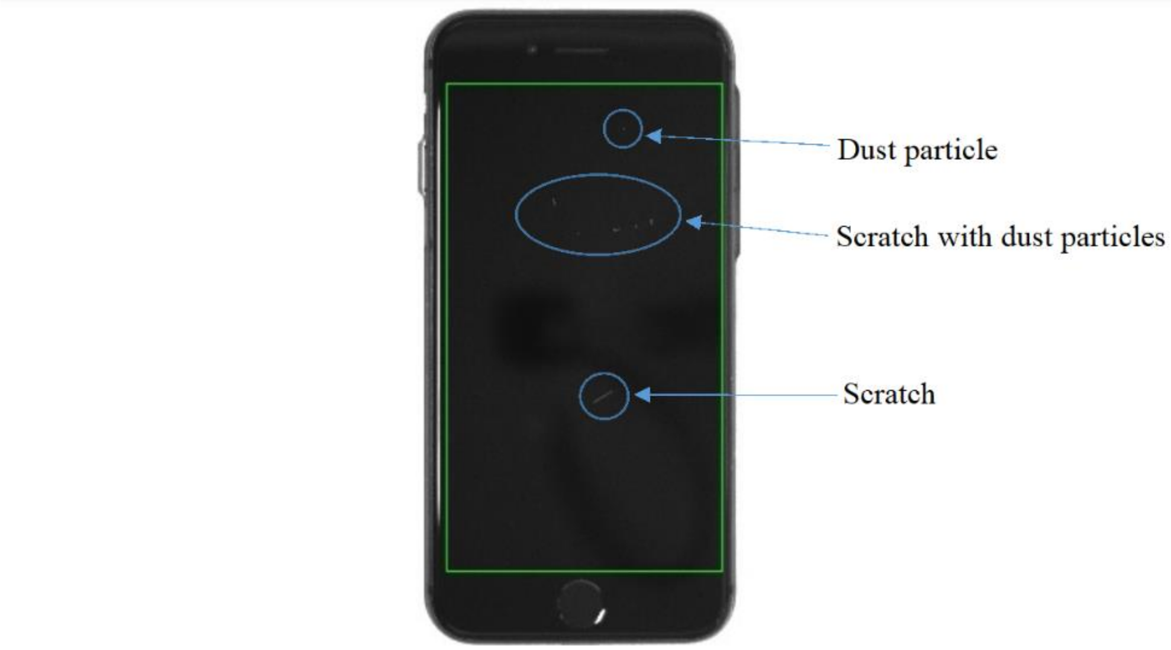

Figure 5.12 iPhone 8 model phone with more than 5 scratches (including dust particles) on the display

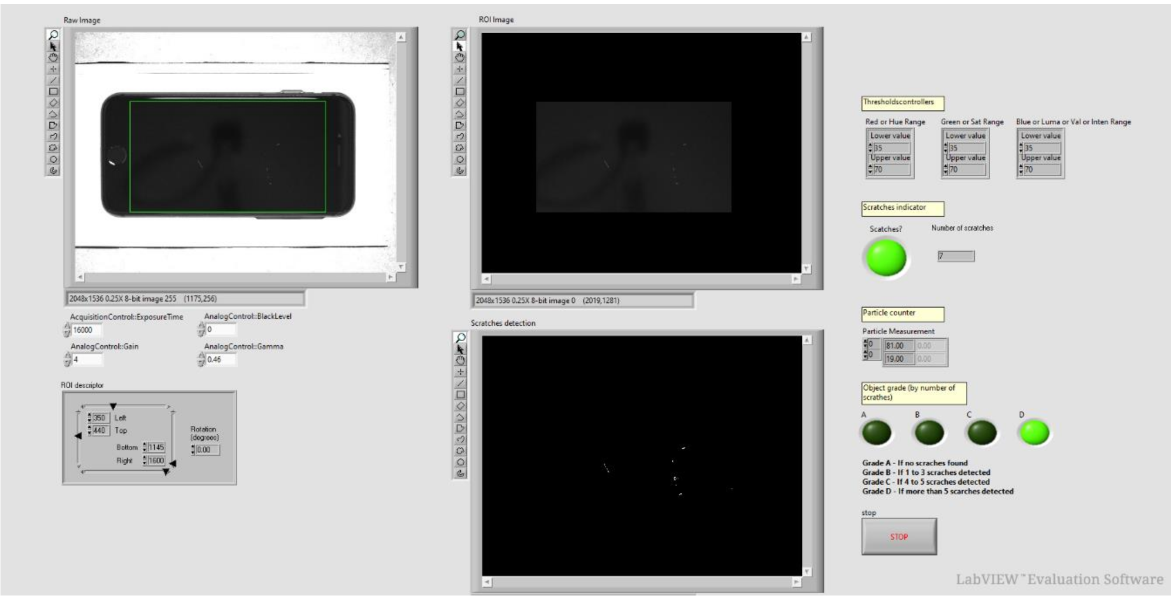

Figure 5.13 Screenshot from the software when the program grade the display as grade D

In this test, the author purposely added some dust particles to the first test display and tested how the system behaves for the dust particles. According to the behavior of the system, the LED diffused lights illuminated all the dust particles, and it graded the display as a grade D display. The idea is when feeding a phone to the system, the operator must thoroughly check for any unwanted dust particles or fingerprints on the displays. If it is so, the grading of the system will be inaccurate. In this fourth test, the author used the same ROI which was used previously for iPhone 8 model displays and the feeding time was 8 seconds.

5.3 Calculations of the efficiency and the accuracy of the system

In this section, the author wanted to understand how long it takes for a random person to count scratches on a cell phone display with their naked eye. To do this, the author found 10 random people nearby and timed each person's performance in seconds. By doing this for multiple people, then the author was able to calculate the average time it takes for a person to count the scratches. But that's not all the author wanted to know. The author also wanted to understand how accurate people are at counting scratches. So, the author used the same method for multiple cell phone displays and calculated the accuracy of each person's counting.

Finally, using these measurements, the author was able to estimate how long a typical manual user would take to count the scratches on a cell phone display, and how accurate they would be. This information can be useful for understanding the challenges faced by manual quality control processes in manufacturing, or for improving the design of interfaces for automated scratch-counting tools.

Table 5.2 The details of the complete time and accuracy of manual counting by 10 random persons

No	Name of the tester	Location	First sample		Second sample		Third sample	
			Time for the counting (s)	accuracy of the counting (1/0)	Time for the counting (s)	accuracy of the counting (1/0)	Time for the counting (s)	accuracy of the counting (1/0)
1	Mart	NRG building	204	0	93	0	138	1
2	Kati	NRG building	176	0	82	1	116	1
3	Kristjan	NRG building	154	1	114	1	76	1
4	Liina	NRG building	234	0	134	1	148	0
5	Jaan	NRG building	200	0	110	0	122	1
6	Anu	NRG building	216	1	114	0	109	1
7	Marko	NRG building	249	1	124	1	150	0
8	Tiina	NRG building	190	1	135	0	100	1
9	Tõnis	NRG building	199	0	79	1	144	1
10	Kadri	NRG building	149	1	82	0	109	1
Total			1971 sec.	50%	1067 sec.	50%	1212 sec.	80%

Table 5.3 The details of the complete time and accuracy of the systems' counting

No	Name of the tester	Location	First sample		Second sample		Third sample	
			Time for the countin g (s)	accuracy of the counting (1/0)	Time for the counting (s)	accuracy of the counting (1/0)	Time for the counting (s)	accuracy of the counting (1/0)
1	The system	NRG building	8	1	8	1	8	0
2	The system	NRG building	7	0	10	1	8	1
3	The system	NRG building	10	1	10	1	9	1
4	The system	NRG building	8	1	8	1	10	1
5	The system	NRG building	9	1	9	1	8	1
6	The system	NRG building	9	1	9	1	9	1
7	The system	NRG building	9	1	9	1	8	1
8	The system	NRG building	9	1	9	1	8	1
9	The system	NRG building	9	1	9	1	10	1
10	The system	NRG building	9	1	9	1	9	1
Total			87 sec.	90%	90 sec.	100%	87 sec.	90%

By analysing both above tables, The author identified the following equations to find the average time to grade a cell phone display in both ways manually and by an automated system

$$X_1 = \frac{(A + B + C)}{D} \tag{5.1}$$

$$X_1 = \frac{(1971 + 1067 + 1212)}{30}$$

$$X_1 = 141.66\ s$$

$$X_2 = \frac{(A_1 + B_1 + C_1)}{D_1} \tag{5.2}$$

$$X_2 = \frac{(87 + 90 + 87)}{30}$$

$$X_2 = 8.8\ s$$

Where X_1 – Average scratch counting time by random persons, s,

X_2 – Average scratch counting time by the system, s,

A – Total scratch counting time by persons for the first sample display, s,

A_1 – Total scratch counting time by the system for the first sample display, s,

B – Total scratch counting time by persons for the second sample display, s,

B_1 – Total scratch counting time by the system for the second sample display, s,

C – Total scratch counting time by persons for the second sample display, s,

C_1 – Total scratch counting time by the system for the second sample display, s,

D – Number of sample displays being inspected, nos.

To determine the efficiency of the automated system compared to a human grader, the user can calculate the percentage of time saved by the automated system. The time saved by the automated system is obtained by subtracting the time taken by the human from the time taken by the automated system. For this calculation, the following formula can be utilized:

$$Y = E - F \tag{5.3}$$

Where, Y = The time saved, s,

E = The time taken by human graders, s,

F = The time taken by an automated system, s.

$$Y = 141.667 - 8.8$$

$$Y = 132.867\ s$$

Now, the user can calculate the efficiency of the automated system as follows:

$$Z = \frac{Y}{X_1} \cdot 100\% \tag{5.4}$$

Where Z = Efficiency, %.

$$Z = \frac{132.867}{141.667} \cdot 100\% = 93.85\%$$

Therefore, the efficiency of the automated system compared to a human grader is approximately **93.85%**

For finding the accuracy user can use the following formula:

$$J_1 = \frac{(L + M + N)}{O} \tag{5.5}$$

$$J_2 = \frac{(L_1 + M_1 + N_1)}{O} \tag{5.6}$$

Where, J_1 – Average accuracy of counting on the sample displays by humans, %,

J_2 – Average accuracy of counting on the sample displays by the system, %,

L – Accuracy of scratch counting by persons for the 1st sample display, %,

L_1 – Accuracy of scratch counting by the system for the 1st sample display, %,

M – Accuracy of scratch counting by persons for the 2nd sample display, %,

M_1 – Accuracy of scratch counting by the system for the 2nd sample display, %,

N – Accuracy of scratch counting by persons for the 3rd sample display, %,

N_1 – Accuracy of scratch counting by the system for the 3rd sample display, %,

O – Number of sets of sample displays being inspected, nos.

$$J_1 = \frac{(50\% + 50\% + 80\%)}{3} = 60\%$$

$$J_2 = \frac{(90\% + 100\% + 90\%)}{3} = 93\%$$

The accuracy of the automated system compared to a human grader can be found by calculating the percentage improvement in the accuracy of the automated system over the human grader. This can be achieved using the formula:

$$K = \frac{(J_2 - J_1)}{J_1} \cdot 100\% \quad (5.7)$$

Where K = Accuracy of the automated system compared to a human grader, %.

$$K = \frac{(0.93 - 0.6)}{0.6} \cdot 100\% = 55\%$$

Therefore, the accuracy of the automated system compared to a human grader is approximately **55%** better.

6 DISCUSSION AND FUTURE PLANS

6.1 Discussion of the findings and their implications

The findings from the evaluation of the machine vision system for scratch detection on cell phone displays reveal compelling advantages over traditional human grading methods. The first notable finding pertains to the time taken to grade a display. The automated system demonstrates remarkable efficiency, requiring only 8.8 seconds per display compared to an average of 141.7 seconds for a human grader. This translates to a substantial time-saving of approximately 132.9 seconds per display. Such a significant reduction in grading time has profound implications for streamlining quality control processes in manufacturing.

In addition to the time-saving aspect, the second finding highlights the accuracy of grading displays. While human graders achieve an average accuracy of approximately 60%, the automated system achieves an impressive accuracy rate of 93%. This indicates a remarkable improvement in accuracy of approximately 55% when employing the machine vision system. The superior accuracy of the automated system is a significant advantage as it reduces the risk of errors in grading and ensures a higher quality of finished products.

These findings underscore the transformative potential of the machine vision system in the context of grading displays for mobile phones. By significantly reducing the time and effort required for quality control processes, manufacturers can achieve increased productivity and operational efficiency. The speed and accuracy of the automated system enable manufacturers to handle larger volumes of displays while maintaining consistent quality standards.

Moreover, the higher accuracy offered by the machine vision system mitigates the subjectivity and variability associated with human grading. This not only improves the reliability of the grading process but also enhances customer satisfaction by delivering consistently accurate and reliable products. The implementation of the machine vision system in the manufacturing industry has wider implications for the overall production cycle and the circular economy. The efficiency gains realized through the system's faster grading process allow manufacturers to optimize their resources and reduce costs. This aligns with the principles of sustainability and waste reduction, as it enables the reuse and recycling of cell phone displays, contributing to a more sustainable and eco-friendly manufacturing approach.

However, it is important to acknowledge that the successful implementation of the machine vision system relies on robust hardware and software components. The utilization of LabVIEW software, JAI GoX 3201M USB camera, M2514-SW Computar lens, and LED diffused lights underscores the importance of leveraging advanced technologies to achieve accurate and efficient scratch detection.

Furthermore, the use of 30 x 30 mm aluminum profiles and HDF boards for the prototype construction showcases the significance of appropriate material selection in creating a reliable and stable system. These choices contribute to the durability and performance of the machine vision system, ensuring its effectiveness in a real-world manufacturing environment. The discussion of the findings emphasizes the transformative impact of the machine vision system for scratch detection on mobile phone displays. The system's superior efficiency, accuracy, and potential for scalability offer substantial benefits to manufacturers, including reduced grading time, enhanced product quality, increased productivity, and sustainable manufacturing practices. By embracing automated grading processes, manufacturers can elevate their operations, deliver high-quality products, and contribute to a more efficient and environmentally conscious circular economy.

Table 6.1 Parameters of the prototype

Parameter	**Achieved value**
Length of the frame, mm	400
Width of the frame, mm	400
Height of the frame, mm	872
Approximate weight of the setup, kg	9.75
Working distance of the camera, mm	695 ± 5
Proper angle of the lighting, ^{0}	67.5
Top speed per display grading, s	8.8
Accuracy of the grading, %	93

6.2 Further research directions and recommendations

The author employed the LabView program for image processing in the current system, primarily due to its user-friendly nature and its use of visual programming language. LabView is a helpful tool for those who may have logical thinking skills but lack coding expertise. However, the author recommends considering the use of other image processing software such as MATLAB or openCV in the future, as they offer the same features in image processing and capabilities but in the coding environment.

In the current system, the operator is responsible for manually defining the Region Of Interest (ROI) by entering specific values into the ROI descriptor. This process requires the operator to input the coordinates or dimensions of the area of interest on the cell phone display. However, this manual definition of the ROI can be time-consuming and prone to human error. To address this issue, the author proposes enhancing the program by implementing an automated method for defining the ROI. This can be achieved by incorporating a feature that allows users to select the appropriate phone model from a list of available phone models. Once the phone model is selected, the program would automatically determine the ROI based on the predefined dimensions and specifications associated with that particular phone model. By automating the ROI definition process, the program eliminates the need for manual entry and reduces the effort required from the operator. This not only improves the efficiency of the grading process but also reduces the chances of errors or inconsistencies in defining the ROI. With the automated ROI definition, users can expect a more streamlined and user-friendly experience when using the system. The program will provide accurate and standardized ROI settings based on the selected phone model, ensuring consistent and reliable grading results. Overall, the proposed development of an automated ROI definition feature in the program simplifies the operator's tasks, improves efficiency, and enhances the accuracy of the grading process. By leveraging phone model information, the program eliminates the need for manual input, reducing potential errors and saving valuable time during the evaluation of cell phone displays.

In the current setup, the user's ability is limited to manually counting the number of scratches on cell phone displays. The grading of the displays is then determined based on these counted numbers. However, this method may have its limitations and may not provide the most precise and detailed assessment of the scratches present. To address this limitation, the author suggests the development of a program or algorithm that can accurately calculate the number of pixels associated with each scratch on the display. By analyzing the pixels, which are the smallest units of an image, a more precise measurement of the scratch's size and extent can be obtained. By incorporating pixel calculations into the system, a more sophisticated and data-driven approach can be adopted for evaluating the condition of cell phone displays. This enhanced approach can potentially provide better and more detailed output regarding the severity and distribution of scratches on the screen. By having a program that calculates the pixels of each scratch, the system can capture finer details and nuances that may be missed by a simple manual count. This pixel-based analysis enables a more comprehensive understanding of the scratches, allowing for more accurate grading and assessment of the display's condition. Overall, the proposed development of a program to calculate the pixels of each scratch aims to enhance the accuracy and reliability of the system in evaluating and grading cell phone displays. By leveraging advanced image processing techniques and precise pixel measurements, the system can provide users with more comprehensive and informative output, facilitating better decision-making regarding the reuse, repair, or replacement of cell phone displays within the circular economy framework.

In the current system, a significant challenge arises due to the presence of dust particles inside the enclosure, which can adversely impact the accuracy of the scratch detection process. Recognizing this issue, the author proposes a solution to address the problem of dust accumulation. To mitigate the impact of dust particles, the author suggests utilizing aluminum sheets for the enclosure cover. Aluminum sheets have favorable properties that make them effective in preventing dust from entering the system. By using aluminum sheets, the system can create a barrier that helps to minimize the entry of dust particles into the enclosure, thereby reducing the chances of interference with the scratch detection process. In addition to the use of aluminum sheets, the author recommends the installation of exhaust fans within the system. These fans would be strategically positioned to blow out the dust particles from the workpiece area. By creating a controlled airflow, the exhaust fans facilitate the removal of dust particles, ensuring a cleaner environment for the scratch detection process. Implementing the suggested measures, such as aluminum sheets and exhaust fans, offers several benefits. Firstly, it improves the overall ventilation within the system, effectively reducing the concentration of dust particles and enhancing the air quality. Additionally, the installation of exhaust fans helps in dissipating heat generated by the lights used in the system. When the system operates for extended periods, the lights can generate significant heat, which may adversely affect the performance and longevity of the system. By actively removing the heat through the exhaust fans, the system can maintain optimal temperature levels, promoting efficient operation and prolonging the lifespan of the equipment. In summary, incorporating aluminum sheets for the enclosure cover and installing exhaust fans are recommended solutions to tackle the challenge of dust particles in the current system. These measures enhance the ventilation within the system, minimize dust accumulation, and effectively manage the heat generated during operation. By implementing these recommendations, the system can maintain a cleaner environment for accurate scratch detection and ensure optimal performance and longevity of the equipment.

7 CONCLUSION

The evaluation of the machine vision system for scratch detection on cell phone displays reveals compelling advantages over traditional human grading methods. The system demonstrates remarkable efficiency, grading a display in only 8.8 seconds compared to an average of 141.7 seconds for a human grader, resulting in a time-saving of approximately 132.9 seconds per display. Additionally, the system achieves an impressive accuracy rate of 93%, a substantial improvement over the average 60% accuracy achieved by human graders.

These findings highlight the transformative potential of the machine vision system in grading displays for mobile phones. Manufacturers can achieve increased productivity and operational efficiency by reducing the time and effort required for quality control processes. The system's speed and accuracy enable manufacturers to handle larger volumes of displays while maintaining consistent quality standards.

The higher accuracy offered by the machine vision system mitigates subjectivity and variability, improving the reliability of the grading process and enhancing customer satisfaction. The implementation of the system in the manufacturing industry has broader implications for the production cycle and the circular economy. By optimizing resources and reducing costs, manufacturers can align with sustainability principles, contributing to a more eco-friendly manufacturing approach through the reuse and recycling of cell phone displays.

It's important to acknowledge that the successful implementation of the machine vision system relies on robust hardware and software components, including LabVIEW software, JAI GoX 3201M USB camera, M2514-SW Computar lens, and LED diffused lights. The choice of materials, such as aluminum profiles and HDF boards, also contributes to the system's durability and performance in a real-world manufacturing environment.

Overall, the machine vision system offers substantial benefits to manufacturers, including reduced grading time, enhanced product quality, increased productivity, and sustainable manufacturing practices. By embracing automated grading processes, manufacturers can elevate their operations, deliver high-quality products, and contribute to a more efficient and environmentally conscious circular economy.

8 KOKKUVÕTE

Mobiiltelefonide ekraanidel kriimustuste tuvastamiseks mõeldud masinnägemissüsteemi hindamisel tulid välja kaalukad eelised võrreldes traditsiooniliste inimeste hindamismeetoditega. Süsteem on tähelepanuväärselt tõhus, hinnates ekraani vaid 8,8 sekundiga, võrreldes inimesest hindaja keskmise 141,7 sekundiga. Selle tulemuseks on ajasäästumbes 132,9 sekundit iga ekraani kohta. Lisaks on süsteemil muljetavaldav 93%-iline täpsus, mis on märkimisväärselt parem inimesest hindajate keskmisest 60%-ilisest täpsusest.

Need leiud toovad selgelt välja masinnägemissüsteemi revolutsioonilise potentsiaali mobiiltelefonide ekraanide hindamise paremaks muutmisel. Tootjad saavad suurendada tootlikkust ja töö efektiivsust, vähendades kvaliteedikontrolli protsessidele kuluvat aega ja vaeva. Süsteemi kiirus ja täpsus võimaldavad tootjatel käidelda ekraane suuremates mahtudes, säilitades samal ajal ühtlased kvaliteedistandardid.

Masinnägemissüsteemi suurem täpsus vähendab subjektiivsust ja varieeruvust, parandades hindamisprotsessi usaldusväärsust ja suurendades klientide rahulolu. Süsteemi juurutamisel töötlevas tööstuses on laiem mõju tootmistsüklile ja ringmajandusele. Ressursside optimeerimise ja kulude vähendamise kaudu saavad tootjad senisest enam järgida jätkusuutlikkuse põhimõtteid. Kasutatud mobiiltelefonide ekraanide korduvkasutamise ja ringlussevõtu kaudu saab muuta tootmise keskkonnasõbralikumaks.

Masinnägemissüsteemi juures on oluline arvesse võtta, et selle rakendamise edukus sõltub tugevatest riist- ja tarkvarakomponentidest, sealhulgas LabVIEW tarkvarast, JAI GoX 3201M USB-kaamerast, M2514-SW Computar objektiivist ja LED-hajutatud tuledest. Materjalide valik, nagu alumiiniumprofiilid ja HDF-plaadid, aitab samuti kaasa süsteemi vastupidavusele ja suurele jõudlusele reaalses tootmiskeskkonnas.

Kokkuvõttes pakub masinnägemissüsteem tootjatele märkimisväärseid eeliseid, sealhulgas lühendatud hindamisaega, paremat kvaliteeti, suuremat tootlikkust ja jätkusuutlikust. Kasutades automatiseeritud liigitusprotsesse, saavad nad oma tootmise muuta efektiivsemaks, tarnida kõrge kvaliteediga tooteid ning panustada ringmajanduse veelgi tõhusamaks ja keskkonnateadlikumaks muutmisse.

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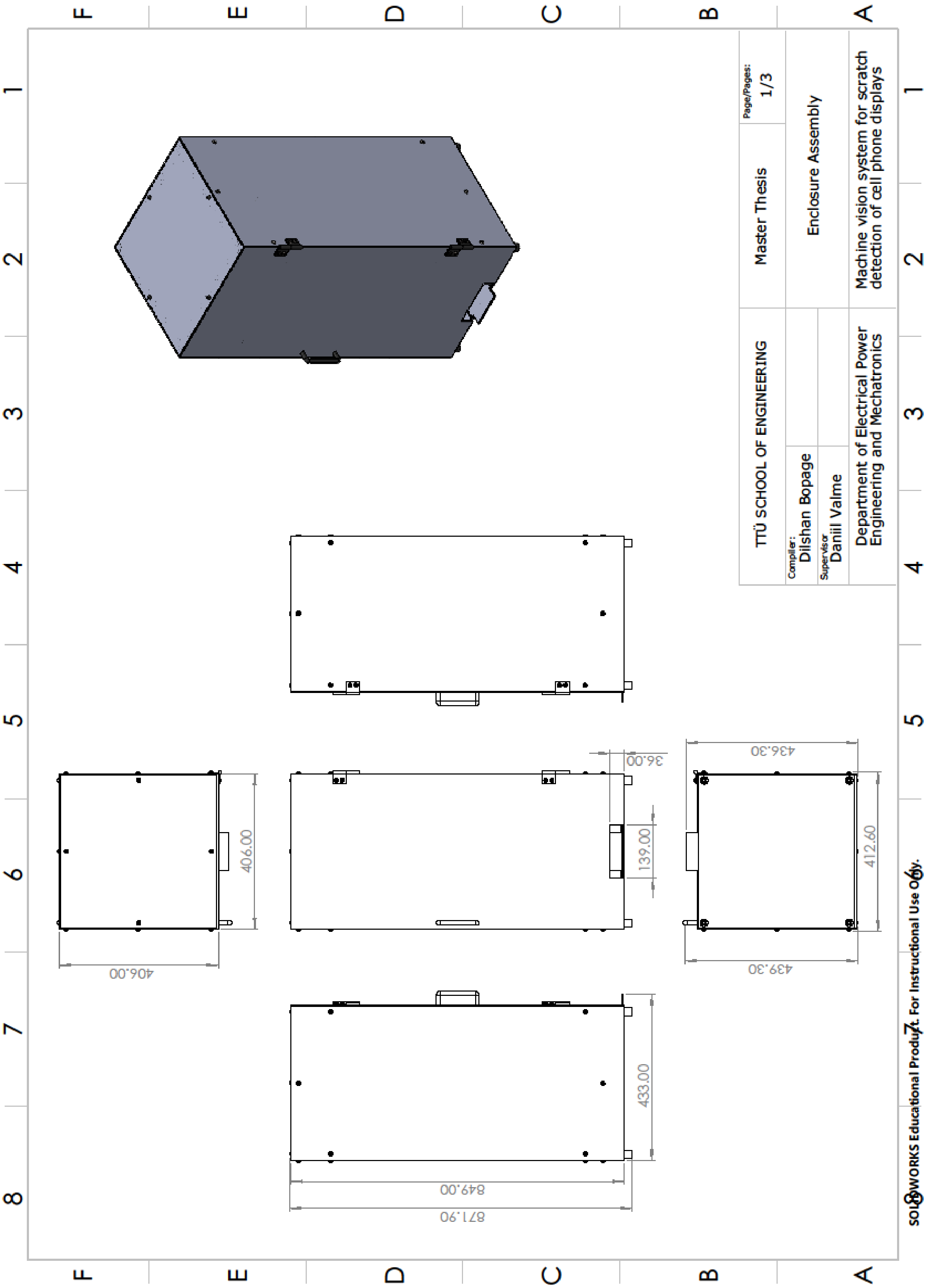
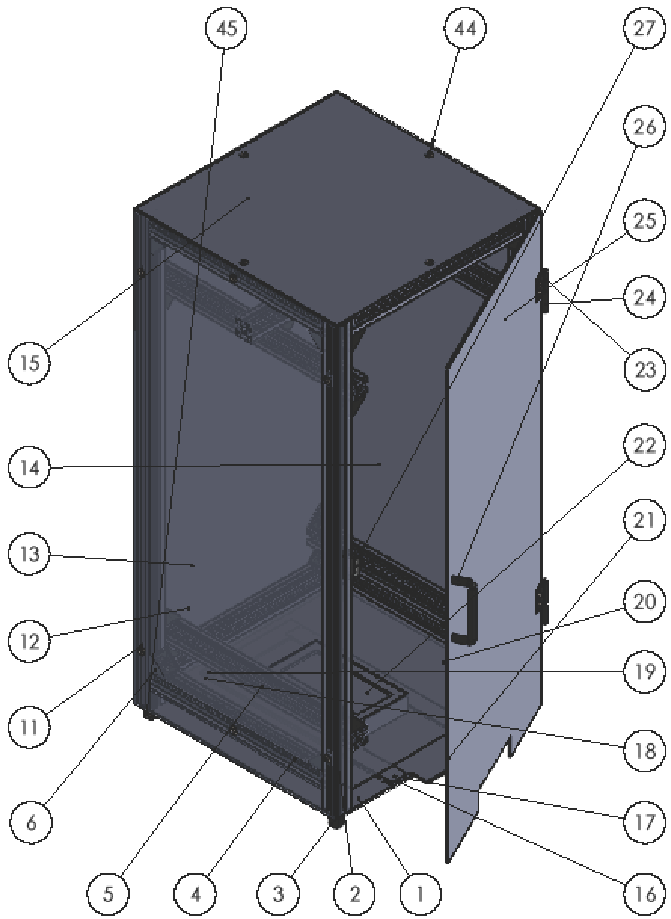
APPENDICES

Appendix 1 – Drawing of the assembled enclosure



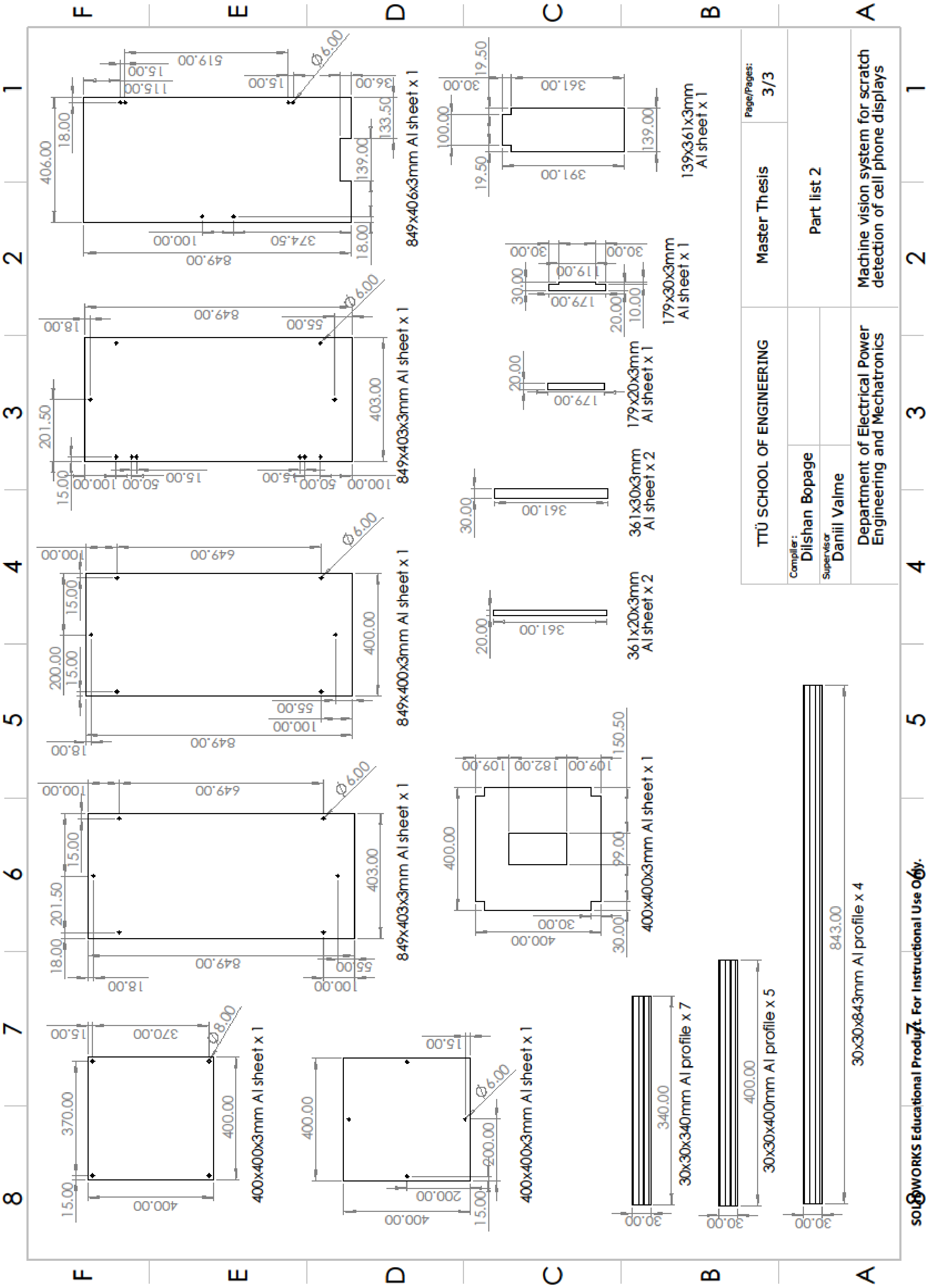
Appendix 2 – Drawing of the assembled enclosure



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	400x400x3mm sheet	For the bottom plate	1
2	30x30x843mm Al profile	For the vertical column	4
3	Bottom nob	3D printed plastic nobs	4
4	30x30x340mm Al profile	For the horizontal column	7
5	30x30x400mm Al profile	For the component mount	5
6	Mounting angles with screws	Mounting angle 30 GD-Z (Article Nr. 21.0905/0)	24
11	Fastning profile	3D printed plastic profile	22
12	849x403x3mm sheet	For the side cover_L	1
13	849x400x3mm sheet	For the back cover	1
14	849x403x3mm sheet	For the side cover_R	1
15	400x400x3mm sheet	For the top cover	1
16	20x361x3mm sheet	Guiding strip 1	2
17	30x361x3mm sheet	Guiding strip 2	2
18	20x179x3mm sheet	Guiding strip 3	1
19	30x179x3mm sheet	Guiding strip 4	1
20	400x400x3mm sheet	For the bottom base	1
21	139x361x3mm sheet	For the sliding panel	1
22	Work base	-	1
23	Hing P2	3D printed plastic profile for hinge	2
24	Hing P1	3D printed plastic profile for hinge	2
25	849x406x3mm sheet	For the door	1
26	Handle	3D printed plastic profile for handle	1
27	Magnet	Magnetic catch (Article Nr. 21.1753/0)	1
44	ISO 7380 - M6 x 10 - 10N	M6x10mm hex socket button head screws	32
45	ISO 4762 M8 x 25 - 25N	M8x25mm hex socket head screws	4

TTÜ SCHOOL OF ENGINEERING	Master Thesis	Page/Pages: 2/3
Compiler: Dilshan Bopage Supervisor: Daniil Valme	Part list 1	
Department of Electrical Power Engineering and Mechatronics	Machine vision system for scratch detection of cell phone displays	

Appendix 3 – Drawing of the parts of the enclosure



computar

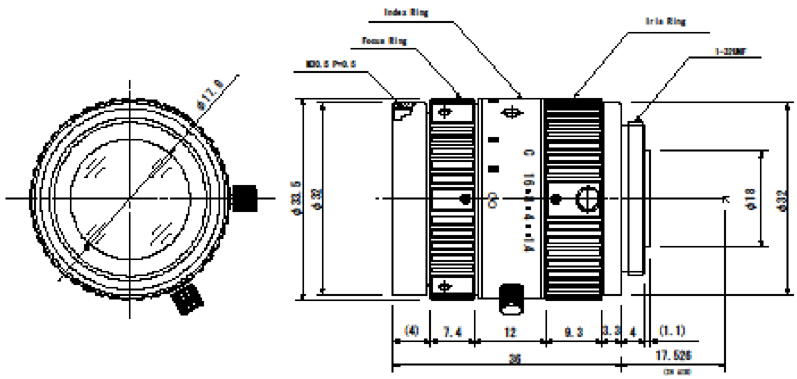
M2514-SW

f=25mm F/1.4
for 2/3 type SWIR (800nm~1700nm) Cameras
C-Mount

Model No.		M2514-SW		Effective	Front	φ 17.8mm	
Focal Length		25mm		Lens Aperture	Rear	φ 12.0mm	
Max. Aperture Ratio		1:1.4		Distortion	2/3type	-0.5% (y=5.5)	
Max. Image Circle		φ 12.3mm			1/2type	-0.2% (y=4.0)	
Operation Range	Iris	F1.4 - F16C		Back Focal Length		13.4mm	
	Focus	0.3m - Inf.		Flange Back Length		17.526mm	
Control	Iris	Manual		Mount		C-Mount	
	Focus	Manual		Filter Size		M30.5 P=0.5mm	
Object Dimension	2/3 type	10.5cm x 7.8cm		Dimensions		φ 33.5mm x 36mm	
at M.O.D	1/2 type	7.6cm x 5.7cm		Weight		71.2g	
Angle of View	D	2/3 type	24.7°	1/2 type	18.1°		
	H	H8.80mm x V6.60mm	19.8°	H6.40mm x V4.80mm	14.5°		
	V		14.9°		10.9°		
Angle of View	D	640 x 512	27.6°	320 x 256	23.0°	320 x 256	18.5°
(InGaAs Detector)	H	(Pixel Pitch : 15 μm)	21.6°	(Pixel Pitch : 25 μm)	18.1°	(Pixel Pitch : 20 μm)	14.5°
	V	H9.60mm x V7.68mm	17.3°	H8.00mm x V6.40mm	14.5°	H6.40mm x V5.12mm	11.6°
Operating Temperature		-10℃ - +50℃					

M.O.D : Minimum Object Distance

Dimensions



Specification is subject to change without any notice.

2015.02

Appendix 5 – Datasheet of GoX-3201-USB camera

▪ 2048 x 1536 ▪ 55 fps

Go-X Series

GOX-3201-USB

3.2-megapixel CMOS global shutter

USB3 VISION

- *Go-X Series delivers exceptional combination of price and performance*
- *3.2-megapixel, 1/1.8" CMOS imager (global shutter)*
- *Up to 55 fps at full resolution (2048 x 1536)*
- *3.45 µm square pixels*
- *8/10/12-bit* output in choice of monochrome or raw Bayer color models*
- *ROI settings for added flexibility*
- *Horizontal/vertical image flip function, plus blemish correction and shading compensation*
- *Includes Sequencer function and Automatic Level Control (ALC) for dynamic lighting conditions*
- *Compact size with excellent shock and vibration resistance*
- *Accepts power over USB3 Vision interface or via separate 6-pin connector*
- *C-mount lens mount*

* Not all processing functions supported with 12-bit output

www.jai.com

See the possibilities

Specifications for GOX-3201-USB

Go-X Series

Specifications	GOX-3201-USB
Sensor	1/1.8" CMOS global shutter (IMX265)
Active pixels	2048 (h) x 1536 (v)
Frame rate, full frame	55 frames/sec. @ 8-bit mono/Bayer
Active area	7.07 mm (h) x 5.3 mm (v) - 8.83 mm diagonal
Pixel size	3.45 µm x 3.45 µm
System clock	74.25 MHz (for pulse generator)
Read-out modes Full ROI (single) Binning	 2048 (h) x 1536 (v) up to 55 fps H: 96 to 2032 pixels in 16 pixel steps V: 8 to 1534 lines in 2 line steps 1x2, 2x1, 2x2
EMVA 1288 Parameters Absolute sensitivity Maximum SNR	10-bit output format Mono: 3.29 p Color: 3.59 p (λ = 527 nm) Mono: 39.7 dB Color: 39.7 dB
Traditional SNR*	>60 dB mono, >60 dB color (0 dB gain, 10-bit)
Video signal output	Monochrome: 8/10/12-bits† Color: 8/10/12-bit Bayer†
Gain	Manual/auto 0 dB to +42 dB
White balance	Off, presets, or one-push/continuous AWB
Gamma/LUT	0.45 to 1.0 (9 steps) or 257-point programmable LUT
Synchronization	Internal
Video modes	Normal/Single ROI, Sequencer (Trigger & Command)
Trigger input	Opto In, Pulse Generators (4), Software, NAND Out (2), User Output (4)
Exposure modes	Timed/EPS, RCT, Trigger Width, Auto
Electronic shutter	Timed: 14.73 µs to 8 sec. in 1 µs steps Auto: 100 µs to 18.1 ms at full resolution
Auto Level Control (ALC)	Shutter range from 100 µs to 18.1 ms, gain range from 0 dB to +42 dB. Tracking speeds and max. values adjustable.
Shading correction	Flat shading, color shading (color model)
Pre-processing functions	H & V flip (mirroring), blemish compensation, H & V decimation
Operating temp. (ambient)	-5°C to +45°C (20 to 80% non-condensing)
Storage temp. (ambient)	-25°C to +60°C (20 to 80% non condensing)
Vibration	10G (20 Hz to 200 Hz, XYZ directions)
Shock	80G
Regulations	CE(EN 55032:2015(CISPR32:2015), EN 55035:2017(CISPR35:2016)), FCC Part 15 Class A, RoHS/WEEE, KC
Power 6-pin USB 3.0	+10V to +25V DC. 4.3 W typical @ +12 V +5V DC. 4.2 W typical @ +5 V
Lens mount	C-mount
Dimensions (H x W x L)	29 mm x 29 mm x 51.5 mm
Weight	62 g

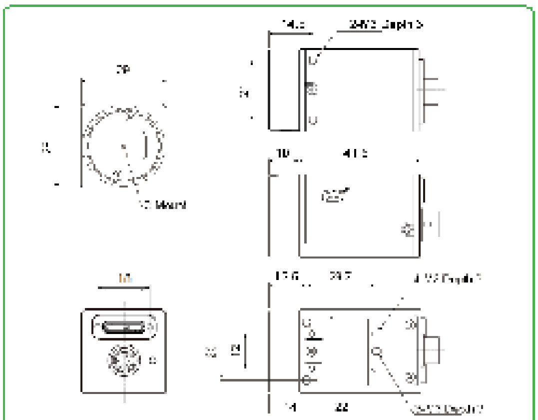
Ordering Information

GOX-3201M-USB	Monochrome camera with USB3 Vision Interface
GOX-3201C-USB	Color camera with USB3 Vision Interface

*Traditional SNR is based on random noise in a single frame, where EMVA SNR measurements consider more comprehensive noise sources and variance over time.

†12-bit output available in video processing bypass mode. See manual for details.

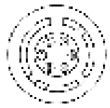
Dimensions



Outside size tolerance ± 0.3 mm

Connector pin-out

DC In / Trigger



HIROSE HR10A-7R-6PB(73)

Pin	
1	DC In +10V to +25V
2	Opto In+
3	Opto In-
4	Opto Out+
5	Opto Out-
6	Ground

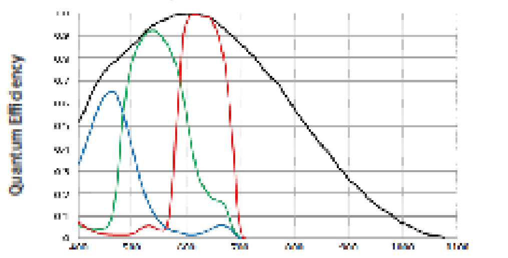
USB 3.0 Interface

Micro B type - ZX3600-B-10P or equiv.

No.	I/O	Name	Note
1	I	VBUS IN	Power (VBUS)
2	I/O	DM	USB2.0 Differential pair (-)
3	I/O	DP	USB2.0 Differential pair (+)
4		OTG ID	USB OTG ID for identifying lines
5		GND	GND
6	O	FX3 SSTXM	USB3.0 Signal Transmission line (-)
7	O	FX3 SSTXP	USB3.0 Signal Transmission line (+)
8		GND	GND
9	I	FX3 SSRXP	USB3.0 Signal Receiving line (-)
10	I	FX3 SSRXM	USB3.0 Signal Receiving line (+)

Spectral Response

(Relative response - monochrome and color not correlated)



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