Raw Material Detection System for Rock Crushers

Master's thesis in Product Development

GUSTAV KOLLEBY
JACOB LARSSON

Department of Industrial and Materials Science
Chalmers University of Technology
Gothenburg, Sweden 2018

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JACOB LARSSON

Supervisors: Anton Bolander, Roctim AB
Dr. Erik Hultén, Department of Industrial and Material Science
Examiner: Dr. Erik Hultén, Department of Industrial and Material Science

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Department of Industrial and Materials Science
Division of Product Development
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: View down into a jammed jaw crusher at NCC Tagene.

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GUSTAV KOLLEBY
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Abstract

Equipment utilization is an important aspect of any crushing operation. Not only is this an important factor for increasing production yield and profit, but also to reduce the resources consumed when operating the equipment. In particular, the thesis aims to improve utilization of primary jaw crushers used in the aggregate industry by means of state-of-the-art technologies and methods. Presented in the thesis are novel concepts aimed to reduce down-time and increase yield of the crusher while creating customer value throughout the crushing process.

From competitor studies, on-site studies, concept development and evaluation, an idea is taken to the prototyping stage and tested in a real-world environment at a Swedish aggregate plant. The thesis covers the development of both hardware aspects of the proposed concepts as well as software methods to achieve improvements of the primary crushing process.

By leveraging today's inexpensive, robust and high-performance embedded computing systems and imaging technologies, the prototype showed great potential in gathering data of the the primary crushing process. In particular, the prototype was able to successfully identify material flow and material size, two very important aspects of this crushing stage, with an accuracy of 100% and 45% respectively.

Keywords: Raw, Material, Detection,System, Rock, Crushers, Embedded, Stereo, Vision, Segmentation.

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Gustav Kolleby, Jacob Larsson, Gothenburg, August 2018

Contents

1

Introduction

This chapter aims to introduce the thesis problem including its background and scope of the issue at hand. Furthermore, valuable hypothesis are presented in the problem formulation which are to be answered in the thesis.

1.1 Background

Roctim AB is a Swedish company that focuses on optimization and control of the rock crushing process and the rock crushers themselves, in order to increase the production yield and efficiency. They offer complete solutions for the entire rock crushing process regarding control and monitoring systems. One area that the company sees a need in, is the monitoring and detection of raw material fed in to the crusher. As such, there is a possibility of using new technologies to solve such tasks, which has the potential to reduce down time of crushers and thus increase their efficiency.

1.2 Aim and Vision of the Project

The aim of this project is to develop a vision based detection system for a primary jaw crusher. The system will be able to identify if there is a rock causing a jam of the crusher and then send an alert signal that there is an issue with the production. It will be able to identify individual rocks, measure the flow rate and estimate their size. This will then be used for statistical purposes and to predict if a rock would cause a jam, even before it has entered the crushing chamber. Also, the project will look in to the economic benefits of the system and what customer values can be met. Furthermore, as Roctim offers control systems for rock crushers, this solution will be integrated to their existing product.

1.3 Limitations

The project and the development of a prototype will be specifically limited to jaw crushers used as primary crushers. Additionally, the development of the prototype and gathering of data for development will also be limited to one field study location. Furthermore, the market analysis and cost calculation will be limited to the Swedish aggregate industry as this is the main market for the company. The prototype is not limited to a strict budget and will be decided during the course of the project, with respect to the potential of the concept. The technology used should be readily available for the company in order to reduce risk of compatibility issues. System safety and security of the product, such as CE markings and data security, is not considered in the scope of this project.

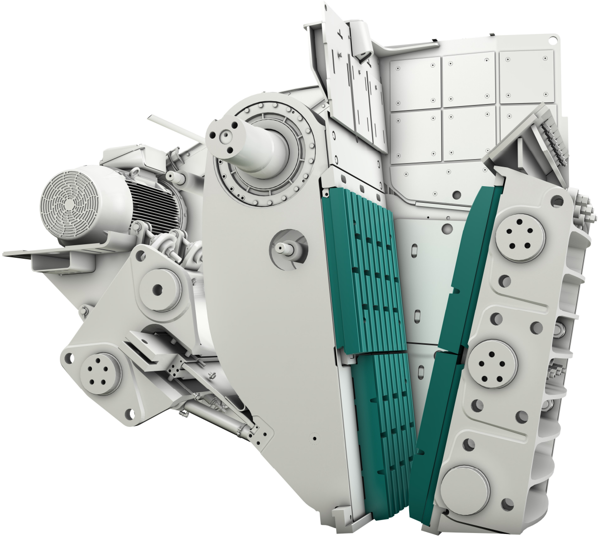


Figure 1.1: Cross Section View of Metso Nordberg C-Series Jaw Crusher (Metso, 2018)

1.4 Uncertainties and Risks

In any development endeavour, there is always risks and sometimes underestimated consequences of an action. For this project, a number of risks and uncertainties can be foreseen. To start, one major risk factor would be that the time estimation for the software development might be inadequate. A consequence would be that the software is delayed, which could result in an unfinished prototype. To lower that risk, a rigorous period of training will be conducted in the early phase to make sure that the team members are up to date with the development methodologies. The hardware-software integration is another potential risk area. Perhaps, some commercially available hardware solutions can present unforeseen issues or requirements of the system that the team is unable to obtain or realize. This would result in a waste of resources, specifically time, causing the team to rethink a part of the solution. A solution would be to test early in the process to make sure that everything is compatible. This ensures that there is enough time to solve the issue and quickly move on. A lack of knowledge and skill in the team might pose a risk. For example, if the team, with the current knowledge, cannot find a suitable solution for the given task. The consequence would be that the product would most likely not meet customer demands. Thus, research in to other similar problems or areas would be of great value to lower this risk. This would ensure that a suitable and tested solution has a greater potential to solve the problem. The solution would be accomplished by early research and training to close knowledge and skill gaps. The major risks that could be identified at the start of the project have a suitable method for avoiding and/or solving the issue. As such, the project itself could be considered safe but of course unforeseen risks can pose a problem during the project.

1.5 Scope

The scope of this project is to develop a prototype vision based system for jaw crusher. The team will, during Q1 and Q2 of 2018, develop the prototype system at Roctims office using the work break-down structure, which is explained further in chapter 2: Methodologies. The prototype itself should have the potential to be a base for expanding the product offerings of Roctim. Furthermore, through the research presented in this report, Roctim should be able to benefit from it and build upon the findings. The prototype should also be able to detect the main issue for the end customer, which is the jamming of jaw crushers. It should also be developed in such a way that it provides a hassle free experience for the end user, i.e. the crusher operators.

1.6 Hypotheses

Three main topics for an autonomous system were identified. They are presented as research questions and are to be answered throughout the course of the thesis.

- What influence would an autonomous detection system have on the crushing operation?
- What external factors may influence an autonomous detection system?
- What methods could be implemented to measure material flow, size, level and what detection accuracy is considered acceptable?

2

Methodologies

In this chapter, the project work flow is described along with the intended development methods to be used. The methods described here are only research methods aimed towards generating concepts, as the more detailed methods of software or hardware development are not yet established. This is due to the potential change of the methods used during the course of development.

2.1 Work Break-Down Structure

To get a better understand the work flow of the project and to further ease the planning, the project divided into eleven steps. Each step is elaborated further in more detail. This includes the work carried out and what methods will be used.

1. Customer Needs
2. Interview customers
3. Competitor and Patent Analysis
4. Litterateur and Technology Study
5. Function Break-Down Structure
6. Idea and Concept Generation for Hardware
7. Concept Evaluation and Stage-Gate for Hardware
8. Software Method Study for Chosen Hardware
9. Software and System Development
10. Prototyping
11. Testing and Optimization
12. On-site Testing

Customer Needs

In order to identify and map the customer needs, site visits will be conducted along side reviewing of articles and news in trade magazines. This would be an effective way of obtaining the customer needs, as many aggregate mining sites vary from each other in terms of layout, way of working and the type of equipment used.

Interviewed customers

During the visits, a number of unstructured interviews were carried out. The reason for choosing unstructured interviews were to ensure that the interview could feel that he and/or she could speak freely and feel more comfortable. This led towards more of a natural discussion during the interview, rather than going through a list of strict questions.

This meant the valuable information regarding their opinions could first be highlighted that then could be the basis that then led to some follow up questions.
The risk with this method is that some questions and/or topics can be left out but due to the surrounding environment but also the fact that the operators could not dedicated a fixed amount of time as they had to tend to alarms, the decisions was to proceed with the unstructured interviews.

Competitor and Patent Analysis

To gain insight into the already existing solutions and ideas, some analysis tools will be applied. These include a patent search, to ensure that the development would lead to an idea that does not infringe upon other companies patents. Also, a competitor analysis will be conducted in order to identify possible differentiation points or weaknesses that could lead to a competitive advantage for our company. Additionally, it would give insight in to the current situation and provide valuable information regarding technologies.

Litterateur and Technology Study

To get a deeper understanding about the designated area and the available technology a literature study will be carried out. This include gathering information from articles, papers, journals and such mediums. Furthermore, the TRL-level investigation needs to be conducted for the technology in order to ensure that the a chosen technology would be a viable solution.

Function Break-Down Structure

From the aforementioned steps a function tree can be generated. It is an important step in the process, as it serves to identify the building blocks of the product at a higher abstraction level. The main and sub functions are generated such that they aid in the next step of concept generation. Preferably, functions are generated with modularity in mind, meaning that main functions are not intertwined but still have the potential to both be integrated or modular.

Idea and Concept Generation for Hardware

Once the team has a common picture of the problem, the idea generation for the hardware can begin. This means that all ideas should be considered and evaluated accordingly. This is preferably done with methods such as brainstorming.(Pahl et al., 2007; Ulrich and Eppinger, 2012). Followed by this will naturally be the concept generation. This means that the ideas will be combined into concepts that later will be evaluated.

Concept Evaluation and Stage-Gate for Hardware

When a suitable number of diverse concepts have been generated, with respect to the hardware, they are ranked based on how well they fulfill the customer needs. First, concepts are quickly screened through an elimination matrix in order to reduce the number of concepts into a more manageable amount, using more basic evaluation criteria(Pahl et al., 2007, Chapter 3). Then, they are fed through a Modified Pugh Matrix and compared with quantifiable customer needs(Ullmann, 2010, Chapter 8). The subsequent results are then taken in to account and one final concept is chosen.

Software Method Study for Chosen Hardware

Since the hardware is to be locked down, research in to software and methods is required. This includes the general method that the hardware will require and the information will be gathered through articles, journals, sample codes, online courses and such.

Software and System Development

When familiar with the concepts for each function, a more detailed software architecture is developed in order to get an overview of how the different modules will interact. Furthermore, the software modules are worked on in more detail and with more functionality in mind as well as overall system compatibility.

Prototyping

Once the initial development of the software system is done, the finalized hardware and the software can be combined. Now the prototype can now be assembled and checked for potential unforeseen compatibility problems.

Testing and Optimization

At this stage the first testing of the complete prototype can be initiated. The first phase of the testing will be conducted in a controlled environment were the whole system can be analyzed immediately and the influencing factors can be controlled. Concurrently will the optimization of the system be accomplished in order to ensure that the system will ready for the on-site testing phase.

On-Site Testing

Once the prototype has been optimized with the estimated parameters from the field, the prototype will be place on rock crusher on-site. This means that prototype will be tested in a operational environment in order to verify the design and the functional performance level. The information gathered at this stage will be the basis for the evaluation of the prototype as well as how the prototype can be even further optimized for future development.

3

Literature study

The aggregate industry has been and still is one of the most basic and essential part of today's society. The extraction of aggregate products has been improved over centuries and the products is used in almost everything around us today, everything from roads to buildings. Between 2015 to 2016 the Swedish aggregate industry increased their total delivery by 2 million tonnes, landing on a yearly total delivery of 86 million tonnes in 2016. The need keeps increasing as the aggregate products is one of the most extracted raw material in Sweden. The aggregate industry in Sweden has benefited from an increased demand for crushed rock and aggregates, mainly from the construction sector. According to SGU (Sveriges Geologiska Undersökning) and Boverket, the yearly construction rate for buildings is estimated between 50-55 000 per year. In terms of aggregates, that would require a yearly production of 100 Mton per year. Looking further in to the future, Boverket forecasts an increase of construction of 70 000 new buildings per year up until 2025. That would amount to an aggregate production of 120 Mton per year. This means that there is a need to increase the production in order to avoid the need to import of the aggregate products. (Norlin and Göransson, 2018) This is not only important from economical point of view but also from an environmental perspective. Environmental regulations are of concern both for aggregate plants and for the transportation of aggregates. As such, plants would benefit from better utilization of resources, energy efficient processes and being closer to construction areas in order to minimize the transportation emissions. As an example, transporting aggregates by truck for 15-30 km would amount the same emissions as it took to crush the material at the plant. Due to these aspects, aggregate producers are looking to increase the equipment availability, equipment utilization and become more energy efficient. Same goes with the cost, at a transportation distance of 30-50 km would the transportation be equivalent to the actual material cost.(Kristian Schoning, 2017) Another aspect to consider when looking into the aggregate industry is the transformation that has been going on over the last decades. Since 1985 to 2016 crushed bedrock has been increasing from only 20% of the total material, up till today where it stands for over 80% of the total material used. The reason for this is that before sand and gravel was the main product that was used, which is a limited resource that have a much higher value than crushed rocks. This can also be seen by looking at the number of quarry permit, that has gone from over 4000 to less than 500 in the last decades. However, the number of quarry permit for the crushing industry has not increased as much, only a couple of hundred. Meaning that they need to produce much more and be more efficient to hold up the production that is needed. (Norlin and Göransson, 2018)

The general process for the aggregated industry is as follow and can be seen in fig. 3.1 were some of the key components of a crushing process is shown. (1) The upstream stages, consists of both transportation of the blasted rocks and the blasting itself. (2) The feeder and primary crusher, consists of feeding blasted material in to the crusher and reducing it's size by crushing. After this the material either run through a screen to sort out certain size and/or to be placed in a stock pile. (3) The secondary crusher, in order to reduce the rocks into finalized products it usually go through a number of crushers depending on the setup, these have a higher accuracy but are more sensitive to incoming rock size. (4) Unloading area, customers comes to buy different product sizes, depending on the usage area.

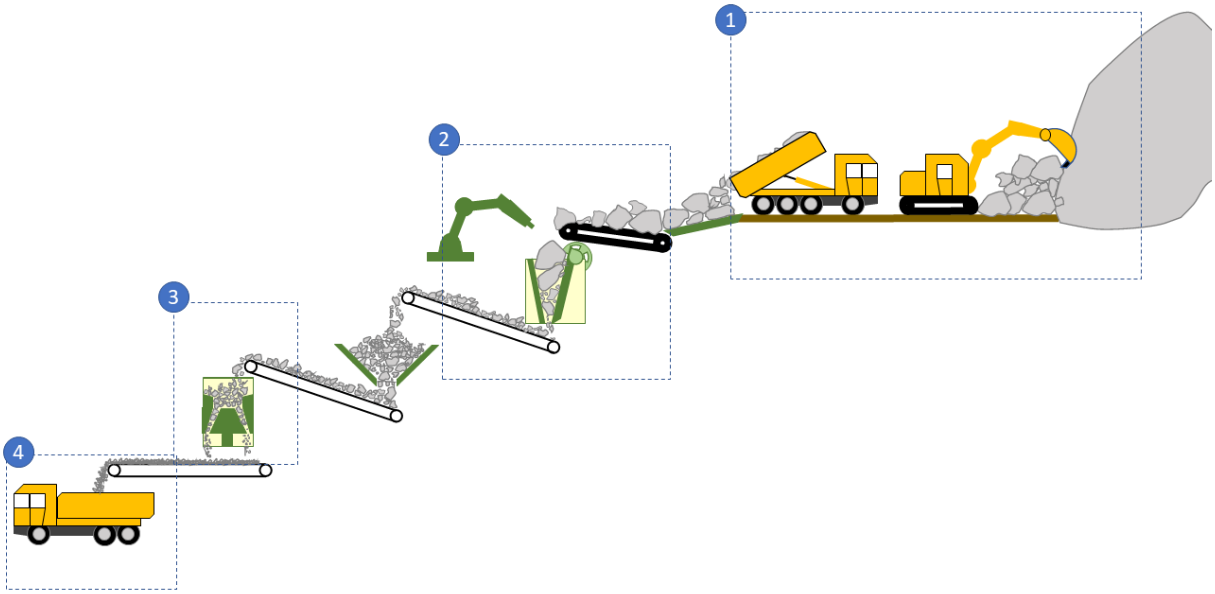


Figure 3.1: Overview of the a crushing process. 1: Blasting and transportation. 2: Primary crushing. 3: Secondary crusher. 4: Outgoing material

This process is highly dependent on many factors and may vary from site to site. First the rock gets blasted into manageable pieces, the size here does vary a lot and maximum allowed size is heavy depending on what the primary crusher are specified for. If the rocks are to big, they will cause jamming and if they are to small they will not be crushed in the primary crusher, leaving the crusher as an unused source. After the primary crusher the rocks has decreased in size were the size is more known but still may vary depending on the primary crusher and how the rock falls through. After this step, there are many options regarding processes that can be used. Usually, there are two or more crushers that will bring down the size of the material that is more commonly used in the industry. Furthermore, sieves are used between different steps in the process to better ensure what size the rock has before it enters the secondary and/or the tertiary crusher. There are different prices for different sizes regarding the end product, which mean that the producer wants to ensure that the same size it kept even though the crushers wears out after a certain point. This is where the industry has improved once it comes to using technology, more specific control systems for the crushers.

As for today, the industry is using many types of different sensors to ensure that the production can continue to run and ensure that as few stops are achieved, but of course also to optimize the production. Many of sensors today are such as level sensors, vibrations sensors, temperature sensors. All to ensure that, for example the secondary crusher runs as optimal as possible. Also, other sensors such as metal detectors are used to prevent stops and unnecessary ware and/or damaged on the machines. However, even though the industry is adapting and investing in newer system it is much more conservative compared to other industries. One reason why the industry is being highly careful with investments may be the need for a permission to operate. These quarry permit usually have a time limit (Naturvårdsverket, 2003), hence the quarry may only be active for that time stated, which may be one of the reasons the investment will may vary within the industry. Meaning that investment might not be the highest on the priory list, rather than keep the production at a steady rate. As every investment, the return of investment must then be much lower than the actual time limit for the permission.

4

Customer needs study

A dialog with potential customers is an important step towards generating new and customer focused products in today's market. This chapter presents the customer needs mapping that underlies the product development phase of the thesis.

4.1 On site study: NCC Tagene

The data gathering for the thesis was conducted on site at the local aggregate producer NCC Tagene, picture of quarry can be seen in fig. 4.1. The site is located 5 km north east of Gothenburg and produces aggregates and asphalt for local construction projects. They blast and crush material from their quarry and take care of asphalt recycling as well. The site consists of one jaw crusher for primary crushing application and cone crushers for the second and third stage. The primary crusher is located at the highest level of the quarry. The setup consists of a jaw crusher, a grizzly feeder, and a hydraulic rock breaker as shown in fig. 4.2. The single haul truck, which runs up and down the quarry, feeds blast rock directly on to the grizzly feeder. The crusher and feeder are encapsulated inside a building, which also contains the control room for the whole site.

Figure 4.1: The NCC Tagene quarry.

Figure 4.2: Primary crusher with feeder and rock breaker.

4.1.1 Interviews

During the interviews, a considerably amount of valuable information was gathered. Not only about what the workers thought was the problems today but also the general way of working and the general attitude towards certain tasks. The result of the interviews showed that, as in many other industries, the workers were getting use to problems such as jamming and often refereed to that *"It is my job to fix it"* while other areas, that they didn't have control over, were more highlighted. The most relevant information gathered can be found in the point-list below.

- According to the workers jamming was not a big problem since *"it only take around 5 minutes to clear it"*.
- They claimed that the flow of the incoming material were often inconsistent and by that causing the primary crusher to be idle, mainly due to the fact it would run out of material.
- The size of the rocks is very dependent on the result of the blasting but also when the material is taken from the blasted section. The first material taken after the blasting, usually had larger rocks and caused jamming. While material taken in the end of the blast section, the size of the material shrunk and could go right thought the primary crusher without the need to be crushed.
- The current system that are installed to kept track of the level within the crusher had some problems, as previously mentioned, the senors was from time to time covered with dust/dirt and therefor indicated that the crusher was full, even though it could be empty.

4.1.2 Observations

Throughout the course of the thesis several visits to NCC Tagene have been made. The purpose was to inspect the primary crusher over a period of time in order to obtain untold information about the process. Several problem areas have been observed and documented, such as material flow, size distribution, jamming, equipment downtime and general issues with the process, which are listed below.

- Some sort of jamming of the crusher seems common, for example too large rocks wedging themselves over the crushing chamber blocking other rocks to fall down. These common issues are usually solved within 15-30 minutes. As the operators mentioned in the interviews, jamming usually takes at most five minutes to clear with the rock breaker. However, to detect a jam takes longer time. As the operators are often focusing on other equipment malfunctions or alarms, the crusher might be jammed for a longer period of time. As such, equipment downtime of around half an hour may be more common than the operators realize.
- Material flow is highly dependent on the blast fragmentation size. On some visits, there have been many oversize rocks causing either a jam or a decrease in outflow due to longer crushing time. On other days, there have been a lot of undersized material being fed in to the crusher. This causes unwanted wear on the plates and lowers the equipment utilization. Also, this is an indication of the blasting process. A lot of undersized material is usually the result of using too much explosive material and drilling blasting holes too tightly together, which causes resources to be wasted.
- The control system for the feeder may be poorly adapted to this crusher. When the crusher is full, the feeder stops and waits for a lower material level. However, there was a significant start/stop delay, which caused he material outflow to be very uneven at times.

4.2 Customer needs analysis

From on site interviews and the observations the primary problem today is that the primary crusher is underutilized, which means that the crusher is not used to its full capacity when crushing material or that it is unable to crush material. This is due to several factors, which are categorized in the cause-and-effect diagram, figure 4.3, below.

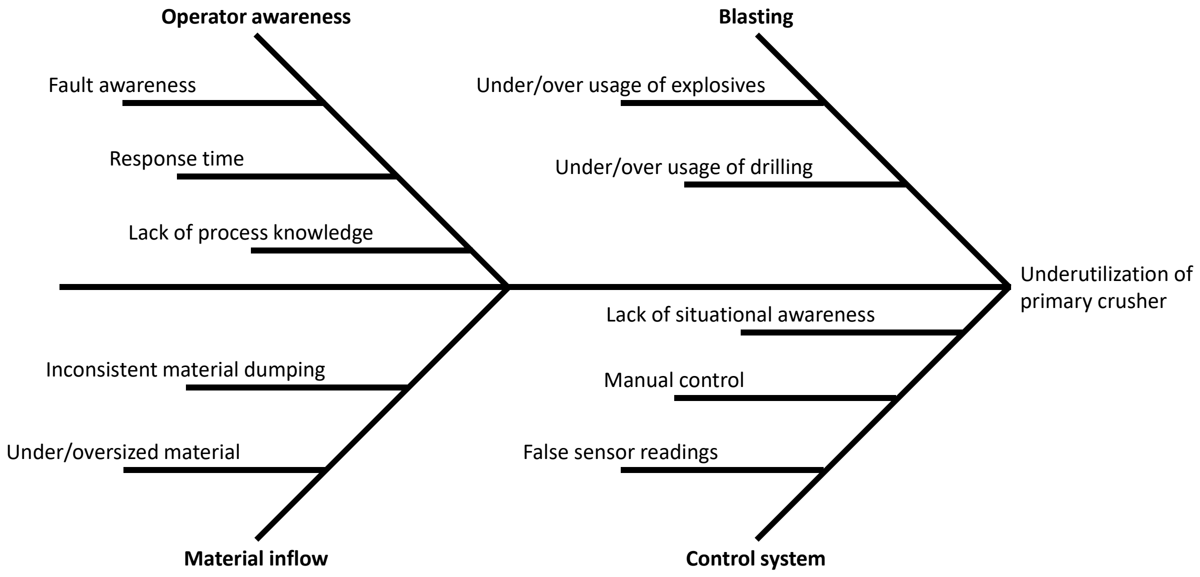


Figure 4.3: Cause and effect diagram for the primary crusher

The crusher is properly utilized when there is a steady flow of appropriately sized blasted rock fed in to the crusher. Every situation that causes a production stop or delay accounts for significant losses in potential revenue. Operator awareness, blasting, differing material inflow and the control system of the primary crusher are the main contributors to the machine being underutilized. For example, if an operator is occupied by another machine, they are usually not aware of other failures at the time. As such, their response time to the primary crusher may cause significant delays in production.

What seems to be a significant cause for delays in production is the blast rock size variation. If the rock is oversized, the crushing time is increased and there are risks of the crusher being jammed. When the material is undersized, the crushing would be a redundant step in the process, as no value-adding work is being done by the machine. Furthermore, inappropriately sized material causes unnecessary wear on the plates, which may reduces wear part life. Also, if the result of the blasting is mainly undersized material, there has been a significant waste of drilling time and explosives.

In fig. 4.4, some of the key components of a crushing process is shown. The main process stages are of concern is the upstream stages (1), primary crushing stage (2) and downstream stages (3). Stage 1 consists of both transportation of the blasted rocks and the blasting itself. Stage 2 consists of feeding blasted material in to the crusher and reducing the size by crushing. Stage 3 involves crushing the rocks to even finer end-products. From stage to stage, material size and material flow are the key components of the plant performance.

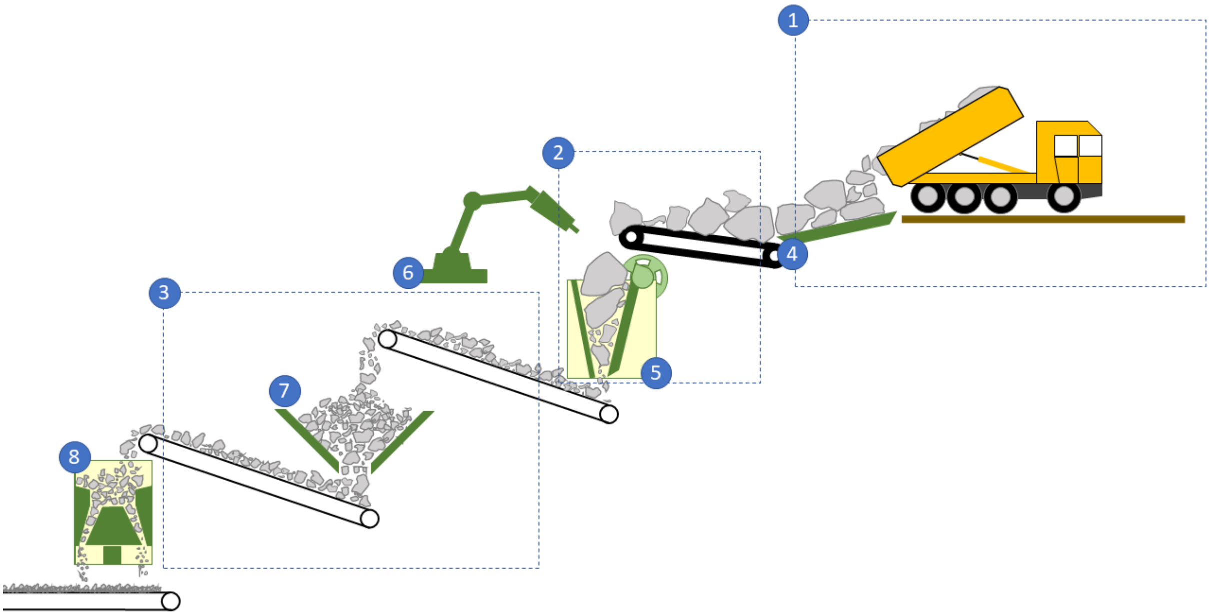


Figure 4.4: Overview of the a crushing process. 1: Blast material in-flow. 2: Primary crushing. 3: Crushed material out-flow. 4: Feeder. 5: Jaw crusher. 6: Hydraulic hammer. 7: Stockpile. 8: Secondary cone crusher.

4.3 Customer needs

When developing a product, it is crucial to specify the needs of all involved parties, in this case the customer NCC (C) and the user/crusher operator (U).Thus, there is a need to concretize the given problems and factors that are previously mentioned from both the observation and the interviews. These comes from both outspoken and unspoken needs and/or problems that have or will have an affect on the crushing process. The needs are presented in table 4.1 where the needs will then be given value between one and five depending on the importance of the need, where one is the lowest and five is the highest importance level. Each need is paired to multiple issuers. As such, it is important to view each instance from all perspectives.

Table 4.1: Table of the needs concretized from observation and interviews.

No.	**Needs**	**Importance**	**Issuer**
1	Detect jammed crusher	5	C, U
2	Detect flow of material	5	C, U
3	Detect size of material	5	C, U
4	Easy to maintain	4	C, U
5	Adaptable to different sites	3	C
6	No additional alterations to site	4	C
7	Inform operator when the machine is stopped and why	5	C, U
8	Provide analytic data for process improvement	3	C
9	Easy to install	3	C
10	Cost effective solution	4	C
11	Simple user interface	4	C, U

5

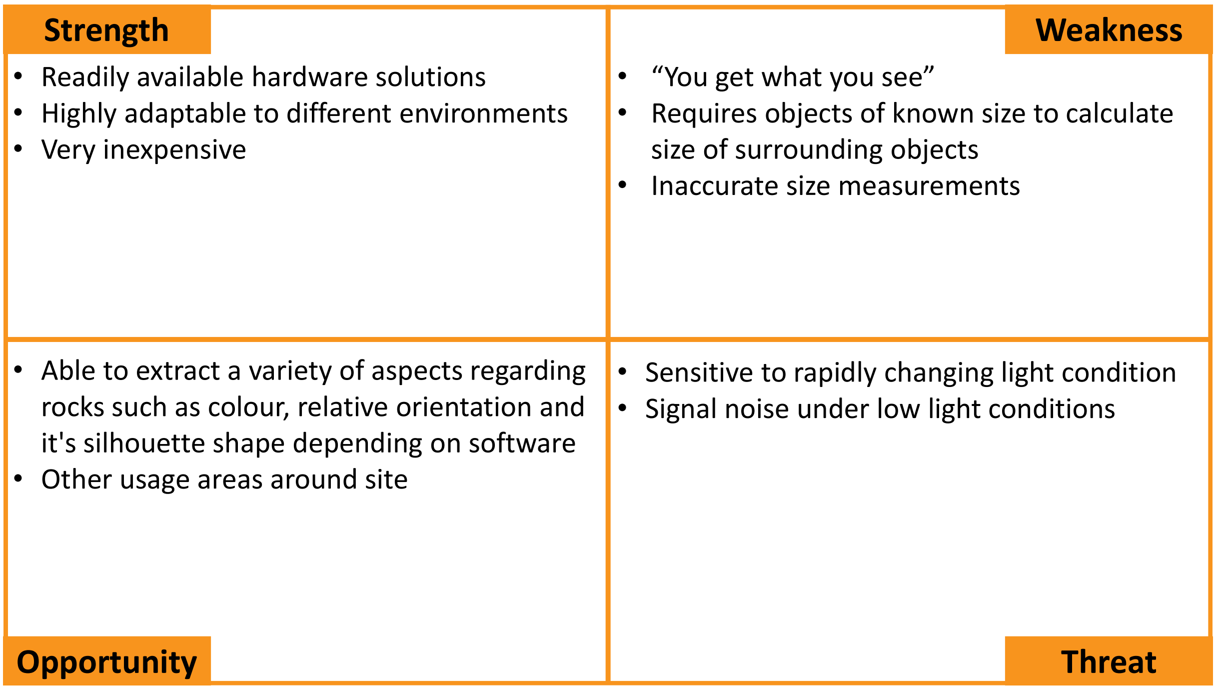
Technology study

In recent years, non-contact measurement techniques have become an important topic for sensing different aspects of an environment. For the aggregate industry, non-contact measurement systems are highly suitable for the type of tasks presented in this thesis, as they can be designed to be highly adaptable and in some cases more affordable than traditional solutions. As such, the technology study focuses on vision and 3D technologies, for example LiDAR and camera systems. The identified technologies that were feasible for the task are:

- 2D camera technology
- 3D camera technology
- LiDAR
- Structured-light 3D scanner
- Time-of-flight camera

5.1 2D camera technologies

The rapid pace of camera sensor development and the relatively low cost makes a camera system a powerful and affordable solution for general sensing tasks. A common usage scenario for single camera setups is object detection, tracking, segmentation and object classification. The application areas range from detecting pedestrian on roads to medical applications to study various samples from patients. Furthermore, distance can be measured by knowing dimensions and distances to certain objects in a scene. If these criteria are known, one can study that plane of known distance and then calculate the size of surrounding objects in that plane. However, if objects are not in the same plane the measurement results are inaccurate (A. Criminisi, 2002). An analysis of this technology, when applied to the aggregate industry, is presented in fig. 5.1 below.



Strength	**Weakness**
• Readily available hardware solutions • Highly adaptable to different environments • Very inexpensive	• “You get what you see” • Requires objects of known size to calculate size of surrounding objects • Inaccurate size measurements
• Able to extract a variety of aspects regarding rocks such as colour, relative orientation and it's silhouette shape depending on software • Other usage areas around site	• Sensitive to rapidly changing light condition • Signal noise under low light conditions
Opportunity	**Threat**

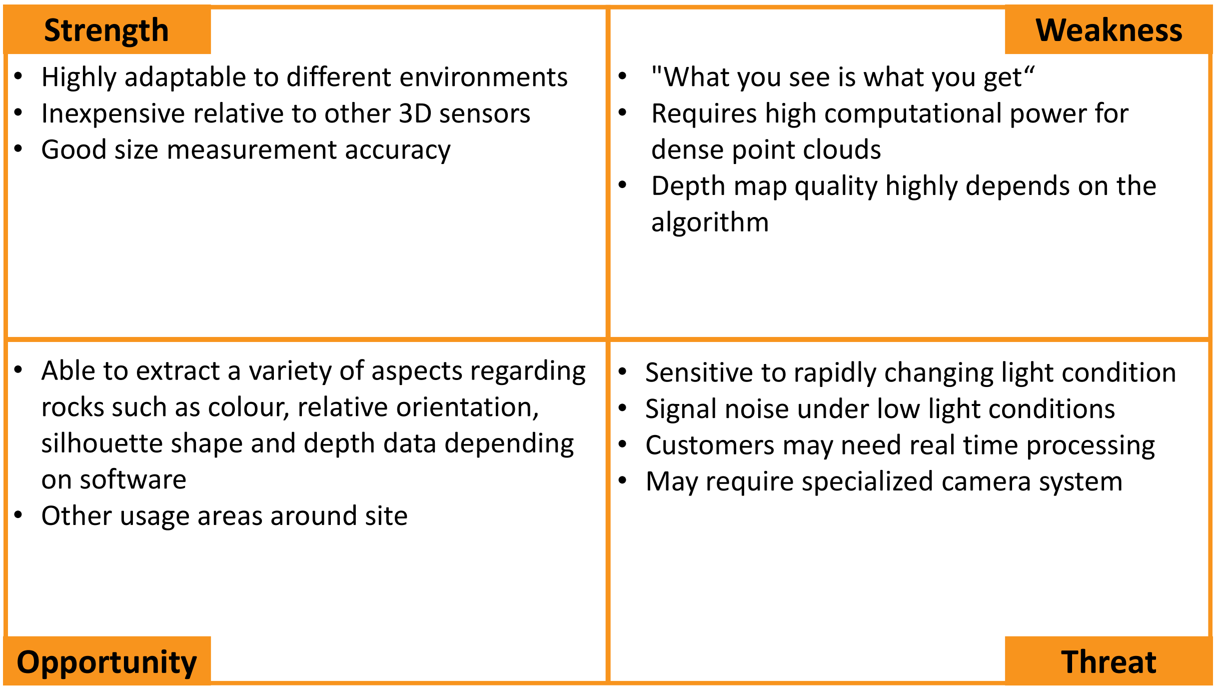
Figure 5.1: Analysis of single camera

5.2 3D camera technologies

As the aforementioned viable 2D imaging technologies inherently lack accurate depth perception one must look at 3D technologies to obtain appropriate information of the environment. There are many different technologies with varying types of ways to obtain a 3D image. However, the end result is the same: a point cloud or surface.

5.2.1 Stereo camera system

To study a 3D space with a camera system, two or more cameras can be combined in to what is called a stereo camera. The addition of one or more cameras enables depth sensing, through triangulation of points in both images. The result of such a process is a depth image with pixels mapped to real world x-y-z coordinates, which can then be translated to a point cloud (R. Szeliski, 2010). An analysis of this technology, when applied to the aggregate industry, is presented in fig. 5.2 below



Strength

- Highly adaptable to different environments
- Inexpensive relative to other 3D sensors
- Good size measurement accuracy

Weakness

- "What you see is what you get“
- Requires high computational power for dense point clouds
- Depth map quality highly depends on the algorithm

Opportunity

- Able to extract a variety of aspects regarding rocks such as colour, relative orientation, silhouette shape and depth data depending on software
- Other usage areas around site

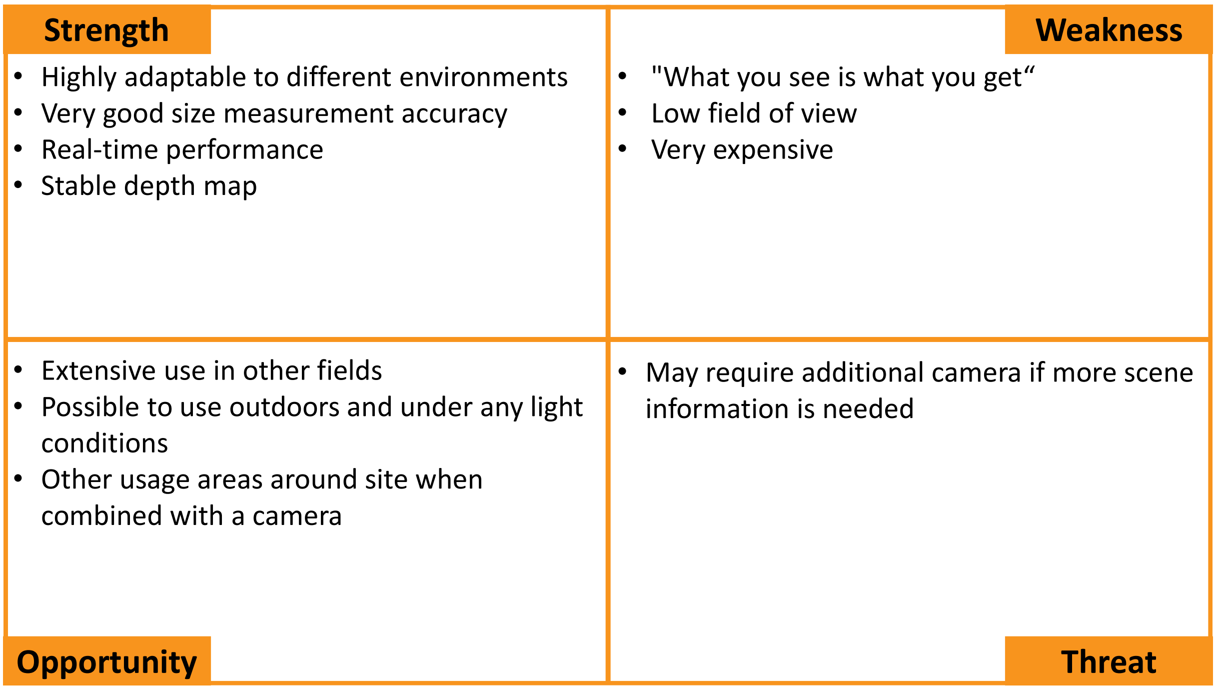
Threat

- Sensitive to rapidly changing light condition
- Signal noise under low light conditions
- Customers may need real time processing
- May require specialized camera system

Figure 5.2: Analysis of stereo camera

5.2.2 3D LiDAR

LiDAR is a Laser ranging systems and is a common way of sensing the environment in various applications, for example self-driving vehicles. These applications require real-time performance, stable measurements, long range and high accuracy, all of which LiDAR can perform well in. However, system cost is high but will most likely be reduced significantly due to the automotive industry fast paced development (Himmelsbach and Wunsche, 2008). An analysis of this technology, when applied to the aggregate industry, is presented in fig. 5.3 below

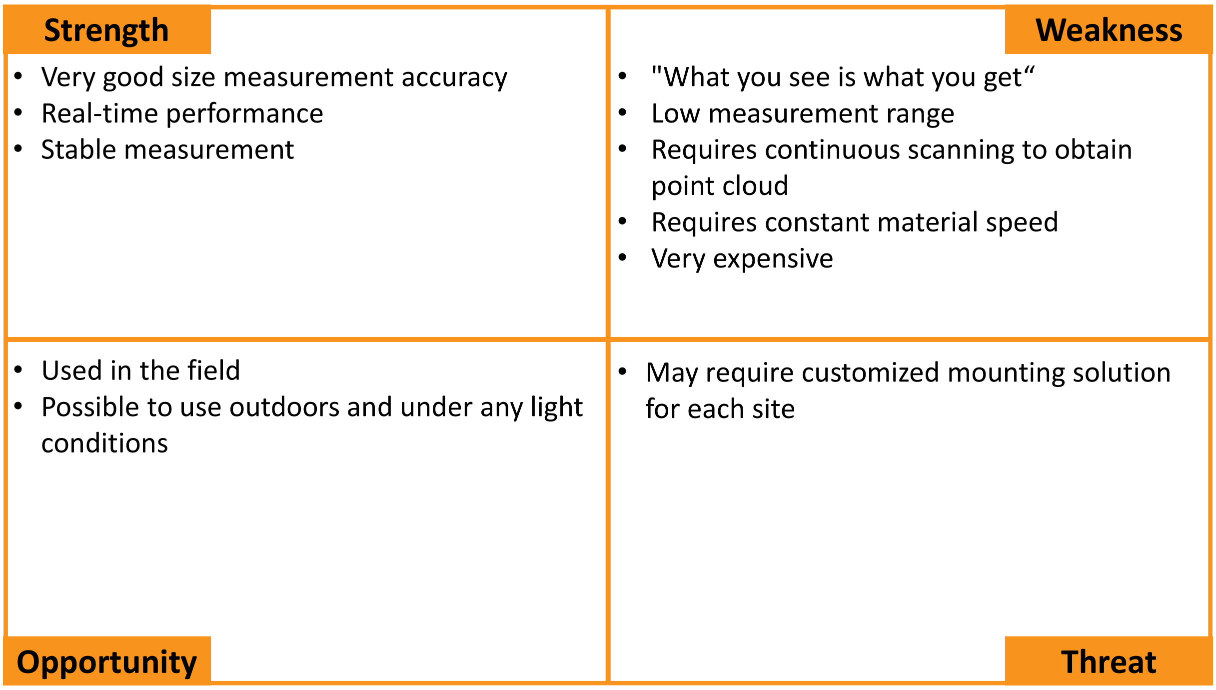


Strength	Weakness
• Highly adaptable to different environments • Very good size measurement accuracy • Real-time performance • Stable depth map	• "What you see is what you get“ • Low field of view • Very expensive
• Extensive use in other fields • Possible to use outdoors and under any light conditions • Other usage areas around site when combined with a camera	• May require additional camera if more scene information is needed
Opportunity	Threat

Figure 5.3: Analysis of LiDAR

5.2.3 2D LiDAR

2D line scanners are used widely in the manufacturing industry to provide detailed scans of parts, in order to ensure product quality. As the system relies on 2D line scanning, a 3D surface can only be obtained when either the scanner is moved along a surface or when the object is moving itself. As such, to properly measure objects they have to move at a constant speed (Himmelsbach and Wunsche, 2008). An analysis of this technology, when applied to the aggregate industry, is presented in fig. 5.4 below.

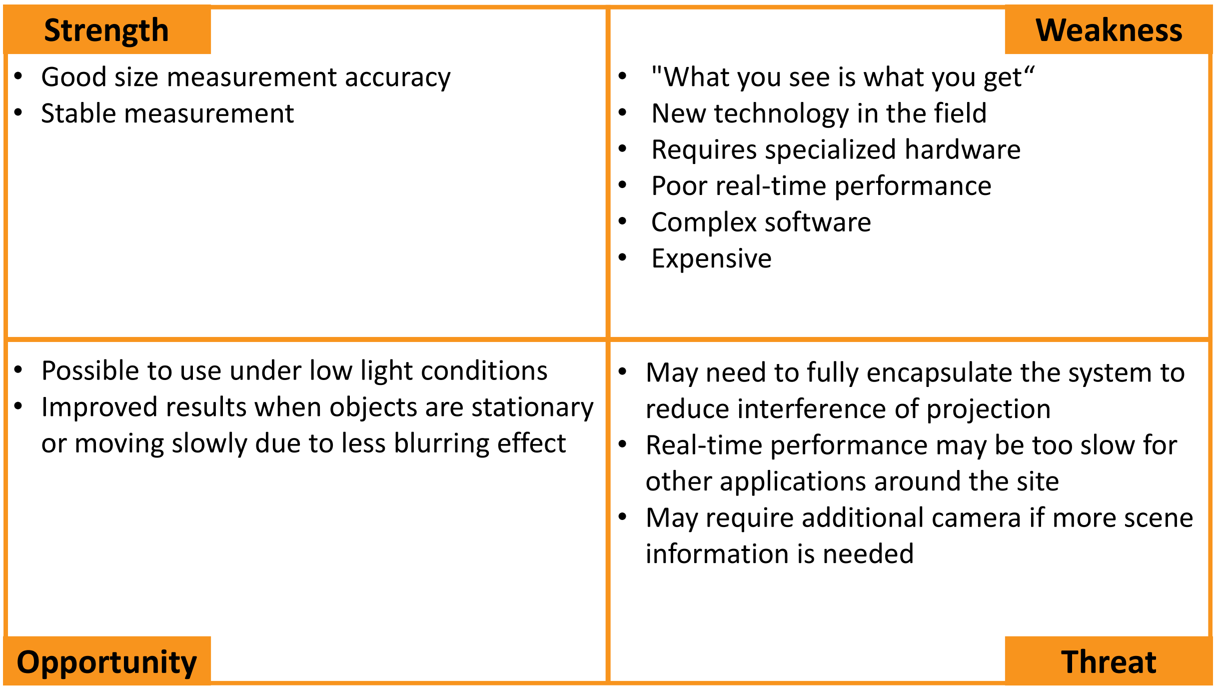


Strength	**Weakness**
• Very good size measurement accuracy • Real-time performance • Stable measurement	• "What you see is what you get“ • Low measurement range • Requires continuous scanning to obtain point cloud • Requires constant material speed • Very expensive
• Used in the field • Possible to use outdoors and under any light conditions	• May require customized mounting solution for each site
Opportunity	**Threat**

Figure 5.4: Analysis of 2D line scan

5.2.4 Structured-light 3D scanner

Structured light systems project a known pattern on to a surface and investigating the distortion of this pattern with a camera. Based on the distortion a 3D map can be computed. However, multiple projection-reading cycles with different projections are usually required in order to obtain a good depth image. Of course, such a process substantially increases the scanning time, but results in a very accurate depth map. Furthermore, the projection may be sensitive to interference from the surrounding environment, for example in bright conditions where the projection may be “washed out” by ambient light (Kutulakos and Stegere, 2005). An analysis of this technology, when applied to the aggregate industry, is presented in fig. 5.5 below.

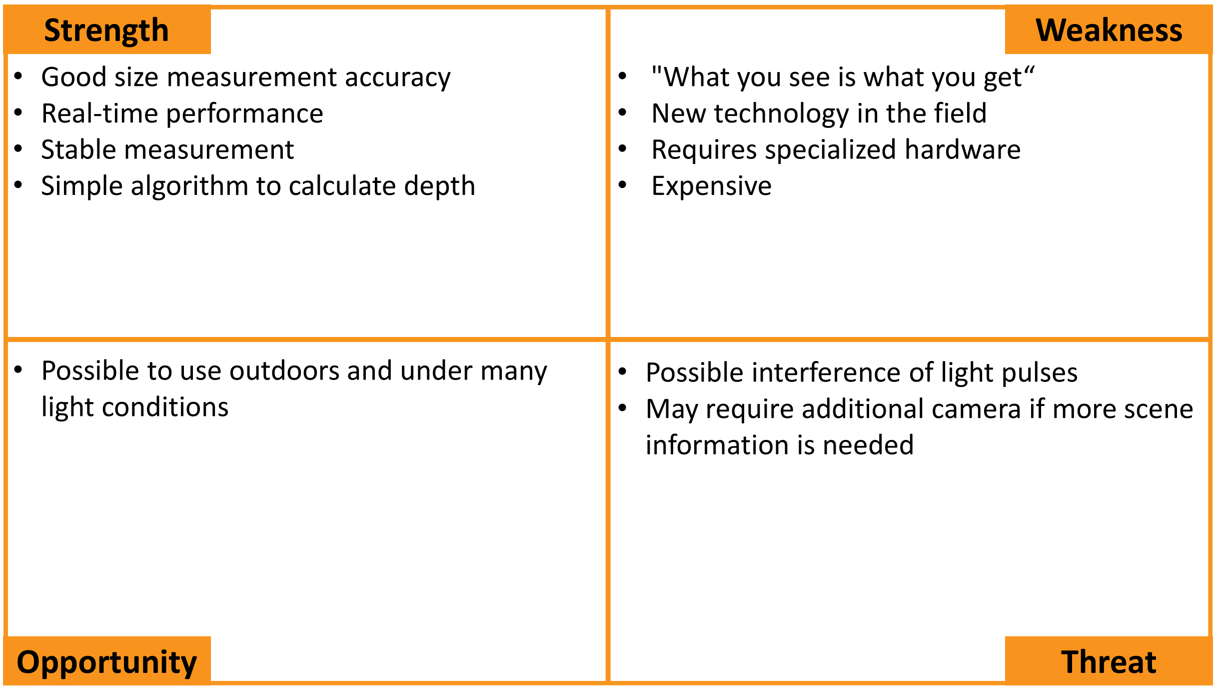


Strength	**Weakness**
• Good size measurement accuracy • Stable measurement	• "What you see is what you get“ • New technology in the field • Requires specialized hardware • Poor real-time performance • Complex software • Expensive
• Possible to use under low light conditions • Improved results when objects are stationary or moving slowly due to less blurring effect	• May need to fully encapsulate the system to reduce interference of projection • Real-time performance may be too slow for other applications around the site • May require additional camera if more scene information is needed
Opportunity	**Threat**

Figure 5.5: Analysis of 3D structured light scanner

5.2.5 Time-of-flight camera

Time-of-flight camera systems work similarly to ultrasonic sensors, but using light pulses instead of acoustic pulses and a camera sensor instead of an acoustic receiver. The time pulse timing and the resulting reflection of light will determine the distance to objects, as closer objects reflect light quicker than distant objects, which translates to a very easy distance calculation. Although a very simple concept in theory, in practice it requires high speed sensors as the reflection time of light is very short, which may require more performance than cheap camera sensors can provide today (L. Li, 2014). An analysis of this technology, when applied to the aggregate industry, is presented in fig. 5.6 below.



Strength	Weakness
• Good size measurement accuracy • Real-time performance • Stable measurement • Simple algorithm to calculate depth	• "What you see is what you get“ • New technology in the field • Requires specialized hardware • Expensive
• Possible to use outdoors and under many light conditions	• Possible interference of light pulses • May require additional camera if more scene information is needed
Opportunity	**Threat**

Figure 5.6: Analysis of Time-of-flight camera

5.3 Competitor analysis

In order to ensure that the product can be a viable and compete with other system on the market, a benchmark were carried out. Today, there are a only a handful solutions that can achieve the same or similar task. Also, other industries were used for inspiration such as the food industry uses the same and/or different solutions to inspect the quality. However, these solutions is highly specialized and often placed in a well controlled environment, which is the reason they are not considered in the benchmark. The benchmark will be focus on which tasks it can solve as well as the accuracy of the product. As the benchmark shows, some products is more focus on solving one or a few tasks that some part of the aggregate industry requests. Also some solutions are heavily dependent were in the process it is placed. The price for most of these solutions are unknown and highly dependent on many factors. One of them being that most of these solutions are relatively new to the market with new technology which means that price can vary from a few thousands to over hundred of thousands euros.

5.3.1 ScanMin Africa

The solution that ScanMin Africa offers is a “Oversize Detection System” (ScanMin Africa, 2018) that is focus on monitoring and preventing blockage in the secondary crusher. The product also have to cover the whole conveyor belt in order to function, hence it needs a controlled environment. However, there are not much information from the supplier regarding the actual technology or the price. This does not necessary means that the competitor should be left out and something to keep in mind in the further.

5.3.2 MotionMetrics

MotionMetrics is a company that offers four different products were all uses a vision system to solve various task. Two of the solutions detecting missing tooth and the surrounding area around excavators and loaders. While two of them are more focused on the usage of measure the size of rocks. One of these two solutions is a handhold portable solution, *PortaMetrics*, that the user can take with them and analyze rocks anywhere. However, the resolution on the cameras is a bit on the lower end which might affect the accuracy on the system.(Motion Metrics, 2018b) The other product is a fixed solution that is installed on the belt. According to MotionMetrics, the solution can detect rocks as small as 0.6 cm with and accuracy of ± 10 %. However, this solutions have a long processing time and with a low capability of only 2 images per minute. This is most likely to low for a primary crusher due to the uneven size distribution of rocks. (Motion Metrics, 2018a) The price for Beltmetrics is said to be around 70 000 EUR but is very dependent of the site. Also the PortaMetrics can be used with an yearly subscription of 12 000 EUR.

5.3.3 MBV-Systems

MBV-Systems offers a systems to 3D-scan the material on the conveyor belt (MBVsystems, 2018). This creates a 3D-map of the material that can be used to analyze the size and the distribution of the material. This solution only focus on the material on conveyor belt since it requires a special installation within a somewhat controlled environment. The system needs to be a fixed installation around one meter above the conveyor belt. The price of the system remains unknown since it will most likely be highly dependent on were and how it will be installed.

5.3.4 Split-Engineering

Split-Engineering offers handful of products that focus on analyzing the size of rocks.(Split Engineering, 2018) Their system can according to themselves be placed at every step of the process in order to analyze the size of the rock and furthermore use this information to validate the different processes. Two of their solutions focus on a more robust camera that can be place on either the excavator, “Split-Shovelcam”, or on place that it is known that the trucks stop at, “Split-Truckcam”. The information regarding the camera system is very limited but every system needs to be calibrated at site. Which is mentioned in chapter 5.1.1, which most likely mean that they use a single camera to capture the images. Regarding the information about the price for different system, is as for most companies earlier discussed, hard to find. However, the price for a licence is about 8000 EUR which gives an indication of which price region they are placing them self in, this does not include any camera or installation costs.

5.3.5 Stone Three Mining

Stone Three Mining is a company that offers four solutions that is specialized in different areas.(Stone Three Mining, 2018) Two of the solutions focuses more on the extraction of minerals such as flotation sensors and bubble sizer. The other two solutions is however more targeted towards detection and information gathering for the material on the conveyor belt. The first solution, Intelliore Lynxx Psa, uses a camera solution to measure the size of the material while ther other solution VMA, Volumetric Material Analyser, uses a 3d laser to measure the volume of the material on a conveyor belt. Although, there are no information regarding the price or the accuracy of the system.

5.4 Competitor and technology mapping

A summary of the competitors and technologies is presented in table 5.1. As described in chapter 5.3.1, ScanMin Africa does not disclose which technology they are using. Therefore, they are excluded from the summary.

Table 5.1: Table of competitor products and the technologies used

	2D Camera	**3D Camera**	**LiDAR**	**Structured light scanner**	**TOF-camera**
Motion Metrics	X	X			
MBV-Systems			X	X	
Split-Engineering	X				
Stone Three Mining	X		X		

6

Hardware development

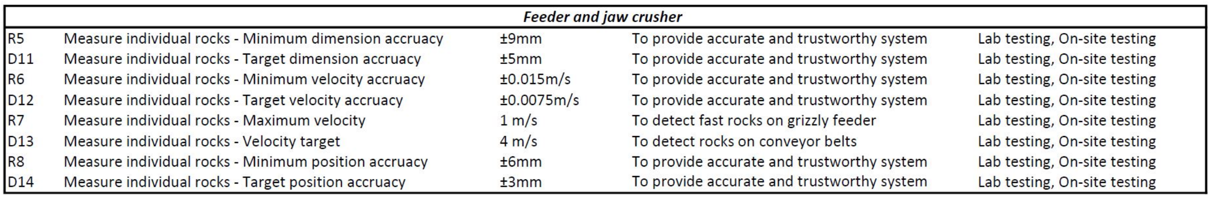
6.1 Hardware requirements

The requirements is an essential part of the development process. It will ensure that all involved parties knows how the product will preform as well as ensure that the product can compete on the market. It is also used to narrow down and evaluate the concepts in the concept screening. The basis of the requirements comes mainly from the customer needs and the competitor analysis. It is also important to quantify the data so it can used for validating the product in order to ensure that the performance level is met. The full requirements list can be found in appendix A while a shorter version with some of the highlighted requirements can be found in table 6.1.

This product has its focus towards the primary crusher and the requirements will be set around that assumption. Since the primary crusher is just one part of the entire process chain, it would be desirable to include other machines as well. Furthermore, since it is a harsh environment it comes natural that the vision system needs to withstand this. There for it is going to need an IP classification of at least IP65. However, the complete system with the processing power can in a control room or similar but it would be desirable to have an IP classification of 68 to be able to place it anywhere at the site.

As the benchmark showed most systems were priced around 10 000 EUR and upwards. However, the systems are highly dependent on unique mounting position which will most likely increase the price. Since Roctim offers products to both small and large companies it would be beneficial if the price could be at the same price range as other product. Therefore the maximum production cost was set to 15000 EUR, this will not only ensure that price is well below other competitors as well as giving the opportunity to offer this product to both small and big companies.

Table 6.1: Accuracy target requirements



		Feeder and jaw crusher		
R5	Measure individual rocks - Minimum dimension accruacy	±9mm	To provide accurate and trustworthy system	Lab testing, On-site testing
D11	Measure individual rocks - Target dimension accruacy	±5mm	To provide accurate and trustworthy system	Lab testing, On-site testing
R6	Measure individual rocks - Minimum velocity accruacy	±0.015m/s	To provide accurate and trustworthy system	Lab testing, On-site testing
D12	Measure individual rocks - Target velocity accruacy	±0.0075m/s	To provide accurate and trustworthy system	Lab testing, On-site testing
R7	Measure individual rocks - Maximum velocity	1 m/s	To detect fast rocks on grizzly feeder	Lab testing, On-site testing
D13	Measure individual rocks - Velocity target	4 m/s	To detect rocks on conveyor belts	Lab testing, On-site testing
R8	Measure individual rocks - Minimum position accruacy	±6mm	To provide accurate and trustworthy system	Lab testing, On-site testing
D14	Measure individual rocks - Target position accruacy	±3mm	To provide accurate and trustworthy system	Lab testing, On-site testing

These requirements are set with the knowledge gained from all steps in the development process such as customer needs, technology study etc. The remaining requirements R8 to R12 takes the performance of the system into consideration. It is most important to set a minimum performance level that needs to be satisfied. Furthermore, it also important to consider inaccurate measurements. The reason why this is important is to ensure that the operator can trust the notifications he receives. If the system falsely indicates that the crusher is jammed too often, the operator will most likely pay less attention to the system.

6.2 Function analysis

The main idea of this thesis is to improve the primary crushing process with new technologies that provide data which aids in the plants strive for continuous process improvement. The function tree was chosen as a method for analyzing the functions, as it gives a clear view of what affects the main function and how to achieve the main function's goal. The full function tree can be viewed in appendix B. In this chapter, a more detailed description of each function is provided along with the reasoning behind them. As the intended system would be used as an analysis tool for decision making, the human functions are listed as blue functions while the analysis functions are marked with orange.
As the primary jaw crusher is the focus, maximizing it's performance is the main function of the system. As such, the overarching function to solve is *"Maximizing the jaw crusher performance"*. This would give a direct impact on the utilization of the crusher.

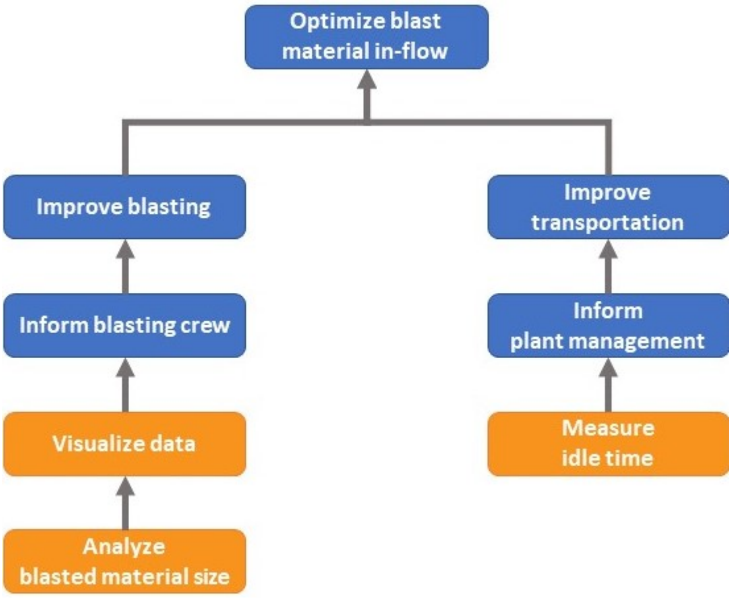


Figure 6.1: Function tree: Upstream process

The material being fed into the crusher is a crucial part of both the plants resources and investments. As such, the first sub-function is *"Optimize blast material in-flow"*. In order to improve this process, one can identify two aspects that affect the material in-flow. Firstly, *"Improve blasting"*, which is directed towards producing appropriately sized material for the crusher. If the blasting is too efficient, the blast material size is very small. Thus, most of the material fed in to the crusher tends to just pass through. This results in a crusher that does no value-adding work. Furthermore, this also means that the blasting process used too much explosive material and/or that they drilled too many holes. All of these aspects translate to real world costs and are a large part of the actual operating costs of the plant.
To improve the blasting there needs to be concrete data and good communication with the blasting crew, which are presented with the functions *"Inform blasting crew"* and

"Visualize data". These functions are based on *"Analyze blasted material function"* in order to quickly produce reports with valuable information such that the blasting crew can receive feedback on their work. Another aspect to improve the material in-flow would be to improve the transportation of the blasted material, represented as the function *"Improve transportation"*. Since the crusher is only utilized when it is crushing material, crusher idle time results in lower throughput of material and wasted power as well. These tasks will provide a *key performance indicator* (KPI) to the plant management. They need to be informed regarding the crusher idle time, time between dumping material and truck idle times. Function *"Inform plant management"* and *"Measure idle time"* covers these areas.

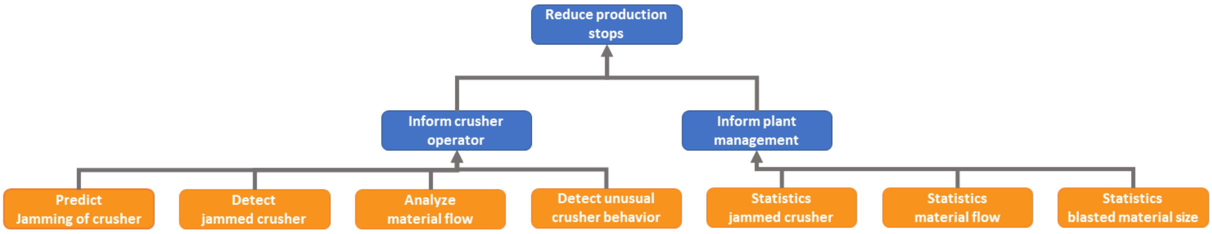


Figure 6.2: Function tree: Primary crushing process

Even though improving the blasting process may significantly increase the crusher up time and utilization of plant resources, there will always be some form of jamming and other faults. *"Reduce production stops"* covers this topic, with sub-functions *"Inform crusher operator"* and *"Inform plant management"*. Firstly, as the crusher operator tends to equipment during their shifts, they may not know that there is a stop or some other fault with the crusher. As such, this function aims to inform and prioritize alarms via its sub-functions *"Predict jamming of crusher"*, *"Detect jammed crusher"*, *"Analyze material flow"* and *"Detect unusual crusher behaviour"*. These functions would provide the operator with status notifications of the crusher and allow the operator to act accordingly. As most organizations have a continuous improvement plan, statistics of the crusher would be an important aspect to deliver. Function *"Inform plant management"* covers this, which is achieved through the sub-functions *"Statistics jammed crusher"*, *"Statistics material flow"* and *"Statistics blasted material size"*. These functions aim to provide such data for process improvement rather than daily fault alarms like the ones operators tend to. The crusher should produce material at a certain size. Although not as important for a primary crusher in comparison to the last crushing stage, producing material at a certain size is the main function of the crusher. In order not to cause jamming of the secondary crushing stage, the material size should be monitored. Function *"Ensure correct product size"* with sub-functions *"Measure product size"* and *"Measure wear"* provide such

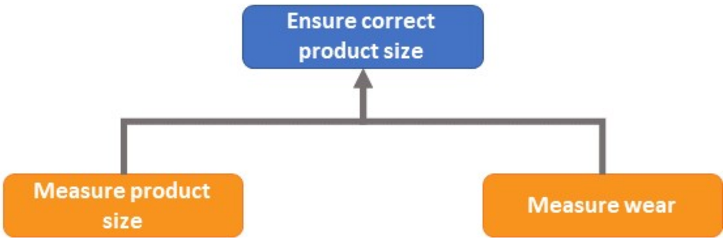


Figure 6.3: Function tree: Downstream process

information to the plant. The system will inform the plant management of product size as statistical data and measure the wear of the crusher. This would both extend the lifetime of wear-parts and enable better planning of wear-part changes.

6.3 Idea generation

The idea generation was based on the previous findings from the customer needs study, observations, technology study and the function analysis. As mentioned before, the process consisted of brainstorming sessions. They were conducted both during visits to NCC Tagene quarry and in the office, which allowed for different perspectives due to environment changes.

As was mentioned previously, the process can be viewed in three stages; Upstream process, primary crushing process and downstream process. When on-site, all of these stages were the environment for the brainstorming session. This involved looking at different placements of the technologies and looking at the different environments of each stage. As some of the technologies are sensitive to, for example differing light conditions, these were taken in to account when spawning ideas. Furthermore, the on-site visit allowed to see opportunities to extend the future functionalists of the intended system.

In fig. 6.4 below, four possible placement of sensors was identified. Here, the sensors looking at the truck could be placed to gain information regarding the size of blast material (1). Sensors could also be placed such that they are looking on to the tipping area and crusher feeder, which could enable measurement of blast material size and flow which would be used to predict jamming and provide analytic information(2). The crushing chamber itself is also a valuable point of investigation. Here, detection of jamming, flow inside the chamber and measurement of wear parts could be achieved through a sensor mounted above it looking straight down (3). In order to improve the downstream process and measure the outflow of the crusher, a sensor could be placed above the belt as well (4).

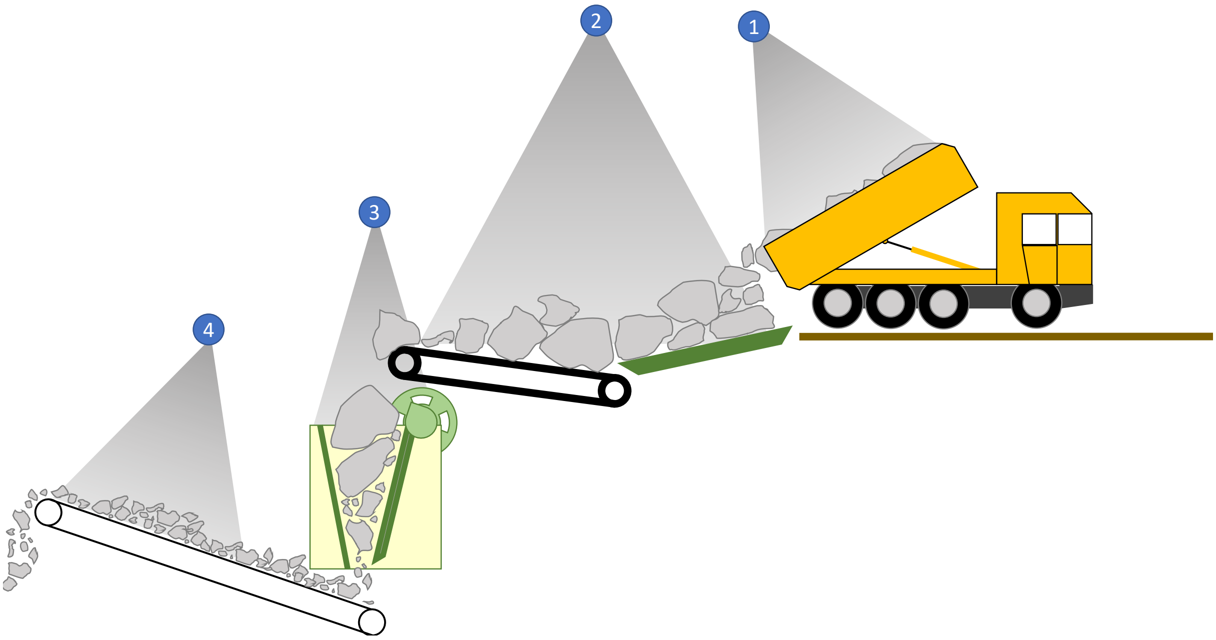


Figure 6.4: The possible placements of technologies identified on site

As depicted below in fig. 6.5, (1) and (2) are quite similar. (1), which consists of the different camera systems - single camera, TOF camera and stereo camera - can all be placed in a similar fashion. Their placement would provide full coverage of all the desired measurement points elaborated before. Also (2), which consists of a LiDAR system, has similar placement and ability to measure the desired aspects. These ideas of (1) and (2) are very flexible in their placement, as they will scan the whole scene at one time and allow for analysis. Moving on to (3) and (4), they both require some sort frame to keep them in place. (3) would require the structured light sensor to be encapsulated in order to reduce the interference of ambient light. Due to the encapsulation, it would only be suitable for use on the conveyor belt or feeder. As mentioned previously in chapter 5.2.4, it requires high computation time and perhaps many measurements, so it is questionable how suitable it would be on the outgoing conveyor. (4), which is the 2D line scanner, has the opposite problem. It requires constant speed of the object in order to get appropriate measurements. As such, it would not be an ideal solution for the crusher feeder.

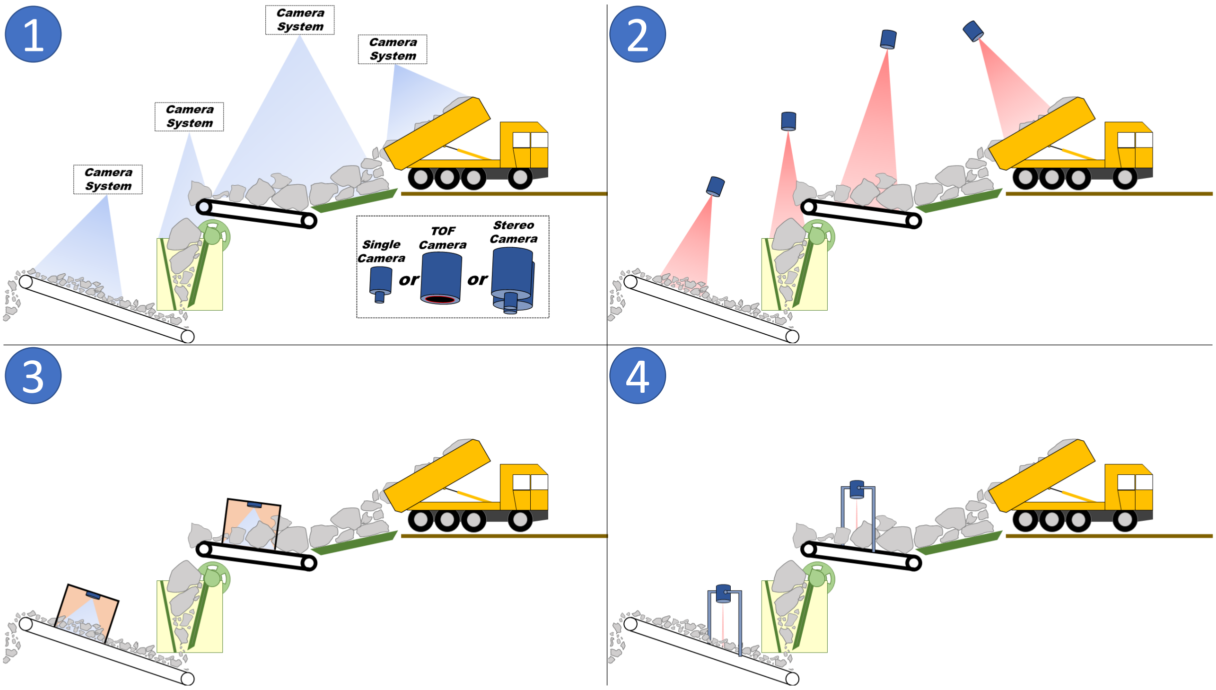


Figure 6.5: Implementation areas of each technology. (1): Single camera, TOF camera or Stereo camera. (2): LiDAR. (3): Structured light scanner. (4): 2D line scanner.

6.4 Concept generation

By combining different ideas from the idea generation, concepts were beginning to take form. At this stage most ideas accepted without reflecting too much of the realization and actual implementation of the system. However, to ensure that the team moved forward efficiently, the concepts were kept at a some what realistic level. All the concepts can be found in appendix D. With the basis of the idea generation and the technology research, the different technologies were placed at different stages of the process where it could be functional and potential solve the given problem. At this stage the focus was on the general idea of the technology and not on a detail level as that is to be considered on a later stage once the technologies would been evaluated.

6.4.1 Concept one

Concept one uses a stereo camera to solve all the given functions regarding the measurement. This means that the solution can be applied for all the functions that are required, such as measuring the material flow, size, position and such. Also, this solution does not need any further calibration on site that might be required for other solutions. Also regarding the installation of the system, it requires a low work effort since the placement of the system is more likely to be dependent on the surrounding environment such as lights conditions rather than the actual placement such as within a certain distance to the feeder and/or conveyor belt. This solution also uses an embedded system which makes the solution even more versatile when it comes to the whole solution. However, this means that the whole system also needs to withstand the harsh environment and live up the the IP classification that is required.

6.4.2 Concept two

Concept two is very much similar to concept one. It also uses a stereo camera to solve all the functions and therefore have all the benefits as concept one when it comes to the measuring system. What do differs is the way of process information. In this concept a server base solution is applied. This could be a on- or off-site server that do the computation of the information. The server based solution can be a good alternative if high computational power of the information is required that the embedded system may not provide to give a real time computational.

6.4.3 Concept three

This concept utilize both a camera and LiDAR in order to gather information about the material. The camera gather 2D information and together with the LiDAR it can be combined to achieve the size as well as position and wear. This solution requires a fixed installation that is predefined on beforehand. This solution also uses an embedded system which makes the solution even more versatile when it comes to the whole solution. However, this means that the whole system also needs to withstand the harsh environment and live up the the IP classification that is required.

6.4.4 Concept four

Concept four consist of a single camera and a 2D line-scanner. The 2D line-scanner will collect the 3D data to calculate such as size and wear while the camera will be used to find the position as well as measuring the flow of the system. This will require a fix installation as well as on-site calibration for the camera. This system utilized an embedded system so the system can be more versatile when it comes to placement.

6.4.5 Concept five

Much like the concept four, concept five uses both a single camera and a 2D line-scanner. All the information gathering is done with the same methods and it requires the same installation procedure when it comes to the vision system. What do differ is that it utilize a server instead combined with a app to provide the operator the information is needed.

6.4.6 Concept six

Concept six is based on a TOF-camera. This solution is much like concept one and two when it comes to the requirements of installation. It can be installed almost everywhere without the need of calibration. Also as mentioned in chapter 5.2.5 it can be used outdoors as well as indoors without extra lights which makes it a very flexible solution. Since the TOF-camera doesn't require as much computational power an embedded system is used together with a dedicated monitor.

6.4.7 Concept seven

This concept has both a stereo camera and also a 2D line-scanner. As the 2D line-scanner will not be enough to provide all the information, it would make it ideal to combine it with a stereo camera. This would most likely ensure that the point cloud is perfect but also ensures that the stone properties such as color etc is retained for analytic purposes. Since this system would require a high computational power a server would be the ideal case together with the visualization on the web that the operator can access anywhere.

6.4.8 Concept eight

The last concept, concept eight, is based on a structural light scanner. This system would be placed around a conveyor belt or similar to create a closed environment to achieve a good and stable measurement. However, this means that the installation will be much more complicated. Since the system is demanding a higher computational power to achieve real-time performance, a server was chosen to process information and were the information is visualized on app.

6.5 Concept screening and evaluation

Once all ideas have been exhausted and all concepts has been created, they need to be evaluated. This was done in two steps, first by the elimination matrix followed by the weighted Pugh matrix. In order to determine which concepts that are viable, they need to go through the elimination matrix first. The result from the elimination matrix can be found in appendix E. If a concept fails at one requirement it will be removed. As the table in appendix E shows, concept one, two and six passes the elimination matrix and therefore moves on to the next evaluation stage. Concept three, four, five and seven are eliminated due to the price. Therefore, they could be discarded for further evaluation with this approach. Furthermore, concept eight failed due to the fact that the technology would not be able to handle the amount of data.

The concepts that passed, concept one, two and six, need to be further evaluated in order to make a decision on which concept to further develop. As the remaining concepts fulfill the requirements, the next step is to compare and evaluate the desires. This is realized with a weighted Pugh matrix that can be found in appendix F.

The result from the weighted Pugh matrix shows that concept one is the best when it comes to the overall performance. However, since the total weight of all criteria is 143, the other concepts falls close behind concept one. This means that concept two might be more beneficial in some cases where there is a need for more data collection. This also means that there is a need for higher computational power and that there is already a control room close by where the server can be placed. Even if concept three falls close behind with respect to the score, concept one outperform it in more vital desires such as *Measure individual rocks - Target dimension accuracy*, therefore making this concept less desirable.

With the result from both the idea generation as well as concept generation and evaluation, concept one is chosen for further testing and development. The concept does not only show the most potential but also proves to be highly versatile when it comes to placement. As highlighted in chapter 3, even if the crushing process may look the same at different quarries, the setup and prerequisite may vary considerably.

7

Software research

The software reserach involves finding methods for solving the stereo vision task. This includes processing the information with a computer for real-time calculation, solving the stereo vision problem from a hardware perspective and a algorithm perspective, finding methods to obtain flow of pixels in an image and the segmentation of individual objects, in this case rocks. This chapter briefly presents methods for these tasks. The findings in this chapter are then used for the subsequent software development, where the methods researched are implemented in to software to solve the functions presented in chapter 6.2.

7.1 Processing approach

The most popular processing architecture for general purpose computing is the use of one or several central processing units (CPU). Usually, the CPU is the only processing hardware available in a device and as such it has to handle not only the software for computing the task at hand, but also to handle the background processes such as the operating system (OS). Modern CPUs have multiple cores (processing units), called multi-core processors, which has enabled execution of multiple instructions in in parallel, depending on the instructions. In general, one can say that –for a highly parallel tasks– having more processing cores results in faster computation. See figure 7.1 for an intuitive explanation of multi-processing on a quad-core CPU.

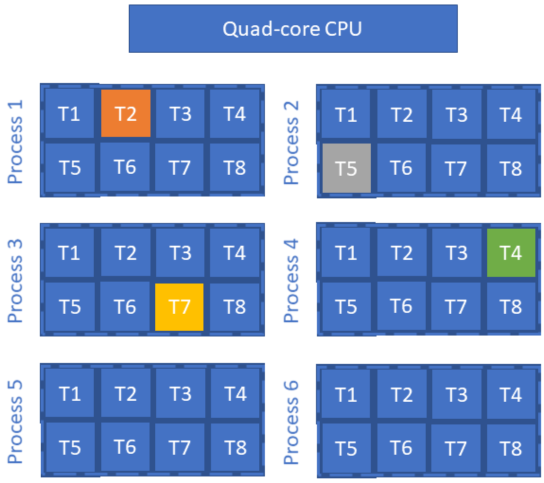


Figure 7.1: A quad-core (4 core) CPU running 6 processes. The CPU simultaneously executes 4 threads (T2 in orange, T5 in gray, T7 in yellow and T4 in green) from 4 processes at the moment and the remaining two processes are on stand-by to receive CPU time.

Graphics processing units (GPU) have become an important topic for image related tasks as they have the advantage of having hundreds of *"processor cores"* on their silicone die. GPUs used for general processing are known as general purpose graphics processing unit (GPGPU). On the chip, they have multiple processors called *Streaming multi-processors* with a large array of cores. As there is a greater number of cores and that they are optimized for graphics processing tasks they become very powerful for image processing and computer vision.

As the intended hardware solution for the final product was chosen to be an embedded system together with a stereo vision camera setup, an ideal solution would be to leverage the inherently parallel task by using a multi-core system with both CPU and GPU cores. The current market leader in this segment is Nvidia Corporation with the Jetson TX2 embedded system. It features two multi-core ARM processors and a graphics processor on board. The development of such a system would involve traditional programming methods but also Nvidia's CUDA architecture. The CPU is still the main processing unit which handles all system related tasks, the applications and communication with other hardware. The GPU is a stand-alone processing unit which is fed with a data stream from the CPU. The CPU (host) streams, or uploads, data to the GPU (device) for processing. The device performs all calculations that were instructed, and then the host downloads the processed data. When the data is streamed to the device from the host, it is split up in to kernel grids, thread blocks and threads.

Each kernel grid contains a number of thread blocks, each thread block contain a number of threads. The threads in this case is similar to threads of a normal CPU. The complete GPU unit contains a number of streaming multiprocessors which in turn contain a number of cores. Each thread is executed by each core, each thread block is executed by each streaming multiprocessor and each kernel grid is executed by the complete GPU unit.

In fig. 7.2, a simple illustration showing the increased amount of processing power for pixel operations that a modern GPU can offer. As an example, the Jetson TX2's graphics processing unit contains one streaming multi-processor chip with 256 cores. As each thread is executed by each core, it amounts to a total of 256 threads executing pixel operations at any given time. In contrast, the Jetson TX2 offers 6 CPU cores which can run 1 thread simultaneously. In theory, the GPU would be able to process an image around 42 times faster than the CPU. In reality, one can expect performance gains ranging from 3 to 10 times faster when comparing to a CPU. Furthermore, moving data from CPU to GPU can take significant time, the data set has to be sufficiently large in order to justify using the GPU for calculations. In figure fig. 7.2, one can see that the required number of CPU operations, n, is much greater than the number of GPU operators, m. Hence, $n >> m$.

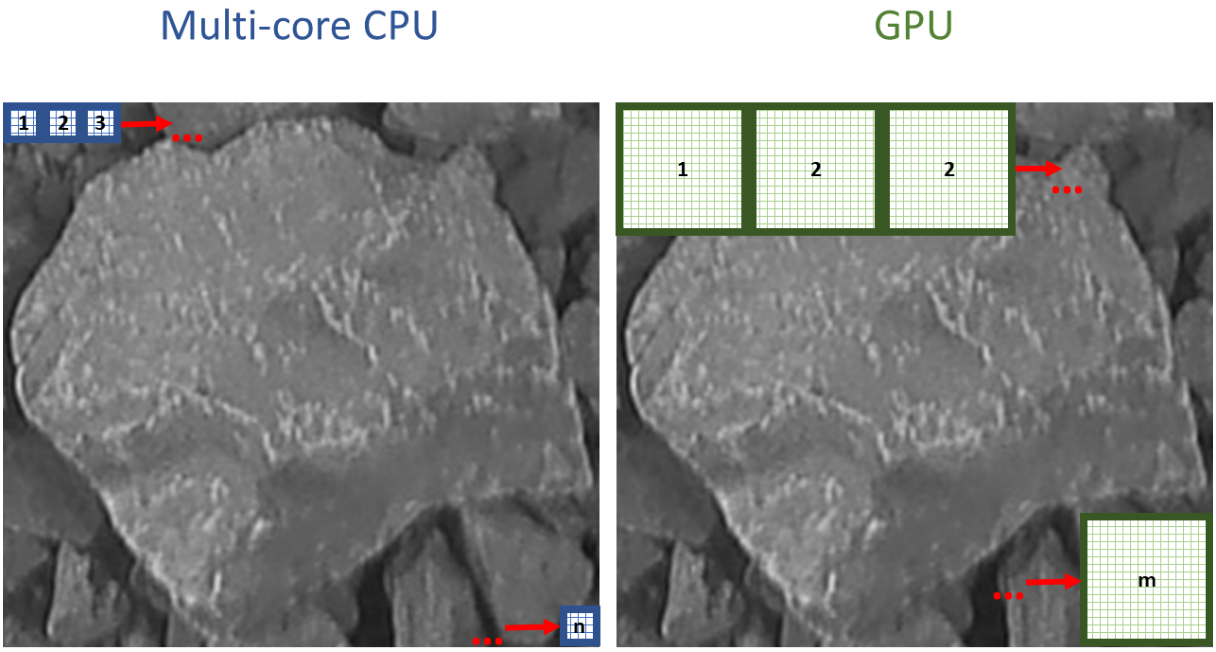


Figure 7.2: Simplified illustration depicting the larger amount of pixels a GPU can process at once, compared to a CPU.

7.2 Image processing techniques

When it comes to image processing techniques, there are many viable methods that serves different purposes. Depending on what information is gathered, it can be used in various ways. One of the more common techniques is edge detection that is used to detect edges, hence the name, of an object. The core function of the technique is based on a gray-scale image were a comparison between every pixel and its neighbors is performed. If the value change drastically it indicates a change which in most cases are an edge, but not always. There are problems with false edges that can be created by many factors. These factors can consist of light differs, noise, shadows, distance etc. To avoid this, a controlled environment is desired but not always easy to achieve. That is why there are multiple methods available to do edge detection that has their own benefits and drawbacks. This means that there are no method that is the given choice, it will more be depending on case. Some of the most commonly used methods are Soble, Canny and Laplacian. These methods can be divided into two different types, gradient based and zero-cross based. The gradient based method utilize a matrix to determined how much the surrounding neighbors effect the given point. The zero-cross based method utilize the first and second derivative to find where the value is changing and by that finding the edge of an object. The result is also depending on the original resolution and its quality in order to achieve a good result. A higher resolution means more pixels within the image which theoretically means that the line should be more precis. However, with a higher resolution there is a risk with obtaining more noise that the algorithm will identify as an edge. To improve the result of the edge detection there are ways to manipulate the picture. One method that is commonly used is to smooth the image with a filter, such as a Gaussian filter. By applying the filter, the noise will be reduced and therefor removing a large number of false edges and increasing the possibility to detect edges that would otherwise be left out. Other methods to manipulate the image are usually used, such as changing the lighting and/or inverting the image. Also, applying different filters such as bilateral filter or different kinds of blur is a possible way to enhance the edges. However, same as the edge detection method, there are no given filter or method that is the given choice. It will be more a matter of testing to conclude which method is more appropriate for the given case.

Another aspect that is possible to compare is the colour of the image and how it alters between the pixel and its neighbors. This technique utilizes the information with the colour that otherwise would be dismissed in methods such as Soble, Canny etc. that requires a gray-scale image. However, since it uses more information the computational power needed will increase and therefor either take longer time or require better hardware. However, the colour does not differ much between rocks which means that the technique will not be as favorable as in other industries and cases (C.Akinlar and Topal, 2017).

7.3 Stereo vision

Stereo vision involves using images from two or more cameras to calculate the depth by means of triangulation. Given two images with the same object in each image, all points of the object are present i both images but with a certain shift in position. This shift, which is caused by the image sensor being separated by a certain distance, can be used to obtain the real-world coordinates of all the matching pixels in both images. By convention, the left image is used as the reference image. This means that for all objects where the same pixel exist in both images, the distance between them can be calculated. This distance, or shift, is called disparity, which is illustrated in figure 7.4. If the object moves further away from the camera, the disparity increases. Thus, there are three major topics in this segment, the camera model, the stereo correspondence problem and distance calculation.

7.3.1 Camera model

To simplify the triangulation, a simple *Pin-hole camera model* with two cameras, parallel image planes and camera center axis offset called *baseline* can be used. This is shown in fig. 7.3.

The pinhole camera model can be described as having a box with a small pinhole on one wall. The light from the scene will pass through the pinhole and be projected on to the back wall of the box, as shown in fig. 7.3 below. The point P is a point in the 3D world coordinate system, with coordinates $(x1, x2, x3)$. Point C is a point in the on the 2D image plane, with coordinates $(y1, y2)$. Distance f is the focal length of the camera and is known. When looking in the negative $X1$ and $X2$ direction, one can identify two rectangles. These rectangles directly map point P to point C through the following relationship. Looking from the negative $X1$ direction, $y1 = \frac{-fx1}{x3}$. A similar equation can be extracted when looking at the negative $X2$. Thus, the following maps the point P to point C $\begin{pmatrix} y1 \\ y2 \end{pmatrix} = \frac{-f}{x3} \begin{pmatrix} x1 \\ x2 \end{pmatrix}$.

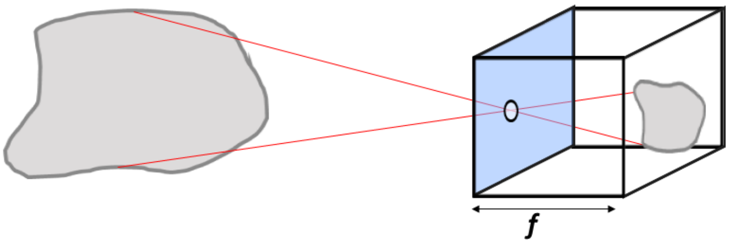


Figure 7.3: How the pinhole camera aperture projects an image

The pinhole camera model is a very simple representation of a complex physical device. It does not take in to account the lens distortion, which is an important pre-requirement for stereo correspondence. Thankfully, as distortion from lenses is constant given the same zoom and focal length, it can be removed through transforming the captured image by calibrating the camera from a known checker-board pattern.

7.3.2 Stereo correspondence

The stereo correspondence problem is another key component of stereo vision. As the triangulation to obtain distance is based on the pixel distance between objects present in both left and right image, the quality of matching two pixels directly influences the quality of the distance measurement. The distance is known as the disparity, shown in fig. 7.4.

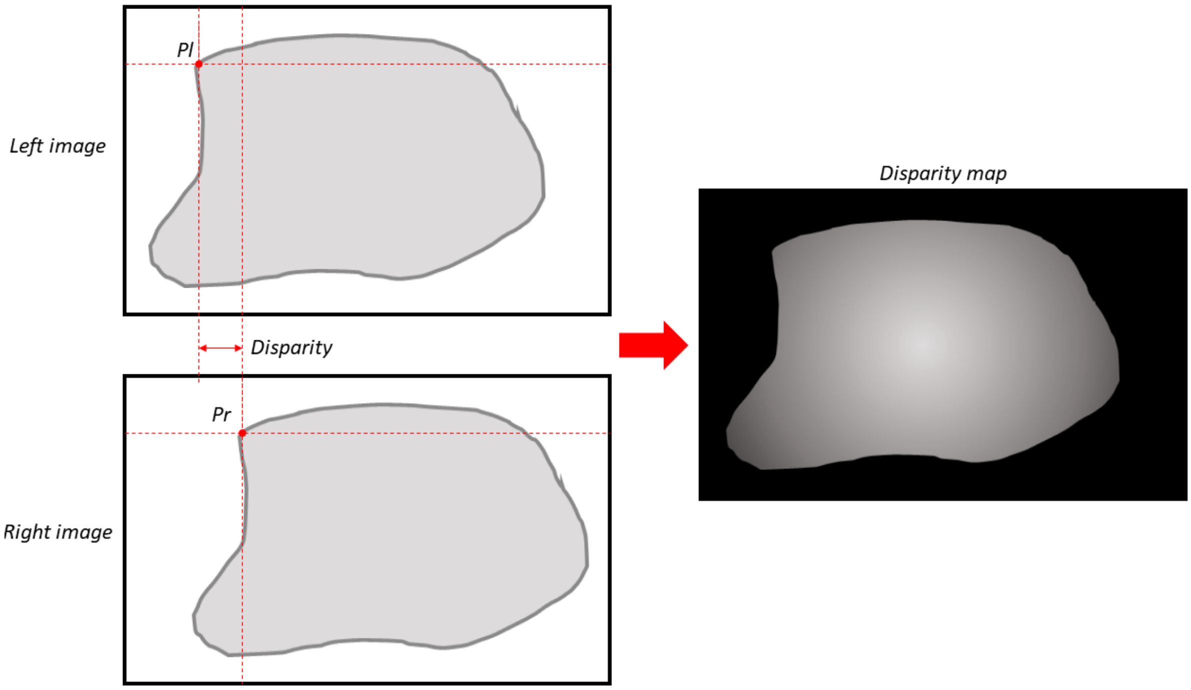


Figure 7.4: In the left image point *Pl* is investigated. The algorithm finds the same point in the right image, *Pr*. In the *disparity map*, brighter values means that the object is closer to the camera, darker values mean it is further away.

There are many algorithms to solve the stereo correspondence problem. The area itself has undergone a significant amount of research as well as development in recent years. While most algorithms are focused on obtaining the best possible matching, they require a lot of computation time. In order to achieve close to real-time performance, block matching algorithms have been developed. For a grid of pixels in the left image, a search is conducted in the right image to find a matching pair of features or points. This particular algorithm searches along the row of the chosen pixel for a matching pair. The search area is usually restricted to within a few pixels. The image regions are then compared using the sum of absolute differences (SAD) and a matching pair is found. This approach is very efficient computation wise, but can produce wrong estimations of depth as well as noise. This is highly visible in images where there are not a lot of features on a surface. The featureless regions would cause the algorithm to find the wrong match, as all of the pixels in the search range have equal or very similar values.

7.3.3 Distance calculation

When the depth map has been extracted from the stereo image pair, actual depth can easily be calculated given the previous assumptions. If the camera lens distortion is removed by calibration and rectification as well as the two cameras being planar and only off-set by baseline b, as shown in fig. 7.5.

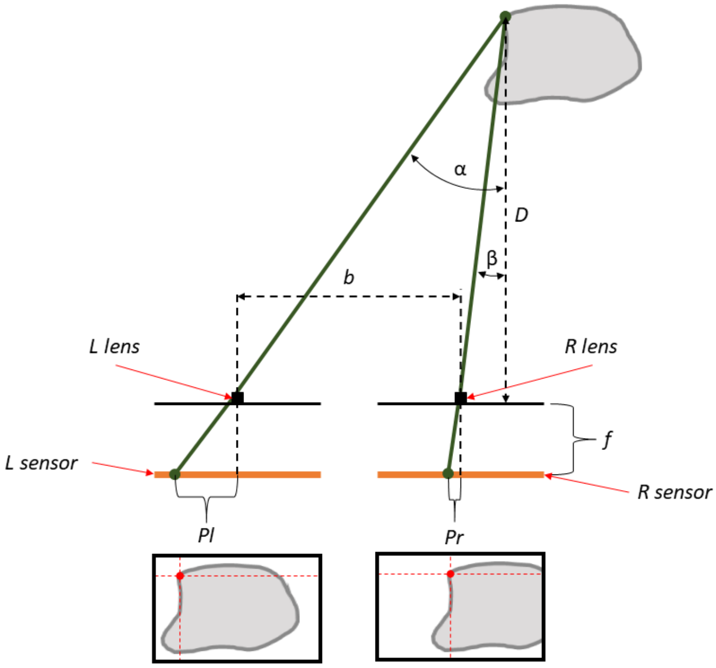


Figure 7.5: Triangulation of a real-world point given an image point and camera parameters.

The depth can be derived from the equal triangles shown in above figure. This would result in the depth being calculated as follows: $D = \frac{f*b}{d}$. Depth D is the depth from the camera lens aperture to the point on the rock in meters. Baseline b is the camera offset distance in meters. Focal length f is the the lens property given by the manufacturer of the lens, in meters. The displacement d is calculated as $d = \mid Pl \mid - \mid Pr \mid$ measured from each image planes origo. As a pixel is a physical sensor part of the photo-sensor array of the camera, each pixel that is captured by this camera would have a size that is the same as the sensor size. As such, displacement d is in meters. The *baseline* is the distance between the camera center axis. This measurement, given the same camera field of view, allows for objects to be detected either closer to the camera or further away from the camera. In fig. 7.6, the red area indicates the zone where objects can be fully seen by both cameras.

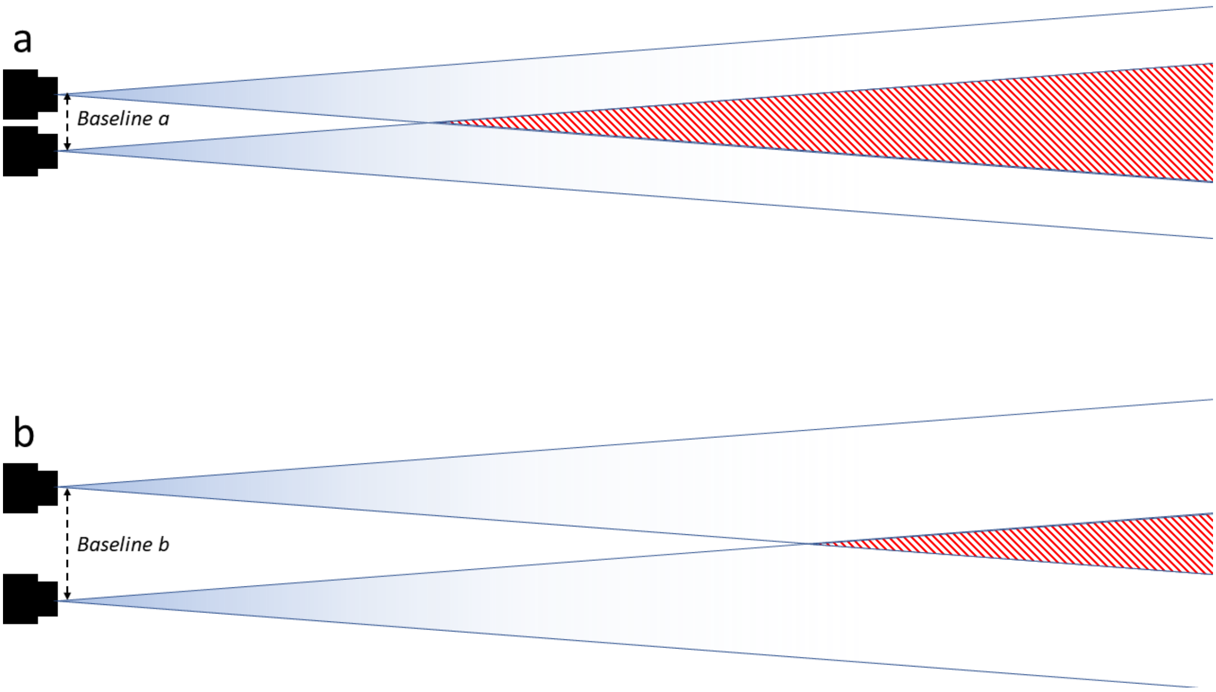


Figure 7.6: Camera (a) has a shorter baseline than camera (b). This allows camera (a) to see closer objects than camera (b).

In fig. 7.7, the importance of choosing a correct baseline can be seen. When the rock is at position a, it can be fully seen by both cameras and a disparity can clearly be calculated since the red point is clearly shifted in both images. When the object is moved further away towards point b, the shift becomes gradually smaller. At point b, there is no clear shift between the points. The camera would then be unable to measure the object. Fortunately, if the baseline is increased, the object would become measurable again.

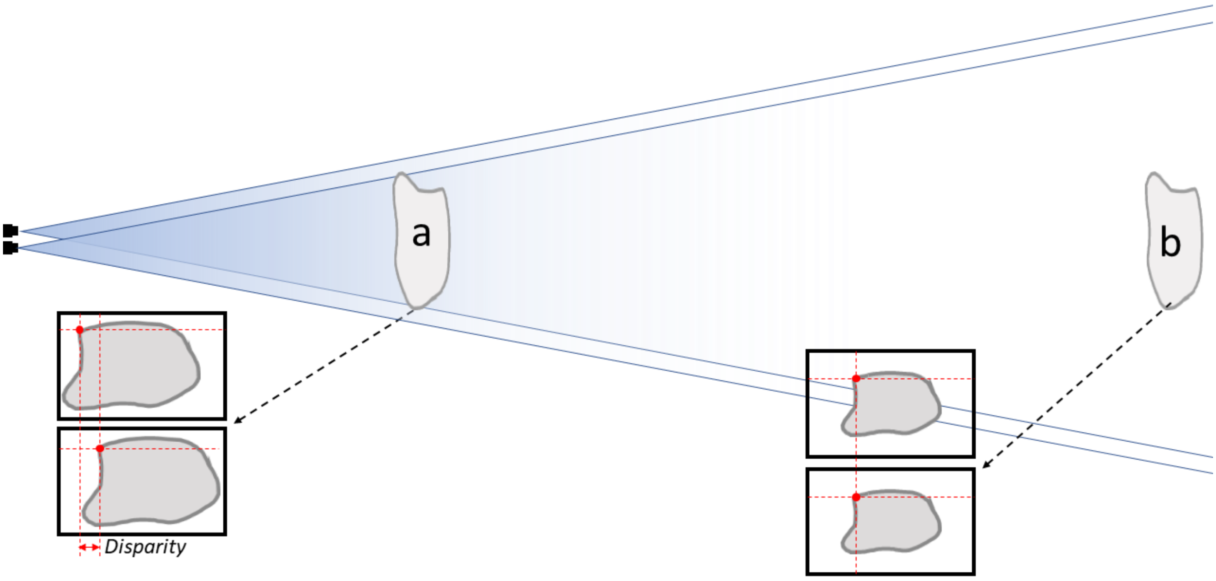


Figure 7.7: Object at position a can be properly measured. At position b, the disparity shift is zero, which inhibits the measurement of the object at this distance.

7.4 Optical flow

Optical flow is the apparent movement of an object from one image to another. Much like the stereo correspondence problem shown earlier, the goal is to match pixels from two images. As shown in fig. 7.8, there are two components of the optical flow. *Magnitude* is the size of the motion vector and *angle* is the angle from the point in image one to the same point in image two. A popular algorithm for dense optical flow is the "Farnbäck" algorithm, (G. Farnebäck, 2003). In the first frame, a region is selected. In the second frame, neighbouring regions are inspected to find a match. Then a motion vector between the origin and the matched region is calculated. The magnitude is the pixel distance.
Figure 7.8 shows a simplified illustration of dense optical flow. In *a*, the first and second frame can be viewd. There is a clear shift of the rock towards the upper right corner in the second frame. Running the algorithm, it would calculate the magnitude and angle of the points on the rock. Shown in *b* is the motion vector of the rock's edge. In *c*, a color representation of the movement is shown. In order to visualize the motion vector in an image, the magnitude and angle is mapped to a hue-saturation-value (HSV) color space. The magnitude of the vector is the saturation value and the hue shows the angle. The value color channel is fixed.

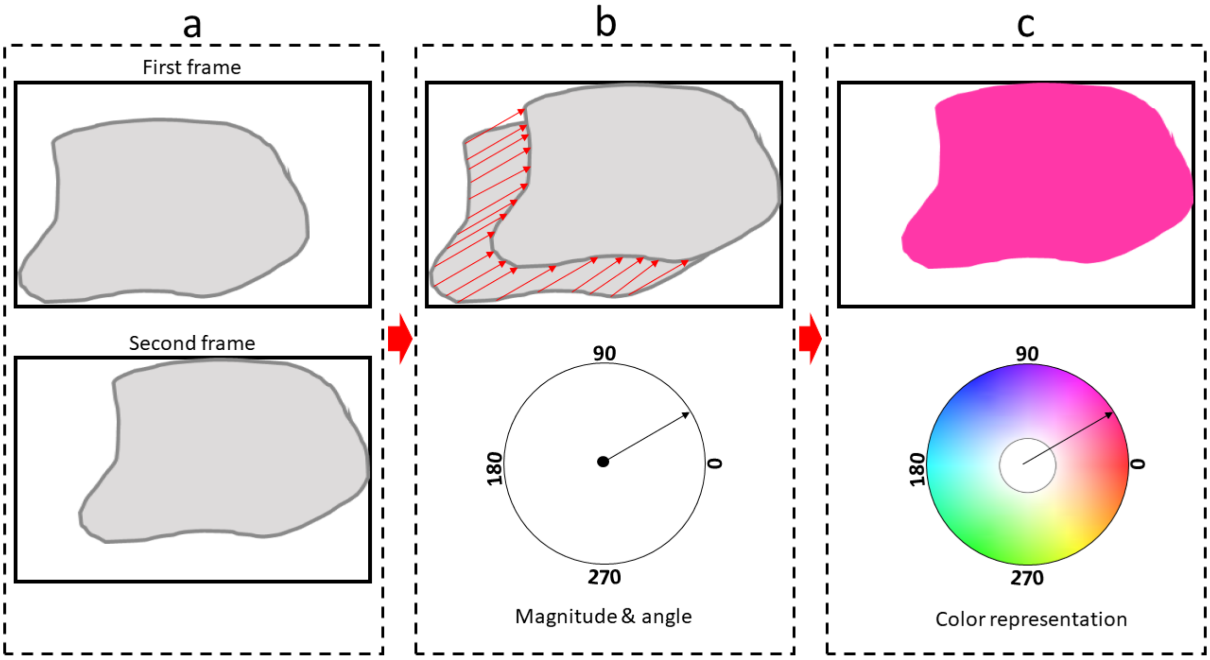


Figure 7.8: Illustration of optical flow.

7.5 Image segmentation

Once it comes to image segmentation, there are a many ways to approach the given task. Even though the approach may vary the idea remains the same. The main idea and use of the segmentation is to separate objects from each other for reasons such as visualization, measurement or analyzing purpose. For the given problem, there are two approaches that remains highly relevant 3D point cloud and watershed segmentation.

7.5.1 3D point cloud segmentation

With the information gathered from systems that regenerate the 3D surface there are much information that can be gathered. Systems like stereo camera and LiDAR are just some of the systems that do have the ability to gather the 3D information about the surface of the object, more information about these systems can be found in chapter 5.2 3D technologies. The most commonly used technique for segmentation is based on clustering of 3D points close to an object. This requires a precise depth map. Then the segmentation can be based around the distance between the points. Meaning that if the distance between is greater than a certain value, it is assumed that the they are two different objects. The problem with this technique is that it relies heavily on the quality of the point cloud.

The other way to use 3D point cloud to do segmentation is a combination between the previously method as well as taking the distance into consideration. By using the distance there are a possibility to detect the edge on an object. The problem with this method is that the methods can "argue against each other" for example if two stones are overlapping but there are less to none difference in the height between them. The distance technique will indicate that the stones are the same object while the more commonly used technique will indicate that they are different object. In theory both of these techniques will work but usually the biggest problem when using 3D point cloud segmentation is that the accuracy of the point cloud as well as noise that that will be produced by the system. The noise can be reduced but it is highly dependent on the system and how much noise that is being produced.

7.5.2 Watershed segmentation

It is possible to do image segmentation in a 2D picture by using a powerful tool, the watershed method. This method is based on an iterative process. The idea behind the method is that it utilizes the high and low peaks of a gray-scale image to determined whether an object is within the image. It enhances the value for every small peak to ensure that it won't blend in with the surroundings. This is often explained with the analogy of a water filled valley, illustration can be seen in fig. 7.9. If the waters enters a isolated valley and as soon as it reached the first peak it creates a border, preventing the water to over flood. It continue to do this for every peak and the border grows until the highest peak in the valley. The watershed method enhance every small peak to the same value as the maximum peak has. The problem with the watershed segmentation is similar to the 3D point cloud. If any noise exists, which it will enviably do, the watershed will increases theses as well and create objects that do not exist in the original image. This is often called over-segmentation. Another problem is the under-segmentation of the result. This often occur if the method has been to limited to much to achieve a viable result. Similar to the edge detection system, this will be highly dependent on the surrounding factors to reduce the noise to a lower level. However, this approach has been highlighted in other industries that faces similar problems were the objects are similar to each other. Industries such medical were it been used to find and highlight cells were it has proven great results.

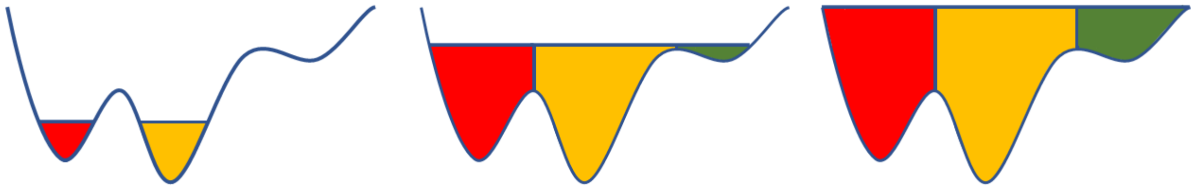


Figure 7.9: Illustration of how watershed works.

8

Software development

8.1 Development approach

As previously mentioned in chapter 7, the different methods are highly dependent on the surrounding environment as well as set-up in general which means that a more traditional way of development, were system are fully developed before being tested, would not be a suitable approach. Also as previously mentioned, the different methods show great potential in different areas, meaning they could not be excluded. Approaching development in an traditional way would be extremely time consuming and not feasible within the time frame of this thesis. Therefore, a “Design-Test-Build” oriented approach would be a better choice seeing that the different methods has their own benefits and drawbacks that would not come completely clear until being tested. Even though this approach is more meant for development of hardware solutions, it can also be used as a development approach when it comes to software development. Once the initial design and tests showed progress the development for the methods continues to further optimize the methods.

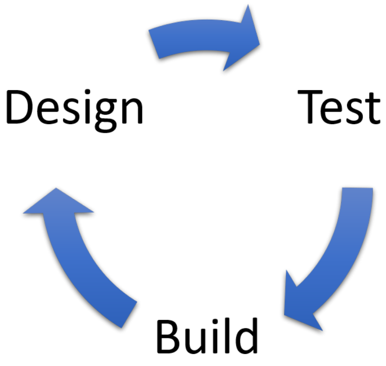


Figure 8.1: Design-Test-Build approach

Also by taking the “Design-Test-Build” approach, enabled working concurrently with different methods but also quickly change or discard different approach once its proven to be an invalid solution to a certain problem. By designing the solution in different steps that weren’t depending on each other was a necessary step to ensure that different solutions could be developed concurrently. This also meant that designing the solutions in small steps and then testing it to ensure that it functioned before moving on to the next step. By doing this also meant that the team always had something to fall back on if something did not function as intended without the need to restart from scratch. Even if the testing may take up extra time, it is essential to not waste valuable time on solutions that may not work once fully developed.

8.2 Measuring material flow

An important factor for the crushing process is the incoming material. There for it should be natural to measure and evaluate the flow of the incoming material to the crusher, both in short term but also long term.

8.2.1 Proposed method

The proposed method for measuring material flow is shown as a black-box model in fig. 8.2. It is an important part of the detection of jamming and provides valuable information for producing performance reports of the primary crushing process. The subroutine takes a single video camera stream –*Video stream left camera*–, a predetermined flow direction of the feeder –*Feeder flow direction*– and a region of interest mask. The scene for the video stream can either be just the feeder, the crushing chamber or both. In the case of investigating the material flow on the feeder, the physical direction of the flow would need to be input in to the function from a user interface, since the camera can be placed in any arbitrary position. In order to reduce the computation time, unwanted areas are removed by the *Region of interest mask*. There are two output from this subroutine, *Flow regions* and *Flow speed*. The flow regions indicate where there is flow in the image. For example, if both the crushing chamber and the feeder is present in the same video stream scene, the flow regions would be the area on the feeder and the area inside the crushing chamber. The information would help to extract relevant data for generating improvement reports. The flow speed provides the current magnitude of the flow vector. The output can either be *off, low speed, medium speed and high speed*. As described in chapter 7.4, the magnitude of the flow is determined by how many pixels the object has moved between two frames. As such, the output is related to pixels and frames, not physical distances and time.

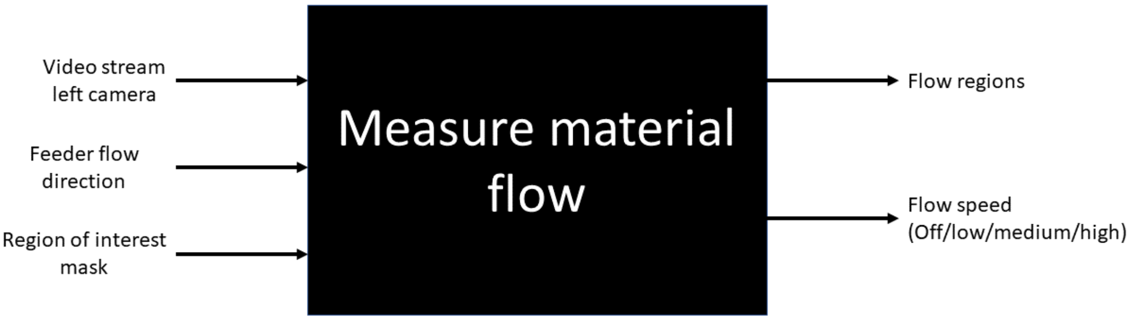


Figure 8.2: Black-box model of subroutine

Each video frame from the stream is subjected to several image processing techniques and algorithms in order to produce the desired output. The procedure to obtain the output from the subroutine inputs is shown by a flow diagram in fig. 8.3. First, the frame is masked off with the region of interest mask. As reducing the number of pixels being processed directly influences the subroutine execution time, this is an important first step. The masked image is then altered by changing its brightness and contrast through histogram equalization. As the dense optical flow algorithm works by matching features in two images, the contrast change helps to bring out more distinct features of the image.

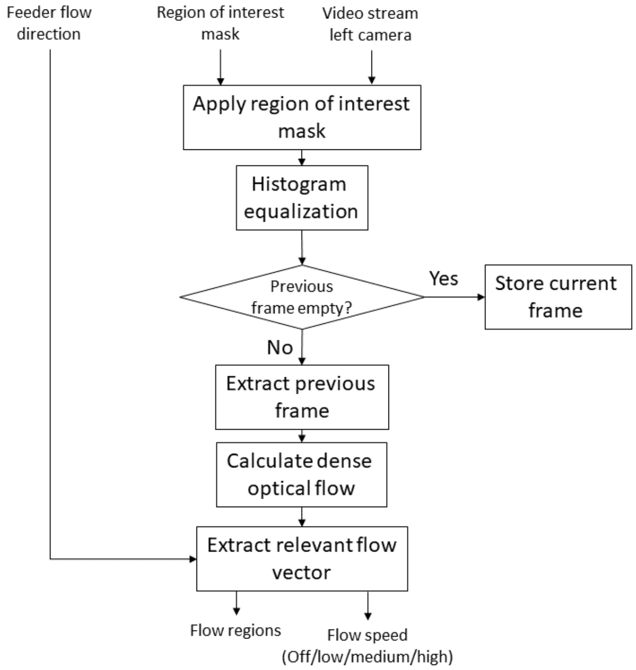


Figure 8.3: Subroutine flow chart

The optical flow algorithm requires two frame in order to compute the pixel distance change of a moving object. As such, on start-up, the first frame has to be skipped and stored so that the displacement can be calculated using the next frame. Subsequently, all frames are stored and used to calculate the optical flow from the upcoming frames. The optical flow itself is calculated as shown in chapter 7.4. As only the flow in the feeding direction is of interest, the feeder flow direction is used to extract only this relevant vector angle. The remaining flow vectors are then categorized in to both their location, i.e. the flow region, and the magnitude of the vector and become the output of this subroutine.

8.3 Measuring material size

The result from the software research showed that there are multiple ways to enable segmentation and measurement objects. However, the testing quickly showed that there were substantial problems with the generated point cloud. The problem is highlighted in fig. 11.8, picture A, where the image is taken from above. The problem with the point cloud is that the points is distributed in layers. When testing, the distance between the layers was usually at a fixed distance of 5 cm. This became problematic when segmenting the rocks, since there are no distinct differences between the height of the rocks. Hence, segmentation of the point cloud is not a viable option with the chosen hardware.

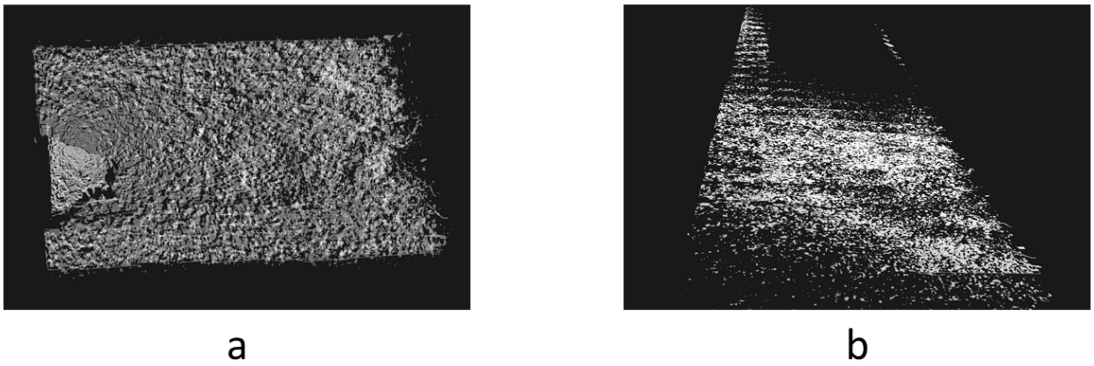


Figure 8.4: a: *The generated point cloud for the overview of the feeder*, b: *Side view of the point cloud*

8.3.1 Proposed method

Measuring material size is the core function in order to predict jamming of the crusher as well as provide important and valuable information for producing reports regarding the result for the blasting process and size distribution. The subroutine is shown in the black-box diagram, fig. 8.5, where the required inputs are shown in order to produce the output of the function, the rock size. As shown, the subroutine requires the video stream from both the right and left camera is utilized in order to calculate the depth map. In addition, one video stream from the left camera and the region of interest mask is needed. The mask is applied to reduce the need for extra calculation power in areas that remains irrelevant. With the these inputs it is possible to perform segmentation in order to extract the rocks as single objects that can than be combined in order to extract the rock size. A flow chart of the subroutine is shown in fig. 8.6.

Figure 8.5: Black-box model of subroutine

The output of the subroutine is the rock size for each and every segmented rock. The information will then be used in other subroutines to determined what the next step will be, whether the rock can potentially be causing the crusher to be jammed and/or if the information should be used for information purposes. This will be further discussed in section *8.5 Jammed crusher detection* and in *section 8.6 Visualization and generating report.*

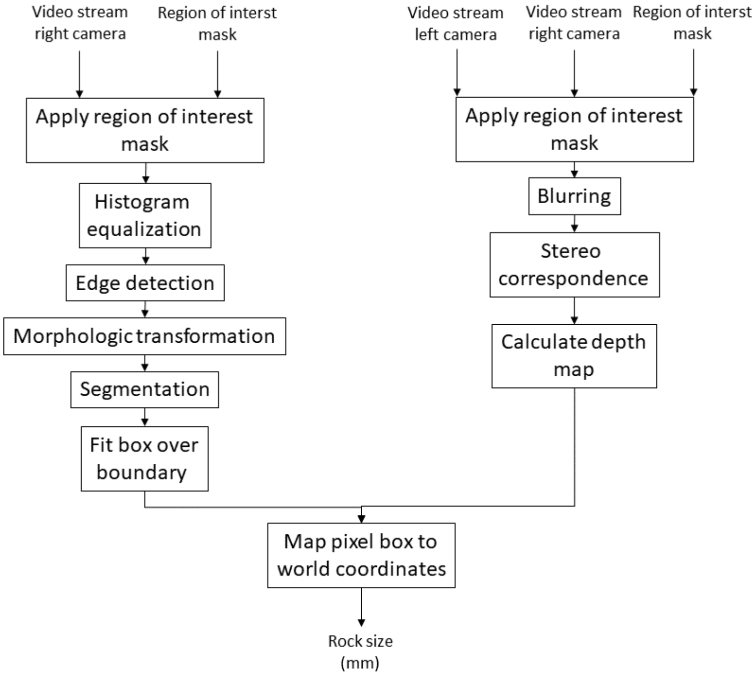


Figure 8.6: Subroutine flow chart

8.4 Measuring wear parts

An important factor for the plant process planning is wear part replacement. As this is part of routine maintenance, extending the time between wear part changes can increase the utilization of the crusher itself.

Proposed method

As the crushed material size depends on the sizing gap parameter,shown in fig. 8.7, measuring this can help to increase wear part life, optimize the power draw of the crusher and ensure that the crushed rock is within specs. The subroutine to measure the wear parts is quite simple. Two camera streams, *Video stream right camera* and *Video stream left camera* are used in conjunction with a region of interest mask to scan the crusher wear parts. The output of this scan is the wear parts dimensions, which can be used in later stages to determine the css, css change over time and the wear over time.

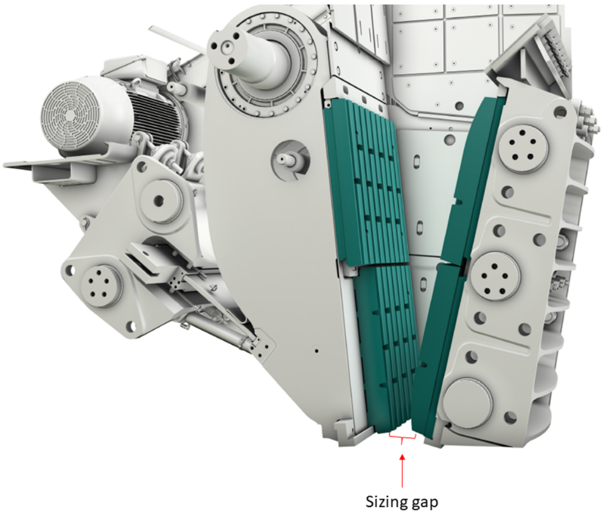


Figure 8.7: Metso jaw crusher sizing gap

Figure 8.8: Black-box model of subroutine

First, a check is conducted in order to ensure that there is no material in the crusher. If this check is passed, the crusher wear parts are scanned and then stored. This process is identical to the stereo vision part of fig. 8.6 and is presented as a separate subroutine in fig. 8.9.

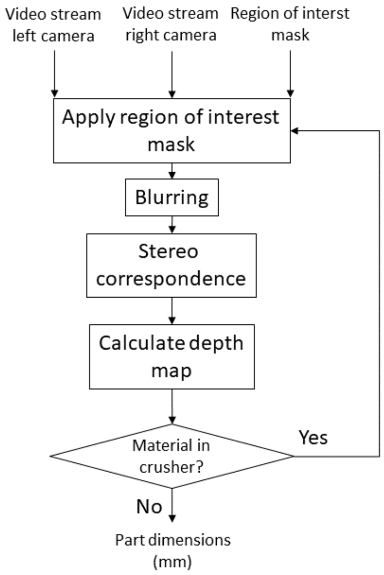


Figure 8.9: Subroutine flow chart

8.5 Jammed crusher detection

Information gathered in previous subroutines are now combined and evaluated in order to predict and/or determine if the crusher is jammed,

8.5.1 Proposed method

The proposed method uses the product of the previously described subroutines, such as *Flow regions* and *Rock size* to determine if the crusher is jammed, hence the output *Jamming*. As for the remaining inputs, video stream and *Region of interest mask* is used to determined and evaluate the material level that is present within the crusher it self. This will give an indication of what the problem can be for the operator. But it will also be a tool to evaluate the utilization of the crusher regarding the downtime but also how the material level varies within the crusher. If the crusher is under utilized the material level in the crusher will be at a low level, meaning that the crusher is not used at it full potential.

Figure 8.10: Black-box model of subroutine

8.6 Visualization and generating report

During the course of the thesis work Roctim introduced a cloud service for machines and plants. This would be a natural step towards visualization of data from the proposed system. The system would then only need simple interfaces for set-up along with windows for basic graph visualizations of the data. The reports for process improvement would then be off-loaded to the cloud. As the operators are often tending to other machines or duties, alarms could be displayed on a phone. There they could see see valuable information, such as alarm texts and also a video stream showing the actual situation. For example, they would then be able to instantly see what the problem is as well as using their own judgment and experience to determined if the crusher is jammed or if it will manage to process the material.

9

Commercialization

The most important aspect of a product is creating value for the customer. In this chapter the product offering and return on investment for the end customer is covered, which gives an idea of the differentiating points of the proposed system given the current market situation.

9.1 Process improvement

The main selling point for the product is the way it can improve the crushing process of the plant. As the proposed system would be used as an analysis tool of the primary process, the product itself cannot improve the process. Rather, it would give the plant the ability to gain a better overview of the process. It is then up to the customer to act upon information they receive. As such, any improvement is mainly in the hands of the customer, not the product. Thus, the selling points of the product would be what kind of data it can provide and what kind of improvements this would have the potential for. In fig. 9.1, the level of process improvement and the time it takes for the improvement to yield results can be viewed. The graph gives a rough estimate of this relationship as well as where the information is used.

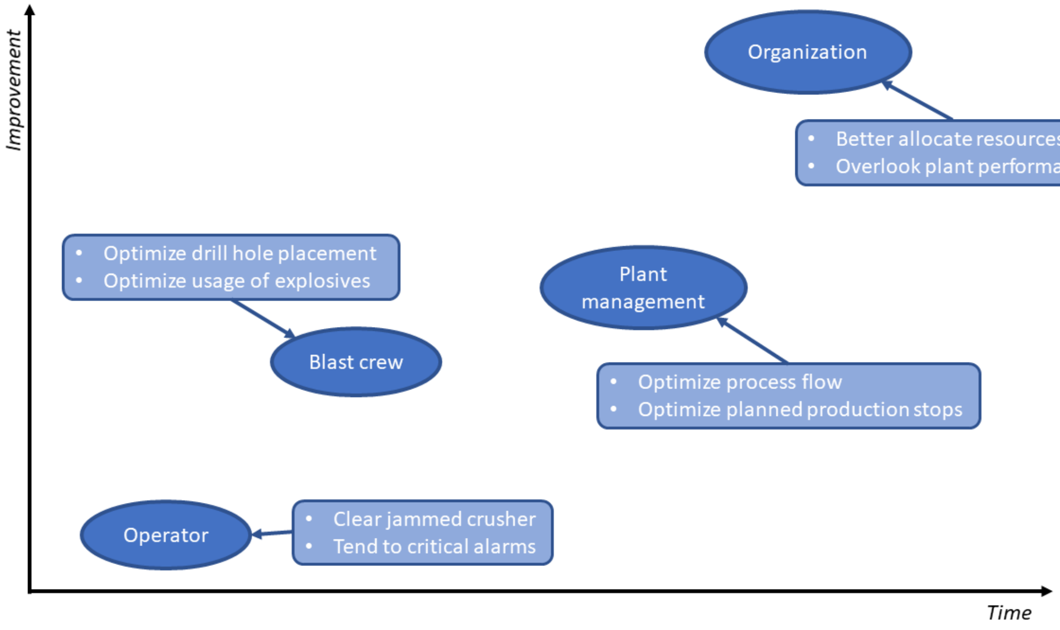


Figure 9.1: Subroutine flow chart

9.1.1 Operator level

The improvements made by an operator can typically be measured in hours. The operator can typically not improve the overall process by making their own decisions. As their main responsibility is to take care of the daily operation of a few machines, their impact would be seen as keeping the current process running more smoothly. They are also the people who have direct control over the machines. As such, information regarding alarms and jamming is a key point for this level. The level of improvements that can be made highly depend on their experience and knowledge of the process. The system would be able to leverage their current abilities by providing accurate information and allow them to be more efficient by providing them with alarms and the severity of the alarm.

9.1.2 Blast crew level

The blasting crews work with drilling holes in the rock and then fill them with explosives. The amount of holes that are drilled and the amount of explosives used to blast the rock directly impacts the resources used at the plant. In order to optimize this process, the proposed system would give the blasting crew a performance report of their work and give suggestions how to improve the blasting. As there is an optimal range where the size of blast rock should be, they can see from the report whether they need to use more or less drilling and blasting. If the performance report tells the crew that the material was too fine to crush, they would drill less holes and use less explosives in the future. That would result in the crusher being utilized more and also reduce the drill and blast costs. If the blasted rocks are too large for the crusher, the crew is using too little drilling and blasting, which leads to production stops at the primary crusher. As such, the performance reports would take the process improvement to another level. Although a slower improvement time, it would still be in the range of a few days to a few weeks for the improvement to take effect.

9.1.3 Plant management level

Plant management has more control and overview of the process than the aforementioned teams, but they are lacking detailed data about the process. On this level, larger improvements can be made to the process. The plant management would like an even deeper look in to their process in order to improve it further. As such, the process flow is an important parameter. For example, the proposed system would show that the primary crusher runs empty 25% of the time. The plant management could then investigate further regarding what is the root cause of this. Either they improve by redesign or allocating more resources to current transportation.

Furthermore, any plant requires planned maintenance of machines. A regular occurrence is the changing of wear parts for the crushers. Currently this is being conducted by the operators via visual inspection now and then. The scanning of wear parts would enable the plant management to see the wear part life and the predicted life left. As such, planned production stops could be made more efficient and with better precision, as to reduce the number of unnecessary stops. The improvements would have a greater impact on the overall process performance and the time-span of the improvements would range from weeks to months.

9.1.4 Organization level

On the organization level even higher decisions can be made. Metrics that were described above may not be of value at this level. However, the overall utilization of the crushers would be of value to them. If the organization operates multiple plants, information regarding utilization of different plants is of value. This information would allow the organization to allocate resources between plants and to improve the overall organization performance. As changes on an organizational level can be rather slow, the time-span for improvements would be measured in months-years. However, changes at this level would also lead to higher levels of improvement.

9.2 Return on investment

As with any product, the return on investment is an important factor for the customer. As described in the literature study, the plants have limited time on quarry permits and also tight budgets. In order to give an indication of the return on investment time, some parameter assumptions have been made which may vary greatly depending on the quarry. Firstly, the assumed profit margin is 6%. Second, an average price of end-product is assumed to be 20€per ton. Thirdly, the price of drilling and blasting is assumed to be 50€per hole (B. Afum and V. Temeng, 2014). The final price of product and installation is estimated to be 20 000 €.

Two cases are presented below, which describes possible scenarios where the system has improved the plant by decreasing production stops and reducing the number of blast holes.

9.2.1 Case 1: Decreasing production stops

When the vision system is installed, the plant management has noticed that the crusher runs empty 25% of the time. Also, the operator is often busy with various problems around the site and can only respond to a jam in 20 minutes. When he finally reaches the crusher, he can clear the jamming in 5 minutes. Thus, every jamming incident would take 25 minutes. The management sees that this happens quite frequently as of late, an average of 3 times per day. The plant management effectivize the transportation of material and the operator prioritizes jamming of the jaw crusher. The changes are able to reduce the time the crusher runs empty by 2% and the average production stop from jamming is reduced by 5 minutes.

Assuming that the plant crushes 5000 tons each day, which is 14 hours long. On average this results in a production of 6 tons per minute. Thus, reducing the production stops by 20 minutes per day, this would yield an increase in production of 120 tons per day. Additionally, when the crusher is able to be fed 2% more each day, that would yield an increase of 133 tons per day. As such, the increased production yield is 253 tons per day. With the previously mentioned parameters, the return of investment is calculate as follows: $Return\ on\ investment = \frac{investment}{increased\ yield * material\ sell\ price * profit\ margin} = \frac{20000}{253 * 20 * 0.06} \approx 70\ operating\ days$

9.2.2 Case 2: Reducing the number of blast holes

The blasting crew has received a report of their previous work. The work resulted in a distribution where most of the rocks were considered too small to be worth crushing. This means that they have drilled too many blast holes and used too much explosives. They blast two times per month and each blast consists of 50 000 tons of rock. This required them to drill 400 holes (B. Afum and V. Temeng, 2014). They revise their plan for the next blasting with the information gathered from the report and were able to reduce the number of holes drilled by 50.

With the previously mentioned parameters, the return of investment is calculate as follows: $Return\ on\ investment = \frac{investment}{reduced\ number\ of\ holes\ *\ cost\ per\ hole} = \frac{20000}{50\ *\ 50} \approx 16\ weeks$

10

Ethical and environmental aspects

As with any product, there are ethical perspective that needs to be considered. As the crushing processes begins to getting observed and analysis, one have to consider the consequences it will have, not only for production purpose but also how to deal with the integrity problems it might cause. With the purpose system, information about every problem will be gathered. Therefor also knowledge such as, when it happened, how long was the downtime of the crusher. Even though this is the main purpose of the system, there will be the potential of tracking whom was in charge when the problem happened. This is of course essential when major problems happens, but the problem may arise if workers are being examined for every second that they are working.
As the operator have many thing to attend to, he or she, might not be able to clear the problem immediately. However, there is a chance that the workers will know that every second that the crusher is not running, it will be placed upon them in the statistics. Meaning that they will rush or prioritize the jammed crusher even if other problems has more importance. Therefore, it is of most importance to ensure that the attitude and the usage of the product is focus on how to improve the process, rather than pin problems on the operator. Also with the system, the is a possibility to reduce the chance of corruption within the system. Even if this may not be a outspoken problem today, one have to consider how constantly prevent the up come of it. It can be decisions regarding an investment or the evaluation of teams such as the blasting team etc. With the system, the fact will be able speak for it self and it will be much harder to hide and cover up problems or shift the problems upon other areas in the process.
As described in *Chapter 3: Literature study*, the demand for more environmental friendly and more efficient processes is constantly increasing. These demands is coming from both industry it self and but also the buyers is starting to requiring that the end product, of the material, has a lower environmental impact. One way to do this is by ensuring that the crushers has a high degree of utilization. As the crusher is constantly running, the energy used when no material is present can be seen as a waste of energy. As the proposed solution will present the degree of utilization of the crusher, the information can give the opportunity to identify which process should be optimized in order to become more efficient. Such process could be the material transportation to the crusher, solutions such as replace dump trucks with conveyor belt to achieve a more steady stream of material, ensuring that the crusher always have material ready to process. Furthermore, the purposed solution also give information regarding how efficient the upstream process such as the blasting process. By optimize the usage of explosives and number of drilled holes, for the explosives, will decrease the environmental impact. By using to much explosives and/or to many holes will both have the direct impact of using to much resources in the blasting process as well as reducing the utilization of the primary crusher. By not use enough explosives and/or holes, will increase the time the material need in the primary crusher and therefore needed increase the energy needed for crushing the material.

11

Prototype development

The project resulted in a prototype system that was installed on the NCC Tagene primary crusher.

11.1 Differentiation from the proposed solution

As with most prototypes, the functionality is limited in comparison to the proposed system. Since development time was limited, both the hardware and software level of functionality differs from the conceptual solutions.

11.1.1 Hardware

As proposed in chapter 6.5 Concept screening and evaluation, Concept one was the concept that showed most potential. Consisting of a stereo camera that is used for capturing and providing the subroutines with the video streams. As for the prototype, two single cameras were used, which meant that the prototype needed extra work to function as a stereo camera, such as calibrations, programming, assembling etc. However, by choosing two single cameras gave the possibility to approach the problem from different angles. Furthermore, both time and money played a significant part of the choice as well. A stereo camera that would perform similar to the single cameras were not available in reasonable time once the concept generation was complete and the decision which concept to continue with was made. Also the price for the given stereo camera was much higher compared with the single test cameras that were used. However, even though some of the problems were to be expected such as synchronization between the cameras, the magnitude of the problem became more than anticipated. The research before the decision was made showed that the synchronization was possible and should not be a big concern. However, once the code for the synchronization were tested and optimized, it became clear that the synchronization would become a bigger issue due to the time delay between the pictures. This also became more clear once the prototype was in place due to other factors that had impact on the capturing process. One of factors that were taken into consideration but became a bigger problem than expected was the vibration that the crusher generated. This was due to the exact placement of the installation, that was decided in a later stage and will be elaborated on in chapter 11.2.1 Setup. The outcome was that the vibration increased the offset that the synchronization created, meaning that the material would not only be offset in the direction of the flow but also ,due to the vibrations, in other directions. Furthermore, since the cameras are not IP classified, it was necessary to build an enclosure to withstand the harsh environment during the testing. Images of the vision prototype can be seen in fig. 11.1 and fig. 11.2.

Figure 11.1: Overview of the chosen vision system. Both the outside once closed as well as the internal cameras.

As for the computational hardware, a Jetson TX2 was used. This was also the solution from the most promising concept and is the proposed solution due to the performance compared to the price. Also this solution is , as previously mentioned, more versatile compared to other solutions when it comes to placement of the system which made it the possibility to place the system anywhere. However, during the development and testing phase a laptop were used. The main reason for this was due to convenience while developing and verifying the test. The laptop used the same operating system as well as the methods, but the main difference is the computational power that will increase. This will speed up the overall process during development, however, occasional tests was performed on the Jetson to verify the it performance. Images of the computational hardware prototype can be seen in fig. 11.2

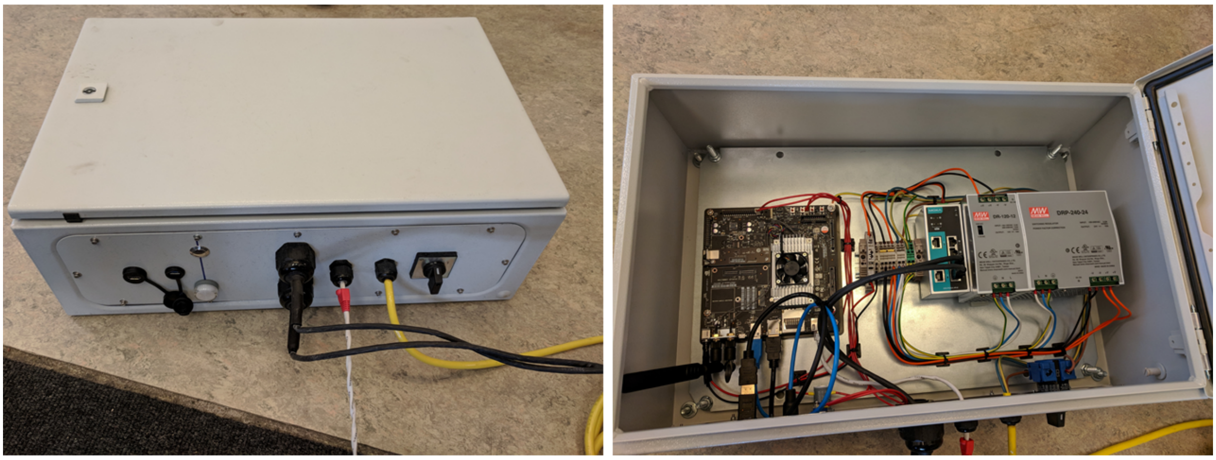


Figure 11.2: Overview of the chosen computational hardware. Both the outside, once closed as well as the internal components.

11.1.2 Software

The software differs in functionality from the proposed solutions in chapter 8. The core functionality of measuring the material size and flow was developed fully and could be implemented during the on-site tests. The subroutines can operate independently and they are able to extract the wanted information. As significant time was spent to reach this functionality on the core functions, the higher level functions of visualization and detecting jamming was only taken to the concept stage. However, as the core functions output is used to sense the environment, most of the hard work has been completed. To develop the detection of jamming to a complete subroutine would not require much additional effort, as the logic itself is quite simple.

As the prototype was tested in the field, further refinement work was conducted during the prototyping stage in order to improve the performance of the software. The core functions went through significant overhauls, as the tests provided valuable feedback regarding the software performance.

For example, as there was significant shaking problems of the camera and that the cameras were not frame synchronized, the initial proposal of 3D segmentation could not be used. This meant a total revamp of segmentation, which resulted in the use of the proposed method shown in chapter 7.5.2.

11.2 On-site tests

As there was limited opportunity to validate the actual measurements of the system during full production of the plant, this portion of the system cannot be fully tested. However, test in a controlled environment on stationary rocks was conducted and provided an idea of the true performance of the stereo vision scanning. The functions that were able to be tested was the segmentation of the rocks and also the material flow. These functions could be validated by inspection of the video-stream manually and the performance of these functions could then be evaluated. The only suitable placement of the prototype is the view showed in fig. 11.6. The placement provided a view of the feeder and crushing chamber. As the system is a prototype, it should not interfere in any way. As such, the view down in to the crushing chamber is occluded. The physical installation can be seen in fig. 11.4.

Figure 11.3: A view from the camera. The entire feeder and and crushing chamber can be seen. The crushing chamber is somewhat occluded by the metal plates and is always covered by a shadow.

Figure 11.4: The camera system is mounted on the platform right above the crusher and feeder.

11.3 Results

Both on-site tests and in-house tests were conducted during the prototyping stage.

11.3.1 Rock detection

Due to shaking and unsynchronized cameras along with the test being conducted during full operation of the plant, only the material flow and detection of rocks could be performed and validated. A series of video sequences were taken during the prototype installation and were then manually checked. The result of the on-site test using the prototype can be seen below in fig. 11.5 and an example of a video frame from one of the test sequences can be seen in fig. 11.6.

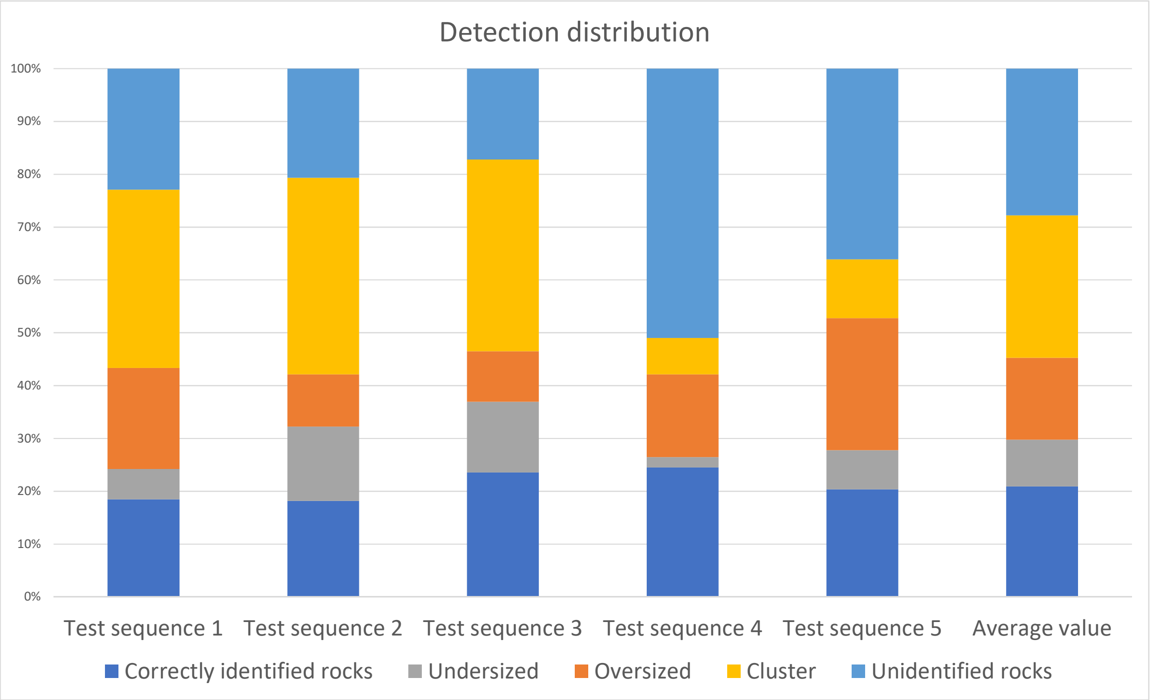


Figure 11.5: The result of the prototype applied on five test sequences captured on-site at NCC Tagene

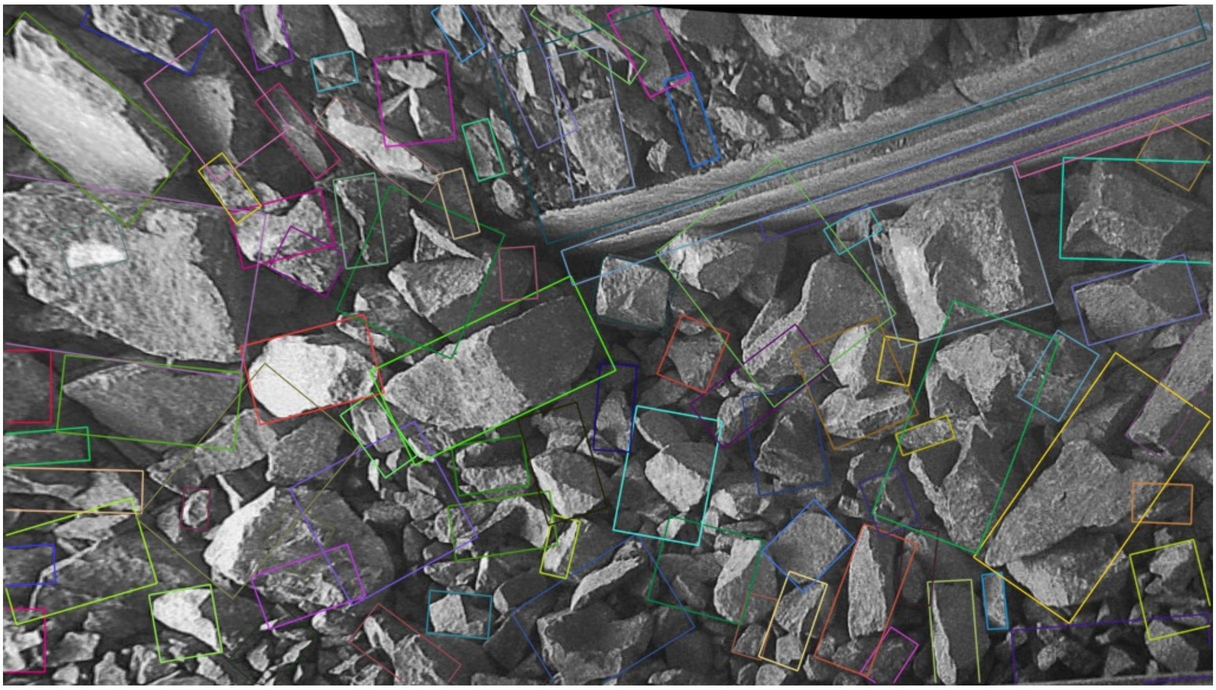


Figure 11.6: One frame from a test sequence.

The detection results could be identified as being grouped in to 5 categories. Here, the result is based on the actual boundary of the rock. Category *Correctly identified rocks* consists of rocks where the bounding box fits around the entire rock with a margin of ±5% from the actual boundary. *Undersized* category covers bounding boxes that were considered between 5% and 15% smaller. The category *Oversized* would mean that the bounding box is between 5% and 15% larger. The *Cluster* category contains rocks that were, due to segmentation problems, considered to be one object. Lastly, if a bounding box considered parts of the feeder to be a rock, or that the rocks were not segmented at all, they would included in the *Unidentified rocks* category. In fig. 11.7, examples of the categorization is shown.

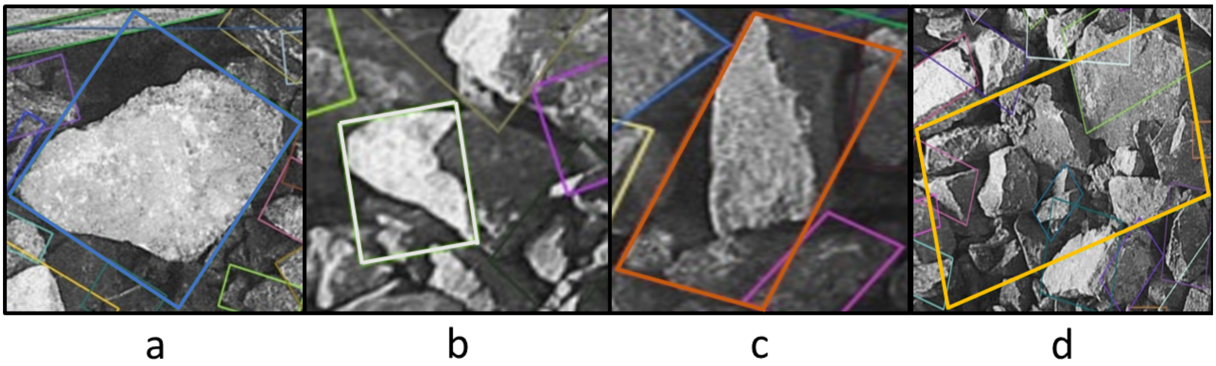


Figure 11.7: a: *Correctly identified rocks*, b: *Undersized*, c: *Oversized*, d: *Cluster*

The results from five test sequences captured on site during full production were analyzed and the results can be seen in fig. 11.5. The prototype is able to, on average, correctly identify 20% of the rocks in the scene. The undersized bounding box and oversize bounding box are identified by the camera in 10% and 15% respectively. These rocks are still considered to be useful for the rock-size measurements. The result also consisted of clusters of rocks that were segmented together, totaling 27% of the rocks in the scene. Lastly, the unidentified rocks made up 28% of the rocks. The unidentified rocks were either not detected at all by the algorithm or detected as internal edges of a larger rock or that the algorithm falsely detected parts of the feeder as rocks. As such, the unidentified rocks and clustering of rocks were concluded to be of negative value towards the material analysis and the remainder were detected as rocks. The resulting detection rate on average is thus 45%.

11.3.2 Rock measurement

Using the point cloud for segmentation showed promising result in the initial testing, in a controlled environment. In figure fig. 11.8, picture A, the segmentation of two "stones/rocks" on a even plane, in this case the office floor. As described in chapter 7.5.1 3D point cloud segmentation, the segmentation is based on isolating objects once the points in the cloud is a certain distance from other points. The rocks could be isolated and the size of the rock could easily be extracted since every point has known coordinates. The result from the measuring the stones showed that the dimensions differed of ±2 centimetre between the real dimensions and the estimated with the point cloud. Several other measuring test were done such as distance to known objects which gave similar result. This validates the performance and capability of the system to be used as measuring for the given task.

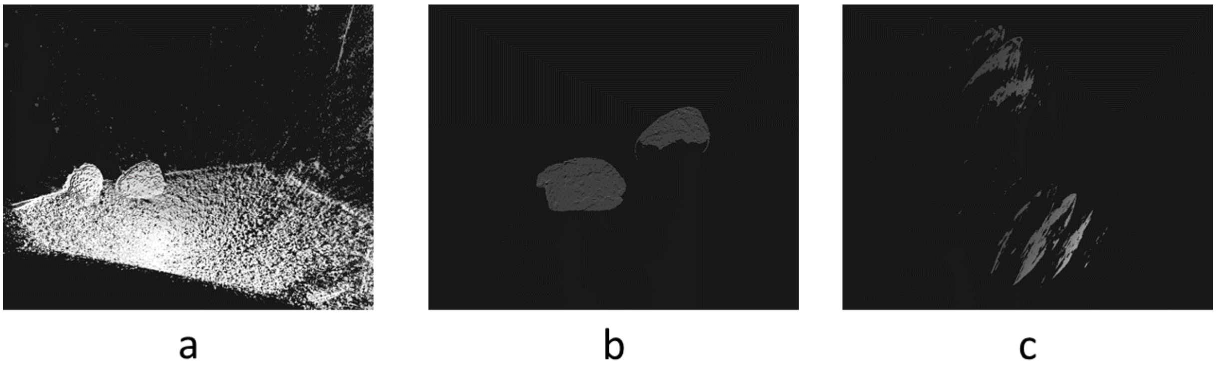


Figure 11.8: a: *The generated point cloud*, b: *The point cloud once the rocks had been segmented from the cloud*, c: *Top view of the point cloud*

11.3.3 Material flow

The algorithm is able to distinguish between when there is flow and when there is no flow with an accuracy of 100%. The different flow speeds were more difficult to varify, as the feeder during the tests was never ran at a variable speed. As such, the speed of the material on the feeder was almost constant. What could be seen however, is that when a rock is falling or when the dumptruck unloads material in the feeder, the speed of the flow changed. Figure 11.9 shows an example of the material flow on the crusher feeder.

Figure 11.9: a: *video stream frame with region of interest being shown*, b: *the resulting material flow*

As can be seen in fig. 11.9, the material on the feeder area remains constant moving in the 0 degree direction. The large rock in the middle of the picture moves in a slightly different direction, as it is tumbling on top of other rocks. The rocks on at the feeder opening to the left are moving slower, as they are piled together and tumbling down in a slower pace than the feeder itself. It can be seen in the figure that the flow on the feeder itself is constant except for the tumbling rock. As such, this is considered to be a very positive result, as the prototype is able to both extract regions of different flow with very high accuracy.

12

Discussion

In the early stages of the project, little information was known regarding how an actual production stop looks like and what is causing the stop. As was observed, a production stop was mostly a result of the crusher being jammed for a prolonged period of time. The operators themselves would probably not regard some of the identified stops as jamming. However, as we were constantly monitoring the crusher during the visits, there was a significant amount of production time wasted when a large rock either got lodged ontop of the crushing chamber, blocking the feeder, or when a large rock was difficult to break. The resulting production delay could easily be up to 45 minutes. The stop would either depend on the operator not actively monitoring the crusher or that they knew from experience that the rock would be crushed within a few minutes.

As described previously in the thesis, there are several contributing factors for production stops in the primary crushing process. As identified by us and as explained by the operators, the blasting plays a vital role at this crushing stage. We were able to witness both when the blasting had been too fine, resulting in rocks just passing through the crusher, and when the blasting was too coarse, such that the crusher got jammed frequently. Thus, feedback for the blasting crews seems to be a very good feature for this site. However, as the proposed system does not directly control any part of the process, the actual improvements have to be made by people on site.

At this particular site, the operators were quite skilled and were able to make good decisions based on the information provided by the plant control system. For them, more information would most likely result in increasing their efficiency and allow them to take better decisions. As such, a system that detects a jamming and can report the fault to the operator would have the potential to significantly reduce the downtime.

When it comes to the blasting crew and also the dump truck drivers, they were hired by an external company. The operators would complain about their efficiency and lack of knowledge, especially for the transportation team. For these teams, perhaps the reports would not be as valuable. However, as the plant management would be able to directly see where in the process there is a fault, they could take the decision to either hire another crew or train the crews to perform better. As was described before, these reports would boil down to higher level decisions about the plant and then be able to trickle down to fault source.

As with any new product undergoing development, there will always be unforeseen problems and factors that will have an impact of the performance of the product. The main question is how big or small these factors are and how much of an impact they will have. During the thesis a number of factors were discovered that had an impact of the detection system performance, one of them being the effect of the light conditions. Even though the feeder and crusher are placed inside a building, in a somewhat controlled environment, the light had a considerable effect on the detection system. The amount of light coming from the outside were heavily dependent on both the weather but also the time after the material being dumped on the feeder. Right after the material being dumped, it usually blocked most incoming light and as the material being process, the light increased. This meant that there were no optimal setting for the vision system due to the variation of the light source. This also created more shadows than expected which the system occasionally picked up as an object.

Other factors that would affect the system but that were expected were the dust and vibrations caused by the crusher and feeder. During the testing phase, it also became very clear that the mounting of the system plays a vital role to enable the possibility to gather valid information. As mentioned, even the slightest vibration will have an effect on the vision system since the images from the cameras needs to match together. Since the idea behind the system, when it comes to mounting, is that the system should be versatile and offer the possibility to be mounted anywhere. However, due to the final placement of the camera, the impact of vibration were highly underestimated. The magnitude of the impact from the vibration also was due to a combination between the vibration and the unsynchronized cameras. As one of the cameras took one picture, more often than not, the picture from the other camera became of offset due to vibrations. But the vibration did not only cause problem with synchronization, the picture also became blurry due the the sudden movement. So even though the problems were expected, the degree of problem it created were unanticipated. Therefor, it is at most importance to continue to search for ways to limit or eliminate the vibrations such as vibration dampening mounting materials.

Furthermore, both before and during the test period there had been less to no rain which meant that there were nothing to bind the dust, causing the dust to be an extreme problem at the quarry. Not only for the testing but also for the quarry and its personal. At the quarry, there certain measurement had been taken to minimize this, such as watering roads, the blasted rocks etc. This meant that the water helped reducing the dust levels but did not remove. This was also due to the extreme weather which made the water evaporation quickly. As a result, there were excessive amount of dust at the feeder and crusher during the testing phase. The dust levels were mainly a problem once the rocks being dumped causing the system to completely lose vision until the dust level reduced, usually taking between 5 to 20 seconds. However, even if the vision were removed the dust did not cause any other issues during the testing phase such as sticking onto the surface of the encapsulation for the lenses. There are reason to believe that the changes of weather and humidity may cause a problem were the dust get stuck on the surface, protecting the lens. However, this is just a theory and needs further testing and evaluation how much of a problem this may cause.

As was shown in the thesis there are many viable technologies that can be used to detect and measure material. Ultimately a stereo vision system was chosen as being the most suitable one based on the price and the performance. Also, for the prototype, it gave the ability to test single camera solutions as well as integrate these with stereo vision. While the cameras were a bit on the cheaper side, as they did not have the functions of synchronization between the cameras, they were still a good foundation for evaluating the performance of stereo vision. However, in a real scenario fully synchronized cameras are a must. Another important aspect of the stereo vision system is the algorithms used to solve the stereo correspondence problem. Most of the tested algorithms that were implemented required high processing time. The problem was even more obvious when using higher resolution images captured by the camera. The problem could be solved by both having more capable hardware to compute the images and also to improve the matching algorithm. The results from the prototype stereo vision system seem very promising, as an accuracy of around 2 centimeter in x, y and z could be achieved with the unrefined set-up.

The segmentation of the rocks is a another important cornerstone of the product itself. During the project, traditional methods for edge detection and segmentation were used. The initial testing of these methods gave quite promising results. However, after trying most of the classic edge detector methods along with extensive use of other filtering techniques, histogram equalization and morphological operations, the results are still not satisfactory for usage in a real product environment. For difficult rocks, i.e. rocks that were under a shadow or that the edge was slightly blurred, the edge detectors failed quickly. This resulted in many rocks being segmented together, which creates a false reading directly.

Furthermore, as edge detectors are based on a 2D image, many internal edges were identified. As such, the edge detection and segmentation would then give out false boundaries inside the rock, making it look like there are multiple rocks at this location. The current system would, on average, be able to correctly identify 20% of the rocks and around 45% of the rocks would be considered as good enough for using as correct measurements. When looking at current systems from competitors and solutions from other industries, they achieve –what the team would consider a correct measurement – around $70 - 90\%$ detection rate. The main advantage of their systems is the in-house developed edge detection system, which more often than not is based on some sort of machine learning algorithm such as deep neural networks. These algorithms seem to more intelligently detect the rock by being trained from manually segmented images. As time was limited during the project, this was not considered to be feasible given the time-span.

13

Future work

The future development work is presented in this chapter. It covers the continuation work of both hardware, software and user experience.

13.1 Hardware

- **Mounting:** As the concepts has focus more towards the versatility of placement rather than the physical mounting hardware. This needs further research since the observation has only been conducted at on quarry which is not sufficient to make a well based decision.
- **Vibration dampening:** The result showed that the vibration has a major impact of the vision system, meaning that vibration needs to be minimized. Therefore, further testing and research needs to be conducted to limit the vibrations, such as vibration dampening materials.
- **Light conditions:** Further testing needs to be done regarding how the light conditions affect the vision system and the ability to gather information. This should also involve do performance test with extra lights to reduce unwanted shadows and bring forth edges.
- **Mixed weather effects:** As the prototype and the testing only was conducted for a short period of time, there were no possibility to see how the weather affect the system. Therefore, the system needs to be tested during a longer period of time as well as during season changing to see how the weather impact the lens protection.
- **Embedded system:** As the embedded system today consists of a Jetson TX2, a development kit, there are reasons to further research if other embedded systems are more suitable for the industrial application. Mainly with higher computational power due to the current calculation time given.
- **User experience:** Since the end product will change with respect to the hardware, the user experience needs to be taken into further consideration. Mainly if the new hardware require any maintenance due to the combination between dust and mixed weather effects.
- **Potential dust problems:** Look into if watering the rocks during the dumping process will reduce dust. Research if there are any options where a lens filter can enable the camera to see through dust.

13.2 Software

- **Rock segmentation:** The edge detection and object segmentation was highly dependent on image quality, lighting and how the rocks are stacked together, further research is needed towards a more intelligent algorithm. A suggestion would be to

look further in to training a artificial neural network (ANN) for improving the edge detection.
- **Data visualization:** As mentioned, the Roctim cloud solution would be an important platform for visualization. Further works is needed to integrate the data stream output with the cloud.
- **Operator alarms:** No work has been put in to visualizing and presenting data for the operator. Thus, a trial application for smart-phones should be developed, which shows alarm messages and can provide the operator with a video stream of the event.
- **Improve stereo vision algorithm:** The current stereo vision is still a bit noisy and can sometime have trouble with certain surfaces. Reducing the noise would provide for stable measurements. Also, computation speed could be improved by optimizing the code and implementing more functions to the GPU pipeline.

13.3 Other usage areas

As a camera system is high flexible and more dependent on the software rather then the hardware when it comes to be able used it in other areas. This means that with further development on the software side, the system could be implemented in other crushing stages, used to measure stockpiles, detect vehicles and people in critical areas within the quarry. Since safety is a hot topic within the industry, the system could be used to increase the safety of the quarry by identifying and alert the surrounding if a vehicle and/or people are in certain areas. As this was not scope of the project no time was spent developing such system but the method is already available as it is used in other industries, such as the automotive industry.

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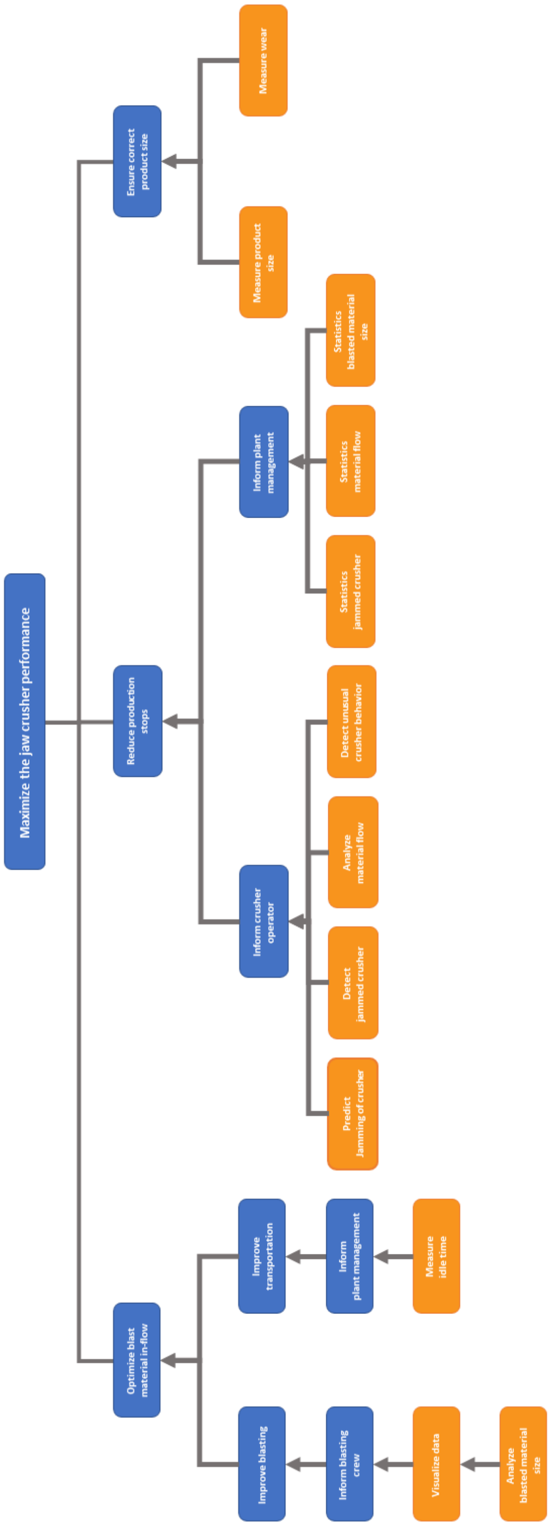
A

Requirement specification

Type	Description	Value	Justification	Verification
General				
R1	Real time computation - Minimum	1 analysis per second	Measure rocks on grizzly feeder	Lab testing
D1	Real time computation - Target	As many as possible	Measure rocks on fast conveyor belts	Lab testing
R2	Provide analytic data		To provide informations to improve the crushing process	Lab testing, Customer feedback
D2	Provide live video feed		Ease the decision making for alarms	Lab testing, Customer feedback
R3	Weather proof vision system- Minimum	IP65	Be weather proof in crusher environment	IP test
D3	Weather proof vision system- Target	IP68	Be weather proof in crusher environment and ease cleaning	IP test
D4	Weather proof complete system- Target	IP68	Be weather proof in crusher environment and ease cleaning	IP test
R4	Production cost per system- maximum	35000 SEK	Viable cost for the value to the customer	Cost calculations
D5	Production cost per system - target	<15000 SEK	Keep costs in line with Roctim products	Cost calculations
D6	Cost for vision system expansion (Adding additional vision sensors)	As low as possible	Less extra costs associated with expanding the system	Cost calculations
D7	Versatility of placement	Outdoor and indoor environment, any placement	Viable for majority of sites and installations	On-site study
D8	In-house production effort	As low as possible	Reduce cost	Prototype building and evaluation
D9	Maintainance	None	No extra work for site personell	On-site testing
D10	Simplicity of installation	Less than 3 steps	Less effort on site	On-site testing
Feeder and jaw crusher				
R5	Measure individual rocks - Minimum dimension accruacy	±9 mm	To provide accurate and trustworthy system	Lab testing, On-site testing
D11	Measure individual rocks - Target dimension accruacy	±5 mm	To provide accurate and trustworthy system	Lab testing, On-site testing
R6	Measure individual rocks - Minimum velocity accruacy	±0.015 m/s	To provide accurate and trustworthy system	Lab testing, On-site testing
D12	Measure individual rocks - Target velocity accruacy	±0.0075 m/s	To provide accurate and trustworthy system	Lab testing, On-site testing
R7	Measure individual rocks - Maximum velocity	1 m/s	To detect fast rocks on grizzly feeder	Lab testing, On-site testing
D13	Measure individual rocks - Velocity target	4 m/s	To detect rocks on conveyor belts	Lab testing, On-site testing
R8	Measure individual rocks - Minimum position accruacy	±6 mm	To provide accurate and trustworthy system	Lab testing, On-site testing
D14	Measure individual rocks - Target position accruacy	±3 mm	To provide accurate and trustworthy system	Lab testing, On-site testing
R9	Identify individual rocks - Minimum	150 mm	To detects majority of rocks from blast site	Lab testing, On-site testing
D15	Identify individual rocks - Target	100 mm		Lab testing, On-site testing
R10	Identify actual jamming	95%	Ensure trustworthy system performance	On-site testing
D16	Identify actual jamming	100%		On-site testing
R11	Maximum false readings jamming	20%	Ensure trustworthy system performance	On-site testing
D17	Maximum false readings jamming	0%		On-site testing
R12	Predict jamming of jaw crusher	80%	Ensure trustworthy system performance	Lab testing, On-site testing
D18	Predict jamming of jaw crusher	100%		Lab testing, On-site testing
D19	Measure liner wear	±2 mm	To provide accurate and trustworthy system	Lab testing, On-site testing
D20	Measure liner gap	±2 mm	To provide accurate and trustworthy system	Lab testing, On-site testing

B

Function tree



C

Function matrix

Function	Solution						
Measuring material size	Camera	LiDAR	Stero camera	2D line-scaner	Active IR-camera	TOF-camera	Structured-light scanner
Measuring material flow	Camera	LiDAR	Stero camera		Active IR-camera	TOF-camera	Structured-light scanner
Measuring positions	Camera	LiDAR	Stero camera		Active IR-camera	TOF-camera	Structured-light scanner
Measuring wear	Camera	LiDAR	Stero camera	2D line-scaner	Active IR-camera	TOF-camera	Structured-light scanner
Process information	Desktop computer	Embedded system	On-site server	Off-site server			
Visualize information	Web	App	Dedicated monitor				

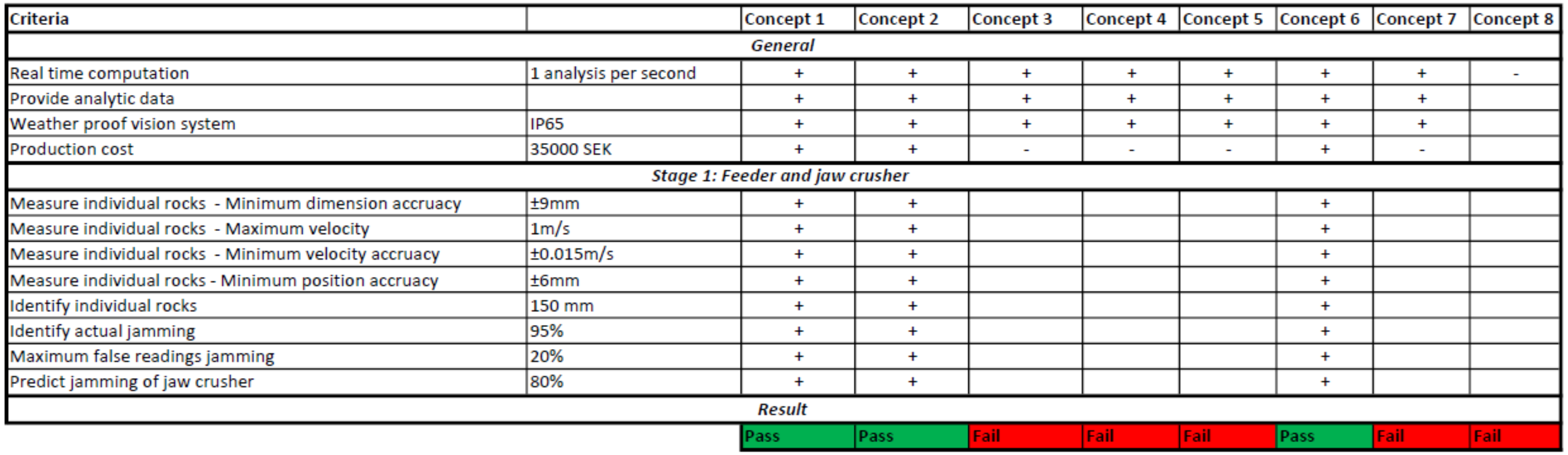
D

Concept matrix

Function	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6	Concept 7	Concept 8
Measuring material size	Stero camera	Stero camera	Camera + LiDAR	Camera + 2D line-scanner	Camera + 2D line-scaner	TOF-camera	Stereo camera + 2D line-scanner	Structured-light scanner
Measuring material flow	Stero camera	Stero camera	Camera + LiDAR	Camera + 2D line-scanner	Camera + 2D line-scaner	TOF-camera	Stereo camera + 2D line-scanner	Structured-light scanner
Measuring positions	Stero camera	Stero camera	Camera + LiDAR	Camera + 2D line-scanner	Camera + 2D line-scaner	TOF-camera	Stereo camera + 2D line-scanner	Structured-light scanner
Measuring wear	Stero camera	Stero camera	Camera + LiDAR	Camera + 2D line-scanner	Camera + 2D line-scaner	TOF-camera	Stereo camera + 2D line-scanner	Structured-light scanner
Process information	Embedded system	Server	Embedded system	Embedded system	Server	Embedded system	Server	Server
Visualize information	Web	Web	Web	Web	App	Dedicated monitor	Web	App

E

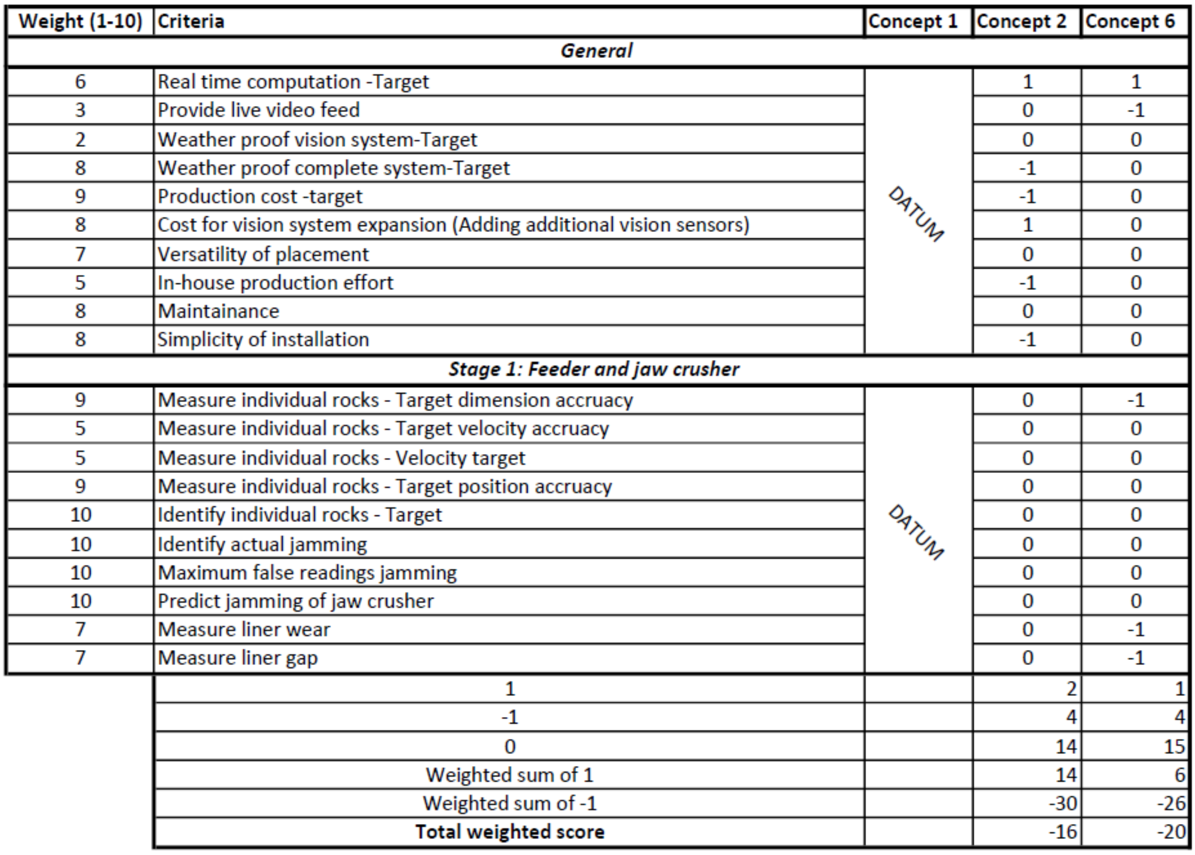
Elimination matrix



Criteria		Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6	Concept 7	Concept 8
		General							
Real time computation	1 analysis per second	+	+	+	+	+	+	+	-
Provide analytic data		+	+	+	+	+	+	+	
Weather proof vision system	IP65	+	+	+	+	+	+	+	
Production cost	35000 SEK	+	+	-	-	-	+	-	
		Stage 1: Feeder and jaw crusher							
Measure individual rocks - Minimum dimension accruacy	±9mm	+	+				+		
Measure individual rocks - Maximum velocity	1m/s	+	+				+		
Measure individual rocks - Minimum velocity accruacy	±0.015m/s	+	+				+		
Measure individual rocks - Minimum position accruacy	±6mm	+	+				+		
Identify individual rocks	150 mm	+	+				+		
Identify actual jamming	95%	+	+				+		
Maximum false readings jamming	20%	+	+				+		
Predict jamming of jaw crusher	80%	+	+				+		
		Result							
		Pass	Pass	Fail	Fail	Fail	Pass	Fail	Fail

F

Pugh matrix



Weight (1-10)	Criteria	Concept 1	Concept 2	Concept 6
	General			
6	Real time computation -Target	DATUM	1	1
3	Provide live video feed		0	-1
2	Weather proof vision system-Target		0	0
8	Weather proof complete system-Target		-1	0
9	Production cost -target		-1	0
8	Cost for vision system expansion (Adding additional vision sensors)		1	0
7	Versatility of placement		0	0
5	In-house production effort		-1	0
8	Maintainance		0	0
8	Simplicity of installation		-1	0
	Stage 1: Feeder and jaw crusher			
9	Measure individual rocks - Target dimension accruacy	DATUM	0	-1
5	Measure individual rocks - Target velocity accruacy		0	0
5	Measure individual rocks - Velocity target		0	0
9	Measure individual rocks - Target position accruacy		0	0
10	Identify individual rocks - Target		0	0
10	Identify actual jamming		0	0
10	Maximum false readings jamming		0	0
10	Predict jamming of jaw crusher		0	0
7	Measure liner wear		0	-1
7	Measure liner gap		0	-1
	1		2	1
	-1		4	4
	0		14	15
	Weighted sum of 1		14	6
	Weighted sum of -1		-30	-26
	Total weighted score		-16	-20