Image Stabilization for Body-Worn Cameras

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MASTER THESIS

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Problem Investigation and Design proposals based on user need identification

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Abstract

Body-worn cameras are cameras that are used by law enforcement and other personnel and act as mobile surveillance and information gathering. When these cameras are worn they can be subjected to a lot of movements and thereby the image captured can be shaky and of poor quality. The purpose of this thesis is to explore, understand and find improvements in the image stabilization of the Axis body-worn camera.

The method that was used as a foundation for the thesis was a combination of Ulrich and Eppinger's Product development and the Double diamond method. Information was collected externally and internally. Information that was collected within the company was done so by several interviews in different stages. Different tests were conducted in order to get a fuller understanding of the problem and customer insights were gathered. The movements that affected the image stability were mainly around the camera's own axis.

Three parts that affected the stabilization were recognized: the mounting, the fixture, and the camera itself. The thesis was limited by looking for a new alternative to the most used mounting solution. A solution was proposed and conceptually evaluated as changing the magnetic mounting alternative to an improved one with a bigger surface area in contact with the body to reduce axial movements, A change of the fixture to one with more fastening points and making closer contact with the camera and mounting solution, The third was to implement a gimbal solution to the camera itself which could compensate for the movements that remain after a stable fixture and mounting were introduced.

Sammanfattning

Kroppskameror är kameror som används av bland annat personal inom rättsväsendet och andra yrken. Kroppskameror är en mobil kamera som sitter på en persons kropp där syftet är att inta information och att övervaka. Då en kroppskamera bärs så kan den utsättas för mycket rörelser vilket gör att bilden blir suddig och av dålig kvalitet. Syftet med detta arbete är att utforska, förstå och hitta förbättringar för bildkvaliten gällande Axis kroppskameror.

Metoden som detta arbete bygger på är en kombination av Ulrich och Eppingers produktuveckling samt "Double Diamond" metoden. Information var hämtat både externt och internt. Den information som var hämtat inom företaget var gjord via flera intervjuer i olika steg av processen. Flera olika test gjordes för att få en bredare förståelse för problemet och även åsikter från kunder samlades in. De rörelser som ansågs påverka bildstabiliteten mest var de röresler runt kamerans egna axlar.

Tre delar identifierades som påverkade bildstabiliseringen vilka var Fästet, infästningen samt kameran. Arbetet begränsades av att kolla på alternativ till det mest använda fästet. En helhetslösning föreslogs och konceptuellt utvärderat vilket innefattar de tre delarna. Att göra ett fäste med större kontaktyta med kroppen för att reducera axiella rörelser, en bättre infästning som ökar mängden fästningspunkter och i sin tur även placerar kameran närmare kroppen. Den tredje förbättringen är att implementera en gimbal-lösning som med hjälp av ett gyro och inbyggda elektroniska motorer kan hantera de rörelser som är kvar efter att resten har kompenserats för.

Acknowledgements

This project was made as a Master's thesis project in mechanical engineering at the Department of Design Science from the Faculty of Engineering LTH at Lund University. The thesis was made together with Axis Communications AB. It was an elaboration between two thesis students involved in every part of the project.

We would like to thank our supervisor Jože Tavčar from LTH for his guidance and knowledge in Design. We would also like to thank our examiner Anders Warell for giving valuable input to the thesis.

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Lund, June 2023
Samuel Bryngelsson and Jonathan Gustafsson

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1 Introduction

1.1 Problem Description

1.1.1 Background

Surveillance is becoming a more significant part of establishing security in today's society. This does not only apply to buildings and locations but also to personal protection. By introducing mobile surveillance to body-worn cameras new challenges are presented. One of these challenges is to gather footage of high quality when exposed to intense movement like running. An issue appearing from these movements is unwanted shakes in the video. This is usually treated by applying different image stabilization technologies.

Axis[1] is a company that develops body-worn cameras and their movements of interest when using a body-worn camera are walking and running. These movements introduce disturbances resulting in a shaky video, loss of details, or general poor image quality.

1.1.2 Purpose and Objectives

The purpose of this thesis is to investigate shakes introduced to video of body-worn cameras to gather the knowledge acquired to develop and evaluate possible solutions to compensate for shakes. The problem regarding specifically body-worn cameras experiencing movements attached to the human body needs to be investigated. Moreover, if possible, solutions in different technical areas will be combined to coexist in a better overall concept.

1.1.3 Limitations

The scope of the thesis is limited to evaluating ways to stabilize the image when subjected to movements or shakiness. Since image analyzing software stabilization already exists at Axis, this thesis shall focus on the physical stabilization of the video image. The different stages of product development shall be observed and analyzed but limited to research, concept, and prototyping. Other stages like usability and manufacturing are not included in the scope. Several concepts should be generated and evaluated with the importance of keeping the project scope open. The project shall undergo 20 weeks which adds a time limitation to the thesis as well.

1.1.4 Contribution

The thesis contributes to knowledge development by investigating the problem of movement specifically related to a body-mounted camera, and different combinations of concepts to counter these movements. Also, the thesis provides a knowledge contribution for Axis[1] to further develop functional solutions to their products affected by this problem. The thesis will also contribute to some extent to the importance of trying to find the actual problem to solve.

1.1.5 Research questions

- **What problems are specifically related to poor image quality when recording video with a body-mounted camera?**
  Before investigating what problems can be interesting coming from body-worn cameras, a review of currently existing stationary cameras will be conducted.

- **Which solutions can be viable to solve the problems with the specifically body-worn poor image quality video?**
  Before investigating which solutions can be interesting to implement in body-worn cameras, a review of currently existing solutions for image stabilization will be conducted.

- **What problems arise when developing a new kind of product for a new set of first-hand users?**
  Before investigating which problems that can arise when developing a product for a new set of first-hand users, a review of methods for product development will be conducted.

1.2 Axis Communications AB

Axis is a company mainly working with video surveillance and integrated network solutions. The company started in 1984 but introduced its first network camera in 1996 which was the first network camera in the world. Today Axis are over 4000 employees over the world with their main headquarters in Lund, Sweden. Now their product range from stationary and mobile cameras, audio solutions and video management systems to mention a few [1].

1.3 Body Worn camera

The body-worn camera refers to a version of a mobile camera made by Axis Communications that is mainly made to be worn by law enforcement for video surveillance from the wearers' point of view. It is a fairly new product in Axis' catalog compared to many of the stationary cameras that have been a part of Axis for a relatively long time. The body-worn camera can be powered during an entire workday by its battery before it needs to be recharged. The camera is relatively sturdy and can withstand poor weather conditions and harsher impacts [1]. The camera is attached to the body via a mount and the mount is attached to the camera by a fixture. The camera does not possess any kind of mechanical stabilization at this point in time.

Figure 1: The Body Worn camera

2 Theory

The theoretical chapter consists of two sections. First, a review of different image stabilization solutions is presented. Second, the Klickfast fixation used by Axis is discussed.

2.1 Image stabilization

Image stabilization is a collection word of different kinds of solutions, all aimed to solve the same problem regarding blurry and shaky videos and photos. However, different techniques are often used for various parts of the problem. The basic use case for image stabilization is to compensate for environmental disturbances affecting a camera system such as shakes and movements. The image stabilization will however not be able to compensate for any rolling shutter or motion blur caused by a fast and significant direction change. These problems are related to the camera's performance and capturing settings. [2]

2.1.1 Optical Image Stabilization (OIS)

Optical Image Stabilization (OIS) is a technology used to reduce blurring caused by camera shake or slow shutter speeds. It works by physically shifting the camera lens to counteract the movement by using gyro data[3]. This method is dependent upon batteries and motors and is often used in applications where the weight or size of the overall camera is not a priority. The technique can differ with different image stabilization goals related to the shake experienced by the camera. Structures like translational, rotational, and by using a deformable freeform mirror[3]. According to Gustavi and Andersson[2] the two main methods of OIS in smaller applications are lens shifting and module tilting. Lens shifting is made by moving the lens in relation to the fixed sensor while module tilting works by moving the entire module(Lens + sensor) together to compensate for movement.

2.1.2 In-Body Image Stabilization (IBIS)

In-Body Image Stabilization(IBIS) works by detecting camera movement and then compensating for that movement by moving the camera's image sensor in the opposite direction. The technique uses battery and motors and it is particularly effective when using a wider field of view, as stated by Canon[4]. The system is designed to detect small amounts of camera shake, which can be enough to cause blur in photos or videos when shooting with slow shutter speeds or when a lot of shakes is introduced. The IBIS system adjusts the position of the image sensor in real time to counteract the camera shake, ensuring that the image captured on the sensor is as stable as possible, resulting in a more detailed capture as well.[4]

2.1.3 Electronic Image Stabilization (EIS)

Electronic image stabilization (EIS) commonly refers to stabilization that is accomplished solely by software. This works traditionally by cropping the part of the images that deviate from an established area and thereafter enlargening the image in order to fit the required size. The upside of EIS is that it is inexpensive since it doesn't require any additional physical parts to be added other than a gyro and accelerometer sensor in some cases where the actual data from shaking could be utilized. The downside with EIS is that large amounts of cropping can occur if the camera experiences movement other than minor shaking, ultimately making the image quality suffer but also smaller. This is a problem when low light performance is of interest. The EIS can not compensate for any blur introduced by shaking, which can harm any details of a video or picture. EIS also requires the camera to manage more data with a higher bit-rate, affecting the battery life. [2]

2.1.4 Active Image Stabilization (AIS)

Active image stabilization combines an electronic, software, and mechanical solution. One example of this type of stabilizer is a gimbal. A gimbal is a device that uses pivoting points to allow an object (a camera) to compensate for external disturbances. It typically consists of two or more axes of rotation that are perpendicular to each other, allowing for movement in multiple planes. By isolating an object from external movements, a gimbal helps to keep it steady and in a fixed orientation. To measure vibrations, a gyroscope and an accelerometer are used, and signals are sent in real-time to the motors controlling the pivoting points, resulting in relatively high energy consumption. This technology can compensate for bigger amplitudes of vibrations but is usually bigger in footprint. [2]

2.1.5 Passive Image Stabilization (PIS)

Passive image stabilization (PIS) refers to pure mechanical stabilization where no electronics nor programming is required, unlike all other image stabilization techniques. This can be accomplished through the use of shock-absorbing materials or other mechanical components that physically dampen vibrations and movements. This group's solutions vary between being small and basic to big and advanced and some of the solutions are among the cheapest way of stabilization. No electrical components nor a battery are needed. The disadvantages are that these systems are often big compared to others and that they are hard to incorporate inside camera systems. One example of these systems is stated by Borys Golik Cologne and is called SteadiCam. SteadiCam is a system that relies upon a sled supported by an elastic spring-loaded arm that is connected to a fixture worn around the chest of the operator. This particular stabilization is quite a complex construction, and thus very heavy and expensive. [5]

2.2 Klick Fast

Klick Fast is the current solution that Axis uses in order to attach the camera to the body quickly. Klick Fast was introduced as a third-party mounting solution to the first Body worn camera model and has been the same since. It attaches at one single point and resembles a small octagon that latches into a socket. After latched in, it can rotate at 7 different positions. The Klickfast solution aims to attach radio and other portable equipment. [6]

. The company never states it to be a camera attachment solution.

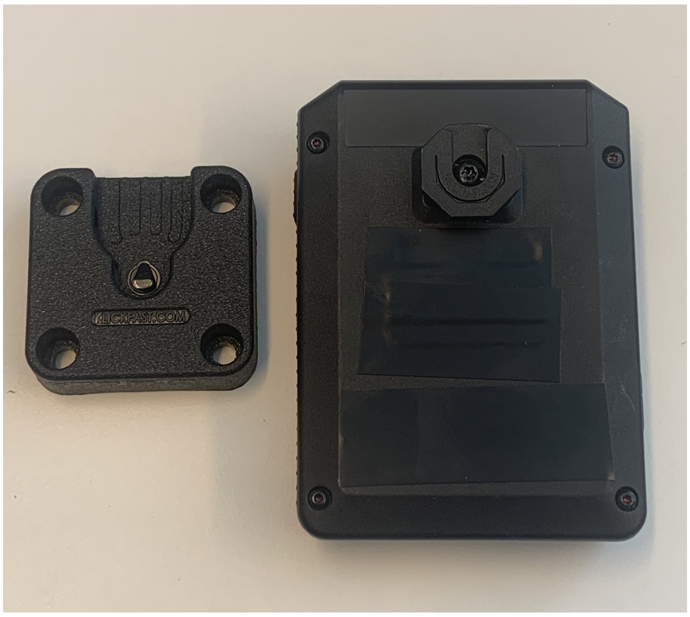

Figure 2: Klick Fast system

3 Methodology

To achieve a good concept and prototyping result, different product development processes and methods need to be evaluated. This section will state and explain various design processes used in the thesis and their corresponding methods. Independent methods used will also be explained. The section will also describe how these methods and processes were used throughout the thesis.

3.1 Methods

Methods are the closest representation of a step-to-step guide on how to go get certain things done. Methods are stated in the report to give an overview and detailed explanation of all the important steps of the project, as well as guide readers on the decisions made in the project. In this project, methods consist of collections related to the status of the project. These collections are called phases.

3.1.1 Interviewing

In order to gather empirical data like information and opinions from within Axis, several interviews were held. Questions for the interviews were prepared in advance and eligible to change during the course of the interview. For interviews that relied on gathering information, facts, and technical specifications, the questions were kept short and further information that was revealed which initially was not a part of the prepared questions was written down as well. The interviewing method that was used was a semi-structured interview. This implied that the questions were prepared in advance but when more elaborated answers were wanted, further questions could be asked on the spot. This interviewing method was relevant since the interviews were longer and the people being interviewed were seen as very knowledgeable about the subject [7]. When interviewing employees at Axis, broad and neutral questions were asked. Any personal opinions on the subject were not shared with the interviewee in order to not influence this person's opinion.

3.1.2 Top-down data collection strategy

To gather information and data for the thesis, different approaches were made. To prepare questions for interviews and meetings with employees and experts within the company we used the semi-structured interviewing process. The information gathering was planned in advance and questions were chosen specifically to answer the areas that were of interest. This is called a Top-down process and is characterized by having a specific goal and intentions with the collection of data and information [8].

3.1.3 Bottom-up data collection strategy

The opposite of a top-down process is called bottom-up. This process is distinguished by a process in which there is no specific goal with the information that is collected. To gather a broad dataset of information and interpreted it without any specific goal in mind. This can be a good process in cases where the goal of a process is unknown and the outcome is a result of the information gathered contrary to the primary intent [8].

3.1.4 Design of Experiments

The design of experiments is used when the real cause of a problem or the various impact of design parameters or functions are unknown. This is often used when other analytical methods are inapplicable to the problem of interest. The procedure consists of several stages and the following were used in the thesis:

- Identify controlled and uncontrolled factors of the problem.
- Determine the objective function.
- Determine the testing procedure.
- Execute the experiment.
- Statistical analysis of the results.
- Conclusions of the results.

3.2 Design Processes

The process of a product development project is the foundation upon which the structure is built and usually consists of one or several phases. An example of these can be seen in Figure 5, where Discover, Define, Develop, and Deliver are different phases. These phases often consist of one or more methods used to achieve the goal of product development.

The design process used in this project is a combination of two established product development processes tuned to the specific needs and scope of the thesis. The combination consists of Ulrich & Eppinger's and Design Council's Double Diamond development process. These processes will be described in the two following sections before presenting the combined process.

3.2.1 Ulrich & Eppinger

Ulrich and Eppinger's book "PRODUCT DESIGN AND DEVELOPMENT" is based on characteristics of successful product development and product development activities that benefit from the core functions of a company. The goal is to present in a clear and easy-to-understand way, product development methods aimed at combining the marketing, design, and manufacturing functions of a company. Marketing handles interactions between the company and its customers. Marketing often enables the identification of product opportunities, the definition of market segments, and the identification of customer needs. Marketing also typically arranges for communication between the firm and its customers. The design function is usually responsible for defining the physical form of the product to best meet customer needs. The design function includes engineering design (mechanical, electrical, software, etc.) and industrial design (aesthetics, ergonomics, user interfaces). The manufacturing function is usually primarily responsible for designing the production to produce the product.[9]

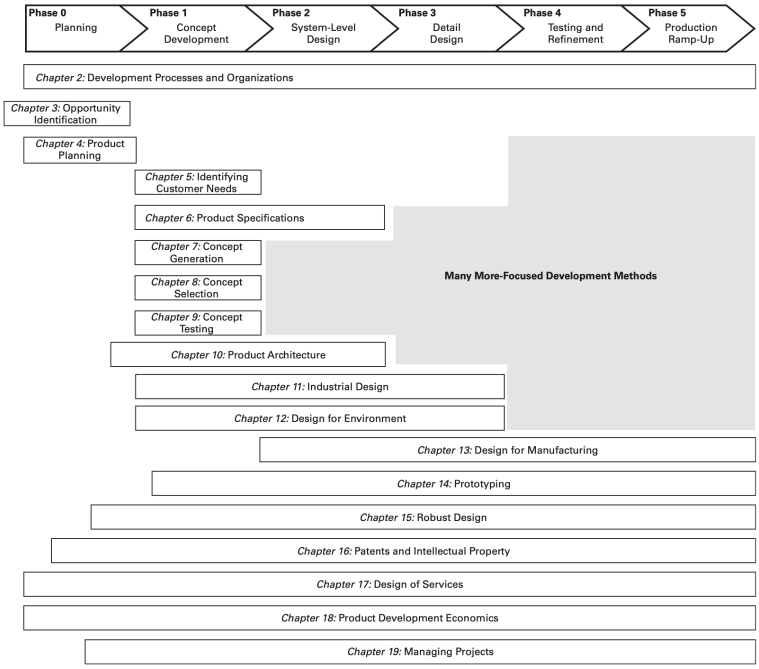

Figure 3: Ulrich and Eppinger's product development process[9]

A holistic overview of Ulrich & Eppinger's design process can be seen in Figure 3 where the phases and their corresponding subphases are listed. Due to the limited time of the thesis and the scope, not all phases will be included and will thus not be described in this section. The phases of interest primarily include Concept Development, which consists of several sub-phases as seen in Figure 4. These sub-phases are placed alongside three areas that guide the development phase. The areas consist of Performing Economic Analysis, Benchmarking Competitive Products, and building, and Test Prototypes.[9]

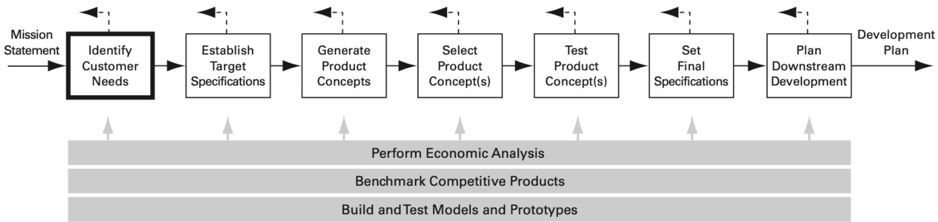

Figure 4: Concept development given by Ulrich & Eppinger [9]

- Identifying Customer Needs: The identification of customer needs sets the foundation for product development. The goal for this method, as stated by Ulrich & Eppinger, was to ensure that the product was focused on customer needs, identify latent or hidden needs as well as explicit needs, provide a fact base for justifying the product specifications, create an archival record of the needs activity of the development process, ensure that no critical customer need is missed or forgotten, and to develop a common understanding of customer needs among members of the development team. The following points are used in this thesis in the identification of customer needs:

  - Gather raw data.
  - Interpret the raw data in terms of needs.
  - Establish the relative importance of the needs.
  - Reflect on the results and the process.

  [9]

- Establishing Target Specifications: Specifications describe the product's design parameters with metrics. ”Target” stands for hopes and possibilities during development and were usually finetuned when the final specifications are set. The following points from establishing target specifications were used in the thesis:

  - Prepare the list of metrics.
  - Collect competitive benchmarking information.
  - Set ideal and marginally acceptable target values.
  - Reflect on the results and the process.

  [9]

- Generate Product Concepts: The concept generation method is used to generate product concepts that may fulfill customer needs. [9]

  The generation of product concepts for the thesis did not follow Ulrich & Eppinger's. The generation followed a more agile method that was introduced during the thesis.

- Select Product Concept(s): The concept selection method is the area where product concepts are analyzed and removed to find the most promising concept. The selection of concepts used in the thesis was the following steps:

  - Pros and cons: The team lists the strengths and weaknesses of each concept and makes a choice based on group opinion.
  - Prototype and test: The organization builds and tests prototypes of each concept, making a selection based on test data.

  [9]

- Test Product Concept(s): In this method, concepts are tested to verify that their customer needs have been met.[9]

  The test of the concepts was not made in the thesis due to the limitations of Axis.

- Set Final Specification(s): In the method of the final specification, the target specifications are adjusted after the concept(s) have been tested. [9]

  The final specifications were included in the target specifications of the thesis. The specifications were adjusted alongside the entire project resulting in the final specifications for the given solution.

- Plan Downstream Development: In the planning of the downstream development, the creation of a development schedule, strategy, and the required identification of resources is made to complete the project and minimize development time. This area creates a contract between the development team and the enterprise. [9]

  The planning of the downstream development was not considered in the thesis due to the scope of the project.

As stated, these phases are guided by criteria given by the economic, competitive, and prototyping areas. These areas are repeatedly visited during the development phase changing the course of the thesis along with it.

- Modeling and prototyping: The prototyping and modeling area is to some extent part of all the phases of the development process. The prototypes can span from the ”Quick and Dirty” ones made with basic building techniques to more advanced prototypes and models made with sophisticated techniques. The goal of these prototypes is to make a proof of concept and or experimental test models, which can be used to set design parameters. [9]

- Benchmarking of competitive products: Benchmarking is important when designing a product. This area sets the references for the product and can work as a resource for new ideas. Measurable specifications of the developed product can be compared to competitive products to give an indication of where to be placed in the market. [9]

- Economic analysis: The economic analysis is often made in collaboration with a financial analyst. This area is where the creation of an economic model is made, for development and manufacturing purposes. This area was not considered in the thesis due to its scope. [9]

3.2.2 Double Diamond

In 2003, Design Council promoted the positive impact of adopting a strategic approach to design and design management. But when trying to promote a strategic way of design management, they realized that they did not have a standard way of describing the process. An experienced team was put together to create a process that was applicable to any field, and client of the Design Council, and thus the Double Diamond process was established. In 2004, the Design Council started to present the Double Diamond process at different conferences, in presentations and they also started to reference and use it with their clients. [10]

The Double Diamond is a deconstruction of the recurring parts from various methods used by experienced product developers and consists of mainly four phases [10]:

- Discover - The process starts by questioning the challenge and quickly leads to research to identify user needs.

- Define - The second phase is to make sense of the findings, understanding how user needs and the problem align. The result is to create a design brief that clearly defines the challenge based on these insights.

- Develop - The third phase concentrates on developing, testing, and refining multiple potential solutions.

- Deliver - The final phase involves selecting a single solution that works and preparing it for launch.

As illustrated in Figure 5, the first diamond consists of the first two phases and can be described as ‘designing the right thing’. The second diamond is about ‘designing the thing right’, exploring the possibility, making iterations, testing, and developing. Today, the versatility of the Double Diamond has gone far, including[10]:

- For an initial assessment of project type and the approach needed to address a specific challenge.
- As a tool to help focus teams at the start of a project.
- As a method for starting to shape the strategy and management of a project.
- To check in on a project in terms of where we are in the process.
- To help people get comfortable with ‘going broad and unfocused’ in both of the divergent Discover and Develop phases.

The original double diamond process may seem quite vague and broad but it is said by Daniel Gustafsson [11] that the design council has made it clear that the model is intended to be modified toward the specific project at hand. Moreover, it was considered that testing the limits of the usability of a more detailed double diamond structure would yield more fruit than sticking to the originally vague. As stated by Daniel Gustafsson [11] the process fits small projects on a highly practical level.

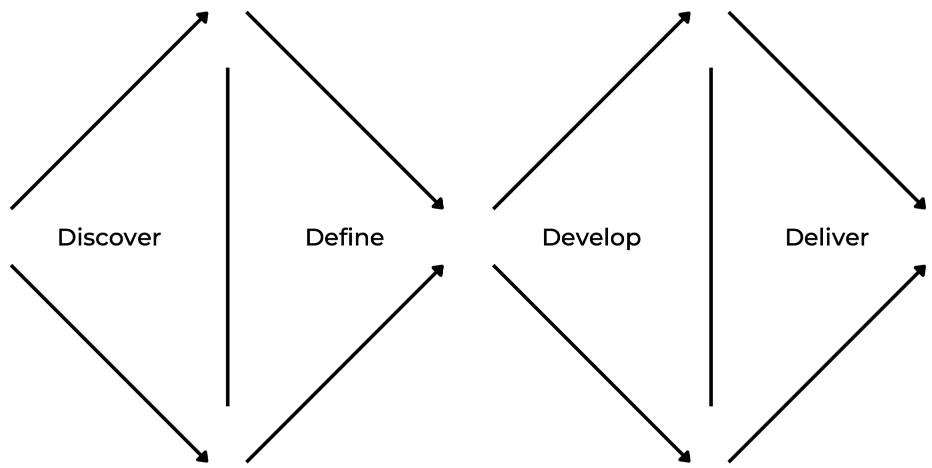

Figure 5: Original Double Diamond Process

3.2.3 Combined Process

The combined process was the development process used in this project. The combination of Ulrich & Eppinger’s concept development phase and the Double Diamond tuned to the specific criteria of the project is the ground for this process. Like the Double diamond process, it consists of four phases. The phases are ”Discover”,

”Define”, ”Develop”, and ”Deliver”. These phases are quite vague and thus complemented with methods from the sub-phases given in Ulrich & Eppinger’s concept development. Another area called ”Develop Target Specifications” was also introduced and added to the process. This states that the evolution of the specifications will be made throughout the process. The last area present during half of the project is the ”Design of Experiments”. This area is a method used for complex systems where experiments can be a foundation for design decisions.

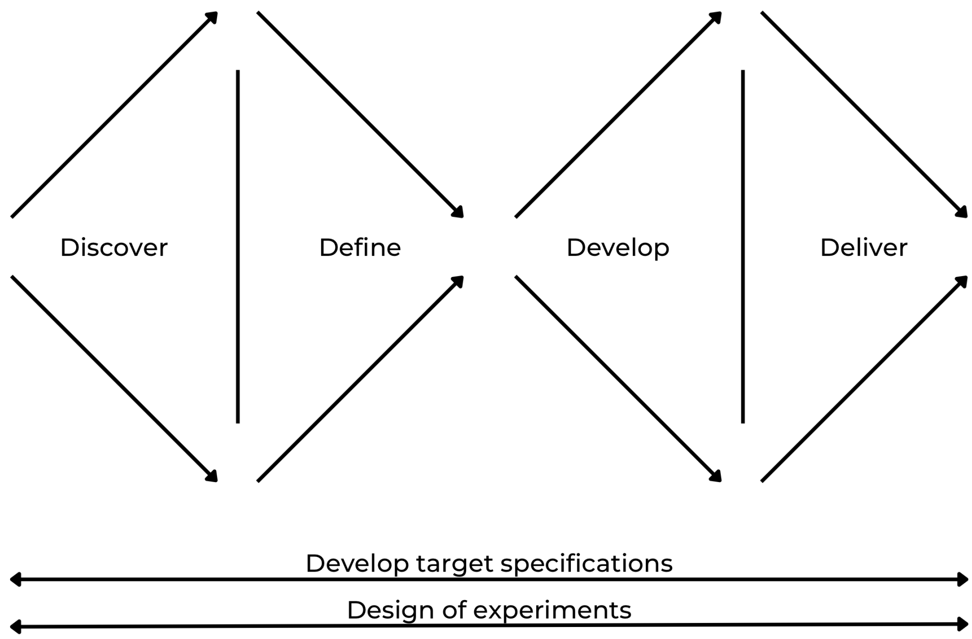

Figure 6: Combined Double Diamond and U&E Process

As stated Ulrich & Eppinger’s concept development phase mostly inspired the methods used in the combined process. By introducing new methods to the four different phases, these changed in regard to the original Double Diamond. The changes and clarifications are stated below.

- Discover - The combined process starts by understanding the technical area and the current product of interest. The different problematic areas are defined.
  - Internal Research. Consisting of interviews and tests of the current product.
  - External Research. Consisting of a literature review.
  - Clarifying Problematic Areas. Presenting the problems affecting the image of the current camera.

- Define - The second phase is to make sense of the findings. The task is to create a design brief that clearly clarifies the problem.
  - Investigating the Identified Areas. Investigation of how and why the identified areas were problematic.
  - Clarifying the Problem. Summarizing and clarifying the current problem.
- Develop - The third phase concentrates on generating, testing, and refining multiple potential concepts.
  - Generating conceptual sketches. Making sketches and brainstorming concepts based on the previously gathered knowledge in the project.
  - Testing the concepts. Simple tests were made for the generated concepts.
  - Refining solutions. The refinement improves the concepts based on the testing or specifications.
- Deliver - The final phase selects one concept as a suggestion for a possible solution to the problem. The phase then explores prototyped versions of the concept to evaluate potential improvements to reduce the original problem.
  - Select product concept. The selection for one promising concept.
  - Prototype and test the concept. Testing for the chosen concept.

The combined process's methods following the entire project were established to have a more agile process. The building and testing of models were made alongside the project to iteratively investigate problematic findings and improvements. The development of target specifications was made to continuously develop the specifications alongside the project due to the limitations of Axis and to stay open for new possible types of solutions or areas of the thesis.

4 Product Development

This section will follow the combined process, presenting the results from the methods covering the entire length of the project and the four phases taken from the Combined Process. A flow chart can be seen in Table 1 where the order of the areas of the process and their corresponding content were stated.

Table 1: Product development structure.

No.	***Area***	***Content***
1	Develop Specifications	Identifying needs, Establish target specifications.
2	Discover	Internal research, External research, Clarifying area of improvement.
3	Define	Investigating the identified areas, Clarifying the problem.
4	Develop	Generate conceptual sketches, Test the concepts, Refining concepts.
5	Deliver	Select product concept.
6	Design of Experiments	Identify controlled and uncontrolled factors, Determine the objective function, Determine the testing procedure, Execute the experiment, Statistic analysis of the results, Conclusions of the result.

4.1 Develop Specifications

4.1.1 Identifying Needs

- **Gather Raw Data**

  - **Interview With Product Owner**
    The product owner explained that the shake of the image was mostly affected by running and walking movements. The major issue with shaky image quality was that it was uncomfortable to look at for a longer period of time. He stated that a bigger and heavier camera could be problematic, especially together with different mounts, making it uncomfortable to wear for longer periods of time. He also said that the camera needed to maintain an all-day battery life.

  - **Interview With Customer Contact**
    In the interview with the customer contact, he said that the shake of the image had not been a problem stated by first-hand users. He explains that the camera is bulky and that it sometimes gets stuck on seatbelts. He says that the camera is often worn on the chest, mostly via a magnet mount. He also says that complaints from people usually include comments about the Klickfast fixation and the mounts.

- **Interpret the Raw Data in Terms of Needs**
  The interpretations of the raw data were made by the thesis group. The needs are formulated in terms of what the product has to do, not in terms of how it might do it. 21 interpreted needs were made and can be seen in Table 2.

- **Establish the Relative Importance of Needs**
  The relative importance of the needs was made by the thesis group through intuition when analyzing the gathered raw data. The relative importance of each need can be seen in Table 2. The importance was measured between 1 and 5 where 5 was considered the most important.

Table 2: Interpreted Needs.

No.	*Need*	*Imp.*
1	A video stream that is comfortable to look at during a longer period of time.	5
2	Should have a low cost.	2
3	Should have all-day battery life.	3
4	Should have low maintenance.	1
5	Should not reduce image quality.	5
6	Should be comfortable to wear.	4
7	Should have flexible mounting possibilities.	3
8	Robust design mechanically.	4
9	A more stable image.	5
10	Dust and water resistant.	5
11	The size should remain quite similar.	4
12	Weight should remain quite similar.	3
13	It should be able to compensate for running and walking.	5
14	The camera is heat-sensitive, temperatures should remain the same or be lowered.	2
15	The camera should have a wide field of view.	4
16	Damage to the stabilization should not jeopardize the basic functionality of the camera.	2
17	It should be easy to mount.	3
18	It should be easy to use.	5
19	Should be robust enough to withstand normal to extreme shaking.	4
20	Easy to put on and off.	2
21	Should be comfortable to wear for longer periods of time.	3

- **Reflect on the Results of the Process**
  The interviews held at Axis were limited as it was not possible to contact any customers at the time meaning specifically the users of the body-worn camera couldn't be interviewed. Instead, only the Product Owner and the Customer's contact at Axis were interviewed. There was a risk that the lack of input from actual users of the camera was impacting the interpreted needs and which are most important. In turn, this was affecting which design parameters are

considered important.

4.1.2 Establish Target Specifications

The metrics were established by the thesis group and based on the previously developed needs. The metrics were constructed from the perspective of image quality due to it being the scope of the project and thus the area of most interest. However, additional needs were established due to some critical practical factors of the current mounting solution that had to be taken into account such as flexible mounting positions and solutions.

- **List of Metrics**
  The total list of metrics sums up to 13 different ones and can be seen in Table 3. The metrics were developed by the intuition of the thesis group by grouping needs for each corresponding metric. All metrics have a relative importance that was measured between 1 and 5 where 5 was considered the most important. The metrics also have their corresponding units to measure.

Table 3: List of Metrics.

Metric No.	*Need Nos.*	*Metric*	*Imp.*	*Units*
1	1, 9, 13	The diviation minimum of the center of the image.	4	%
2	1, 5, 9, 13	Should not get dissy by looking at the footage.	5	Hours
3	2	Maximum total cost.	2	€
4	3	Minimum battery life.	3	Hours
5	5	Minimum image resolution.	4	M Pixels
6	6, 12, 21	Maximum weight.	4	g
7	6, 11, 21	The maximum size of the camera.	3	mm^3
8	8	Shoud widthstand forces.	5	N
9	10	Should withstand dust and water.	5	Rating
10	15	The minimum FOV.	4	degrees
11	17, 18	Maximum time when mounting.	2	s
12	17, 18	Maximum steps needed for mounting.	4	Nbr.
13	21	Minimum time of comfortable wearing.	4	Hours

- **Competitive Benchmarking**
  The competitive benchmarking was based on the interpreted needs. The current Axis Body-Worn camera was made to be the reference of the benchmark. The GoPro 11, DJI Pocket 2, and the Axon Body-Worn 3 were chosen as competitors. The benchmarking can be seen in Table 4 where needs and their corresponding importance were stated. The benchmarking is completely made by the intuition of the thesis group where an interpretation of each competitor is made via the information stated on their corresponding websites. The relative performance was measured between 1 to 5 stars, where 5 stars were considered the best, 3 stars the same as the reference, and the - was too little information to make an interpretation.

Table 4: Competitive Benchmarking Based on Interpreted Needs.

No.	*Imp.*	*Axis BW*	*GoPro 11*	*DJI Pocket 2*	*Axon BW 3*
1	5	***	*****	****	***
2	2	***	****	*****	****
3	3	***	*	*	***
4	1	***	****	***	***
5	5	***	****	*****	-
6	4	***	****	*	***
7	3	***	*****	*	-
8	4	***	***	*	***
9	5	***	****	****	***
10	5	***	*****	**	***
11	4	***	****	****	-
12	3	***	*****	****	***
13	5	***	-	-	-
14	2	***	***	**	***
15	4	***	-	-	***
16	2	***	**	*	-
17	3	***	***	**	****
18	5	***	***	**	***
19	4	***	***	-	***
20	2	***	***	-	***
21	3	***	***	-	***

- **Ideal and Marginally Acceptable Values**
  The ideal and marginally acceptable values were set by the thesis group to each metric previously stated in Table 3. The values were determined by intuition with the Axis BW as a base reference and with insights into the competitive benchmarking and can be seen in Table 5.

Table 5: Ideally and Marginally Acceptable Values

Metric No.	*Imp.*	*Units*	*Marginal value*	*Ideal value*
1	4	%	<15	<1
2	5	Hours	0.5<	2<
3	2	€	-	-
4	3	Hours	6	12
5	4	M Pixels	10.8	12
6	4	g	<250	<200
7	3	mm^3	<200000	<117000
8	5	N	3<	4<
9	5	Rating	IP67<	IP67<
10	4	degrees	130<	141
11	2	s	<10	<5
12	4	Nbr.	<4	<2
13	4	Hours	4	8

- **Reflect on the Results of the Process**
  The competitive benchmarking gave values of the metrics. To get a wide view of the competitive products by looking at the consumer GoPro 11 and the gimbal solution of the DJI Pocket 2 as well as a similar competitor the Axon Body-Worn 3 different angles of the shake problem were able to be investigated. However, the benchmarking and the values were established purely through intuition by interpreting the design parameters stated by their corresponding companies, potentially covering any negative areas when the comparison was made.

4.2 Discover Phase

The Discover phase questions the challenge of stabilizing body-worn cameras. Research is made internally and externally to identify general areas of improvement of a body-worn camera solution in relation to image shakiness. The phase was established to have a more fundamental understanding of the problem to solve. This phase was all about widening the knowledge within the area of research knowledge and the product of interest. Of the quite limited access to first-hand users of the body-worn camera, an understanding of the problem relied more heavily on the thesis groups' tests and interpretation of the product's usage.

4.2.1 Internal Research

The Discover phase started with an early holistic overview of the technical areas and the background of the body-worn camera project at Axis. The idea was to gather knowledge at the beginning of the thesis to have a solid understanding of the problem going forward into early customer statements, tests, and comments from Axis. A top-down approach was initially chosen as the process in order to gather data and information since a specific goal of stabilizing the image was known and the information was gathered from employees with experience and knowledge in the subject. Suspicion arose early of a dampening solution that perhaps could affect the stability of the image in a positive way, and curiosity if a dampening solution could have any effect at all.

Part of the research was to understand the specific camera of interest, the Axis body-worn camera. Initial functionality tests of the camera were conducted by the thesis group, and previous footage was analyzed. Investigations were made by the thesis group regarding previous attempts at solutions for image stabilization, specifications, and product descriptions of the camera.

4.2.2 External Research

Research outside the company was a part of the starting process of the thesis. It was done by gathering information about different stabilizing methods by researching online, reading articles, and gathering information from companies that work with similar products.

Other body-worn cameras that were investigated as a part of the master thesis group external research, often included EIS. This is often seen in cameras of this size since it does introduce an increased weight, additional parts, and furthermore, no additional cost per camera to include this solution. However many cameras that the group researched were often for personal use and for filming shorter periods of footage with a more cinematic approach. The body-worn cameras that were intended for surveillance and could be used by law enforcement that was investigated did not include EIS, at least not clearly stated by the companies that provided the cameras. Stabilization methods like OIS have not been seen in the body-worn cameras that the thesis group investigated. AIS solutions, as a gimbal was seen in examples with both cameras for personal and surveillance use.

Information gathered externally summed up that the most promising stabilization methods used in cameras of similar size were EIS and PIS. These solutions could potentially counter the problems with the image quality introduced by shaking in different directions. EIS by manipulating the video after it was taken and PIS by constructing a passive dampening solution by softening the shakes.

4.2.3 Iteration 1

Knowledge gathered from the external and internal research led to simple tests of the camera with different conditions. A camera mount was made early in order to test differences by dampening the Body Worn camera in a surrounding foam and comparing it with no dampening at all to see the effect of PIS. The foam that was used was Polyurethane-foam and would act like a dampening material to see its effect on the outcome of the recorded video [12]. The sketch of the dampening foam can be seen in 7. The foam-surrounded camera was hung around the neck of a thesis worker by a strap. The video did not show any type of visible improvement by surrounding the camera in foam compared to that which wasn't. However, the videos of the two tests showed very unstable images and pointed to a more substantial problem with the quality of the image due to movements than first anticipated, which made it very difficult to know if the foam actually did a small difference compared to the big difference of the shaky video. The problem was assumed to be the unstable mounting of the camera during the tests and as such could not the dampening be tested reliably.

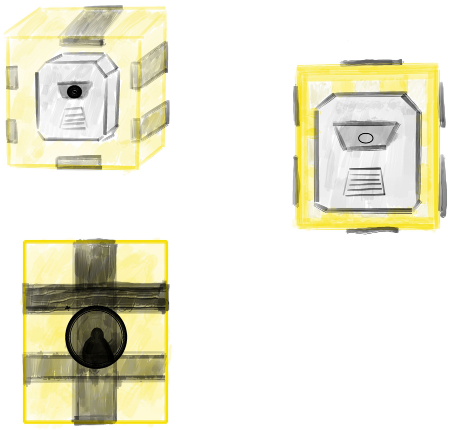

Figure 7: Sketch 1

4.2.4 Iteration 2

The result of iteration 1 gave an indication that the way the camera was mounted had a great effect on the outcome of the video recorded during movements. A new attempt at improving the image by foam dampening was made. The strap that was used in iteration 1 was replaced with a harness from a third-party company seen in fig 8. This strap was more securely attached close to the body. The surrounding foam was replaced by a 3D-printed fixture that included an attachment mounted with bearings that could move freely in the vertical direction but was restricted in any other direction. The fixture was filled with foam at the bottom of the slot in order to have a dampening effect whilst affected by a bouncing movement. The camera itself was attached to the attachment that could move up and down the slot. The 3D-printed fixture can also be seen in figure 8. This was compared to attaching the camera directly to the harness. The videos recorded from the tests in iteration 2 showed significantly better images than the ones from Iteration 1. However, the difference between the 3D-printed dampening fixture and just attaching the camera directly to the harness did not result in a significant difference in video quality. Thus the dampening effect of the foam was minuscule however the difference between the different mounting solutions to the body was immense. This meant that the way the camera were mounted to the body seemed crucial to the outcome of the stability of the image but the way of dampening the shakes with PIS was not as effective.

Figure 8: 3D-printed fixture and harness solution

4.2.5 Iteration 3

With the knowledge gathered from the second iteration, the internal research area was broadened. All mounting alternatives made by Axis in collaboration with Klickfast were investigated and can be seen as illustrations in Figure 9. This research officially broadened the thesis from developing a stabilization solution integrated into the body-worn camera to looking at external factors affecting the image.

All mounting alternatives were tested by the thesis group by mounting them to the body and visually inspecting the movement introduced to the camera when walking. The most reliable camera position in relation to the body was seen in the Klickfast harness mount, similar to the mount used in iteration 2 and the Molle mount used on the tactical vest, which is a mount specifically made to attach to the straps of tactical vests. During the test of the mounts, another potential area of improvement was found. The difference between the third-party mount and the similar Klickfast harness mount was investigated and slipping of the position of the camera was introduced by the design of Klickfast.

A meeting with a customer contact was set up to investigate the potential problem related to the mount to the body and the Klickfast fixture solution. In the semi-structured interview, aspects were brought up of the wearability of the camera and the impact it had on the wearer. According to the customer contact the image quality in itself was fine, however, the attachment of the camera to the body was the main reason for complaints from customers. The weight of the camera, even though it is only around 200 grams, had a big impact on comfort when worn during an entire workday. When discussing which mounting solutions were being used, the magnetic mount stood out as the most frequent one. The Klickfast harness mount, similar to the mount used in iteration 2 was almost never used due to its bulkiness and appearance. These insights narrowed down the most used mounts to the magnetic-, the clamping- and the MOLLE mount. The Klickfast solution was not mentioned as a source of problems, related to the shakiness of the image.

A top-down strategy was used in the beginning since the thesis group believed that they understood what one, or, several possible solutions could be. This was contradicted as the thesis went along and other strategies were used. In an attempt to gather information early about what problems there primarily were with the image quality, some estimations were made by employees that did not reflect the actual problems when testing the camera by itself. This meant that some facts were correct but other estimations weren't when gathering information. To actually realize what the problem affected the camera and what in reality should be made different, the information and data that were gathered were used and analyzed from a bottom-up perspective. What started out to be a top-down approach actually evolved into a bottom-up as the thesis work went along. With the iteration 2 tests, when doing the top-down process, the product owner said that disturbances from vertical movements were most vital to get rid of in the interviews. However, the information and data collected from the test proved that axial movements contributed substantially more to the poor video image. This meant that the process of information gathering switched from top-down to bottom-up.

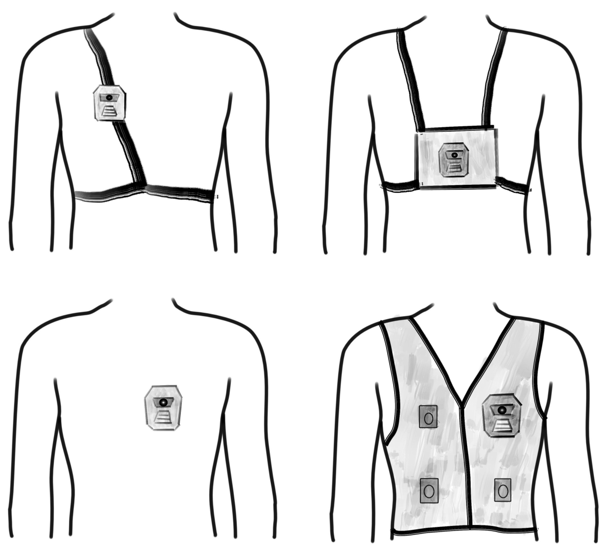

Figure 9: Body mounting alternatives

4.2.6 Clarifying General Area of Improvement

With the knowledge gathered from the research made in the Discover phase three major areas were declared as areas of potential improvement. To move forward and declare a fundamental problem description, a comparison of the three areas was to be made in the Defining phase.

- Mount to the human body
- Fixation between camera and mount
- Image stabilization technique

4.3 Define Phase

The definition was all about defining the actual problem that should be investigated. To completely understand the different areas of improvement and give a complete clarification of the problem several tests on the decomposed problem(Mount, fixation, and stabilization) were made.

4.3.1 Investigating the Identified Areas

The change of perspective started a further investigation of these solutions. These investigations started by doing tests of fixtures and comparing the stabilization methods of similar products. The fixation tests were conducted in a controlled manner where two fixation options were chosen. The two fixations to test were chosen based on them being either one of the most used by first-hand users(Magnetic mount) or the most sturdy fixation determined by the thesis group after testing the mounts (Klick-fast harness mount). The mounts can be seen in Figure 10 to 12. The magnetic mount was chosen to go through the test two times and placed at different heights on a sweater to see the potential impact related to placement. All setups for the test can be seen in Table 6 and the tests were conducted as follows:

- A bright consistent light condition was chosen to have a repeated impact on the result.
- A distance of approximately 10 meters, a consistent direction, and a place were set.
- A time of 10 seconds was determined to be followed to achieve close test results.
- The two mounts were attached to the body, and the exact placement were photographed and noted.
- The tests were made for each mount and placement. The videos were saved with a timestamp.

Table 6: Test 1

Test version	*Test setup*	*Figure*
A	Camera is attached with a harness.	10
B	Camera is attached with a magnetic body mount positioned on the upper chest.	11
C	Camera is attached with a magnetic body mount positioned on the lower chest.	12

Figure 10: Harnsess body mount.

Figure 11: Magnetic body mount positioned on the upper chest.

Figure 12: Magnetic body mount positioned on the lower chest.

The results of the tests, the customer responses, and the thesis group's own interpretation of the problem strengthen the argument for the different areas of improvement previously discovered. The mounting was determined to impact the current quality of the image. The tests of each mount can be seen in Figures 13 to 15 and the performance was measured by picking a point of measurement in the image(the upper chest of the human in the distance) highlighted as a green dot and draw a red box indicating the deviation of the green point in relation to the image. The blue area indicates the entire screen. The red deviation box was made by taking three samples of the worst-case position. A more sturdy mount in relation to the body has more control over the introduced motions to a video.

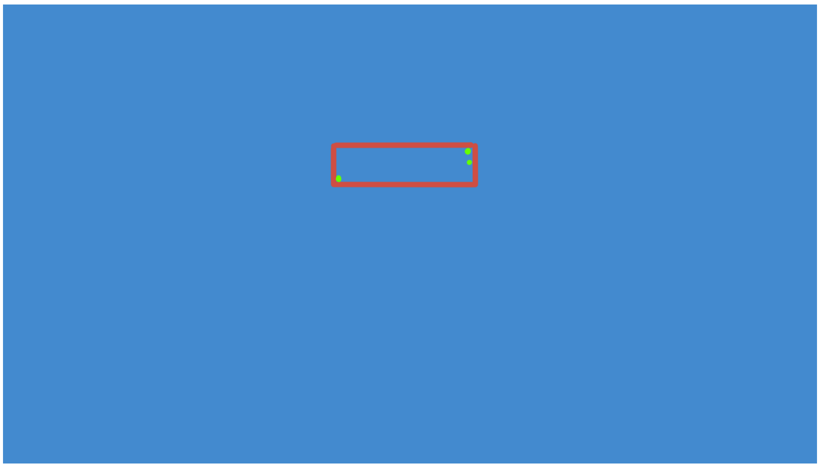

Figure 13: Test 1A: Deviation illustration when the camera was mounted by using a harness. The three largest deviations were taken from the same object at a distance in the early stages of the test.

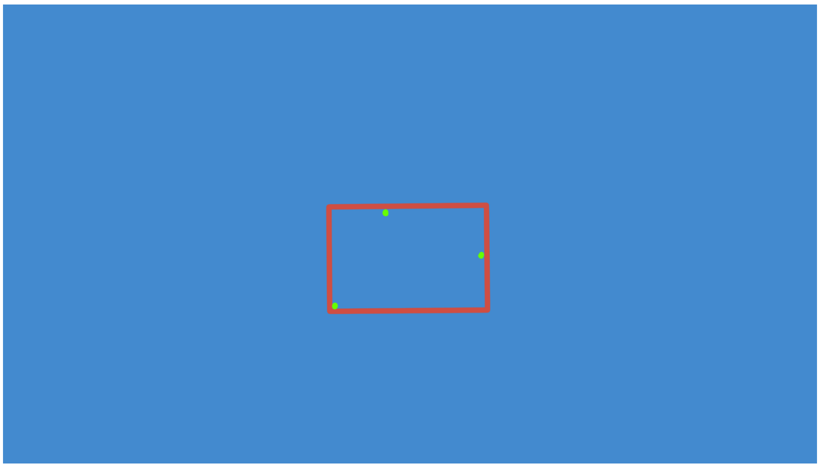

Figure 14: Test 1B: Deviation illustration when the camera was mounted to the upper chest when using a magnet mount. The three largest deviations were taken from the same object at a distance in the early stages of the test.

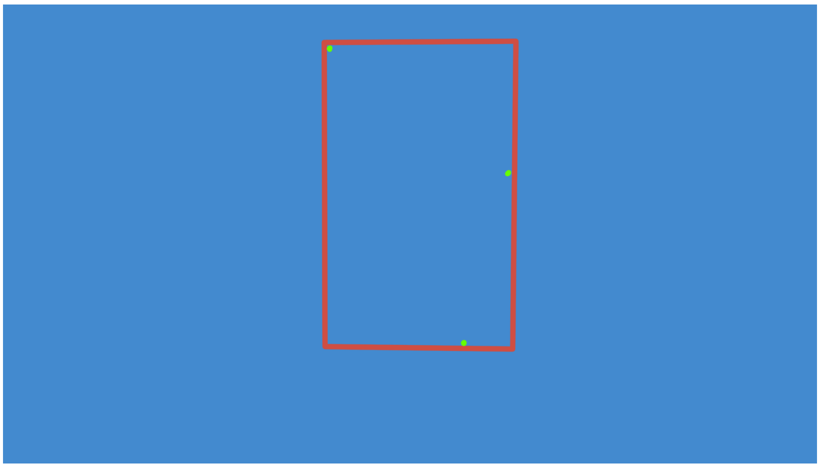

Figure 15: Test 1C: Deviation illustration when the camera was mounted to the lower chest when using a magnet mount. The three largest deviations were taken from the same object at a distance in the early stages of the test.

When analyzing the results from Test 1 further, a mount solution with a ”loose fit” will introduce bigger deviations specifically in the vertical direction in relation to the image area. The continuous increase can be spotted from Figure 13 to Figure 14 and then finally Figure 15.

The details captured by the Axis body-worn camera when freezing the image in Test 1 were similar to each test version. An example of the details from Test 1 can be seen in Figure 16.

Figure 16: Test 1: Frozen image sample

To determine the impact made by the fixation, a separate test was conducted to isolate this issue. One product of each of the most used mounts(Magnetic-, clamping- and MOLLE) were participating in the test. This was to remove potential slipping in the fixation caused by isolated faulty products. The camera was mounted with Klickfast on each mount, the mounts were held up securely against a wall to remove their impact, and the camera was pushed slightly in every direction to inspect any slipping. The Klickfast introduced an average natural slip of around 3mm perpendicular to the front of the body-worn camera measured from the bottom of the camera to the wall. When inspecting the footage taken from these tests the shake introduced in relation to these small movements was big.

The results were presented to the supervisors. Issues regarding the fixation and mount and their vast impact on the stabilization were something that Axis themselves was not aware of. The decision to include mounts and fixations as an area of interest was shared by the thesis group and the supervisors. The arguments presented by the thesis group were backed by the recordings from the different tests and were stated as follows:

- The different mounting solutions to the body result in the biggest deviation in the image quality in comparison to the current fixture.
- The customers' responses pointed towards problems with the current fixture and mounting solution.
- Research done by the thesis group showed evidence of the same problem regarding the mounting solutions affecting the image quality in similar products.

- The thesis group argued for a higher probability of producing a closer to the final prototype through rapid prototyping of a mounting solution.
- The thesis group also argued for a bigger contribution of knowledge for Axis and the area by further investigating the first-hand users' experiences with these types of products.

All investigations into the identified areas pointed to all areas making a big difference in the shake introduced to the image, but the type of movements affecting the image the most were still to be determined. The thesis group compared the magnetic-mount positions of the first test of the Define phase seen in Figure 11 and 12. These two tests had a big difference in shake introduced to the image even though the mount and fixation remained the same. On a close inspection of the position of the camera in relation to the body in the two performed tests, the vertical and horizontal positions of the camera remained similar. Assumptions were made by the thesis group that the rotational movements of the camera could be the core problem of the shaky image rather than the linear movements. The results from the different movements of the camera were illustrated in Figure 17.

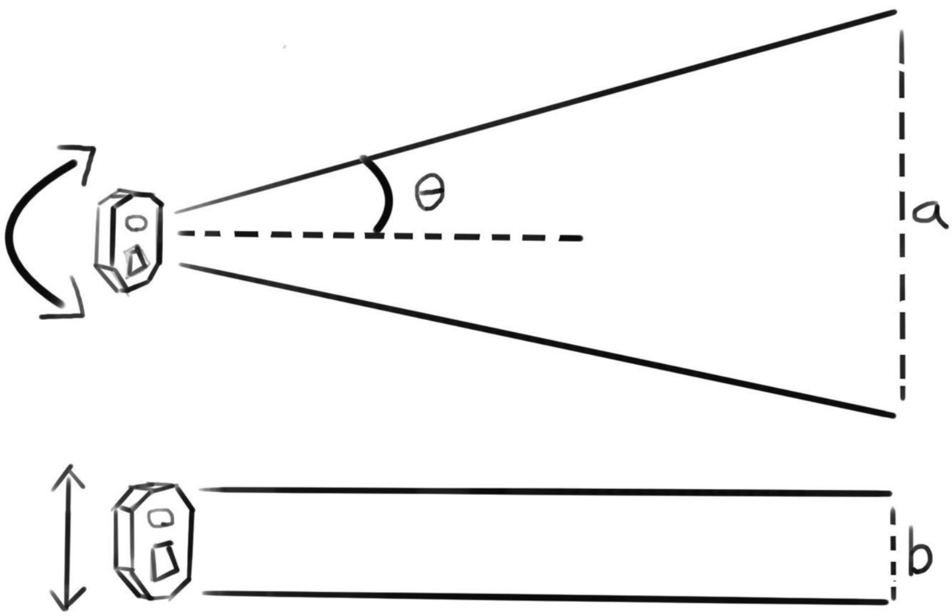

Figure 17: An illustration of how the movements of the camera impact the image.

4.3.2 Iteration 1

The first iteration of the Defining phase was made to confirm the previous assumptions regarding the impact of the rotational movement of the camera and how this movement potentially could be reduced by the different areas of improvement. This included several improvements to the testing. A shirt used by similar to the one used by the police and a third-party camera similar in size to Axis camera including a gimbal solution were purchased. The test was conducted four times named ”Test 2A” through ”Test 2D” with different setups as listed in Table 7.

Table 7: Test 2

Test version	*Test setup*
A	No stabilization, attached to the upper chest with a magnet mount.
B	No stabilization, attached to a harness.
C	Gimbal is enabled, attached to the upper chest with a magnet mount.
D	Gimbal is enabled, attached to a harness.

These tests were made only with the third-party camera to have a completely comparable result. The relevance of the gimbal function could be determined and compared but also the impact made from a ”normally” attached and positioned mount on clothing used by customers. The harness mount used in the tests was the previously tested Klickfast harness and the setup for Test 2B can be seen in figure 18. The setup used for Test 2A with a ”normally” attached magnet mount can be seen in figure 19. Test 2C and 2D had the same setup as the previous two just with the stabilization deactivated which can be seen in Figure 20. The gimbal of the third-party camera was physically disabled. The tests were conducted as follows:

- A consistent light condition was chosen to have a repeated impact on the result.
- A distance of approximately 10 meters, a consistent direction, and a place were set.
- A time of 7 seconds was determined to be followed to achieve close test results.
- The two mounts were attached to the body, and the exact placement were photographed and noted.
- The tests were made for each mount and with stabilization activated and deactivated. The videos were saved with a timestamp.

Figure 18: A DJI Pocket 2 attached over a shirt by a Klickfast harness.

Figure 19: DJI Pocket 2 attached on a shirt with the standard magnet mount.

Figure 20: DJI Pocket 2 with a disabled gimbal.

The tests were analyzed and compared by looking at the movement of the hand-held phone in relation to the video frame captured by the third-party body-worn camera. The deviation results from these tests can be seen in Figure 21 to 24 for each setup and they were based on the same criteria as Test 1 previously mentioned(three measurements of the green dot illustrated in a red box compared to the blue are indicating the size of the image). The improvements from Test 2A to 2B and 2C were very similar and the combination of the two different solutions had a major improvement in the deviation in the image.

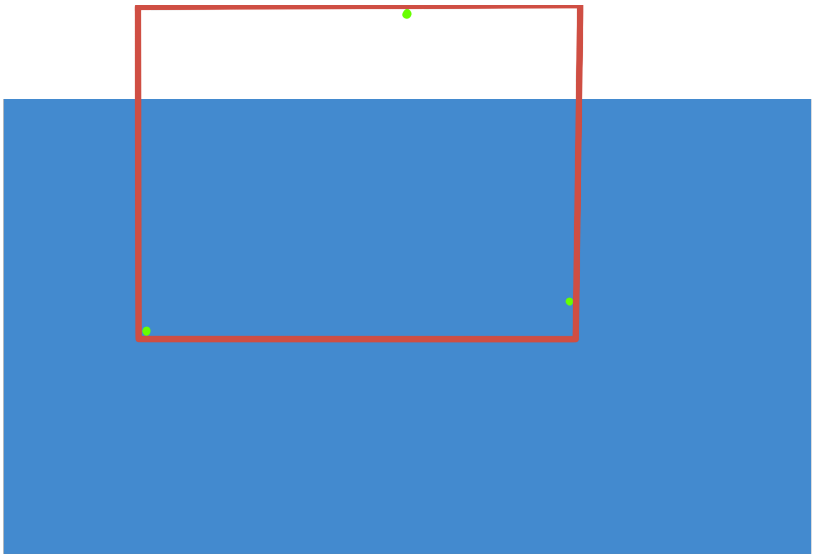

Figure 21: Test 2A: Deviation illustration when the third-party camera was mounted with a magnet mount and its gimbal stabilization deactivated. The three largest deviations were taken from the same object at a distance in the early stages of the test.

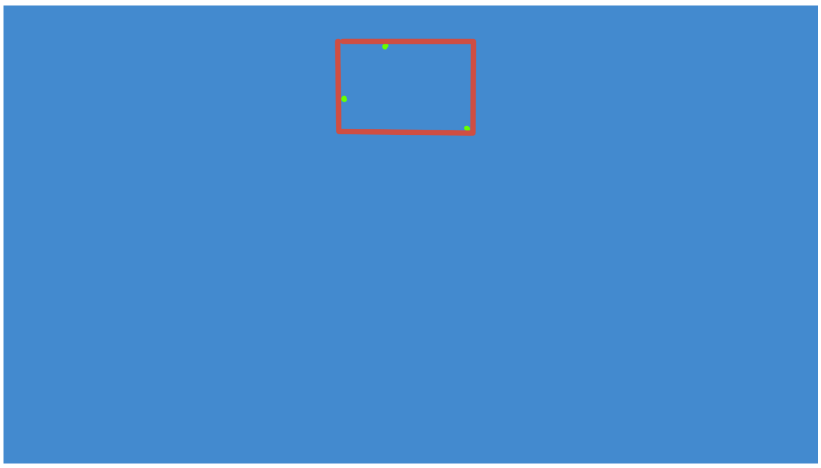

Figure 22: Test 2B: Deviation illustration when the third-party camera was mounted with a harness mount and its gimbal stabilization deactivated. The three largest deviations were taken from the same object at a distance in the early stages of the test.

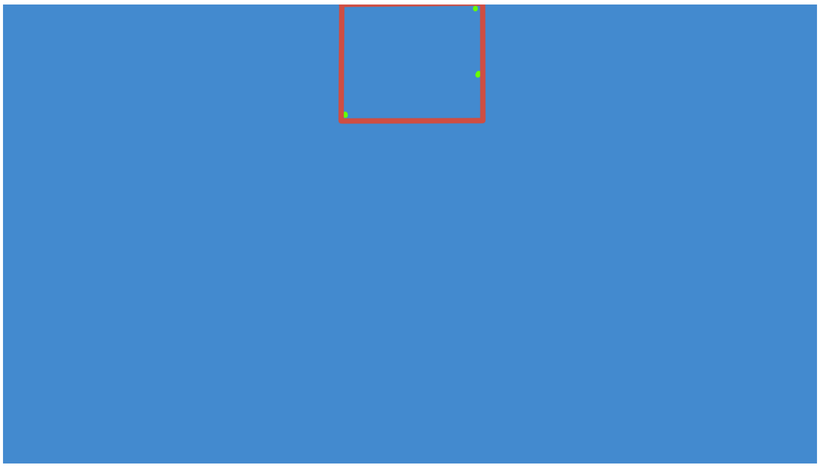

Figure 23: Test 2C: Deviation illustration when the third-party camera was mounted with a magnet mount and its gimbal stabilization activated. The three largest deviations were taken from the same object at a distance in the early stages of the test.

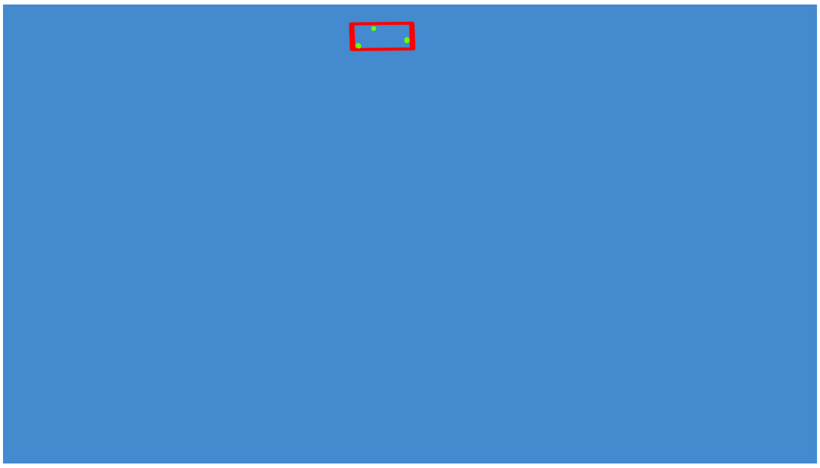

Figure 24: Test 2D: Deviation illustration when the third-party camera was mounted with a harness mount and its gimbal stabilization activated. The three largest deviations were taken from the same object at a distance in the early stages of the test.

The corresponding worst and best case of each test were also illustrated as frozen images and can be seen in Figure 25 to 32. These results together with a visual inspection of each video taken indicate the major importance of both areas contributing to a complete solution. Most of the image shake can be reduced by introducing a gimbal solution or a more secure mount. A combined solution of these two can almost completely remove the shake introduced by moderate running and walking. The gimbal solution can not compensate for the linear movements of the camera, it was only able to compensate for rotational movements, thus also strengthening the argument for the rotation.

Figure 25: Test 2A: Best case

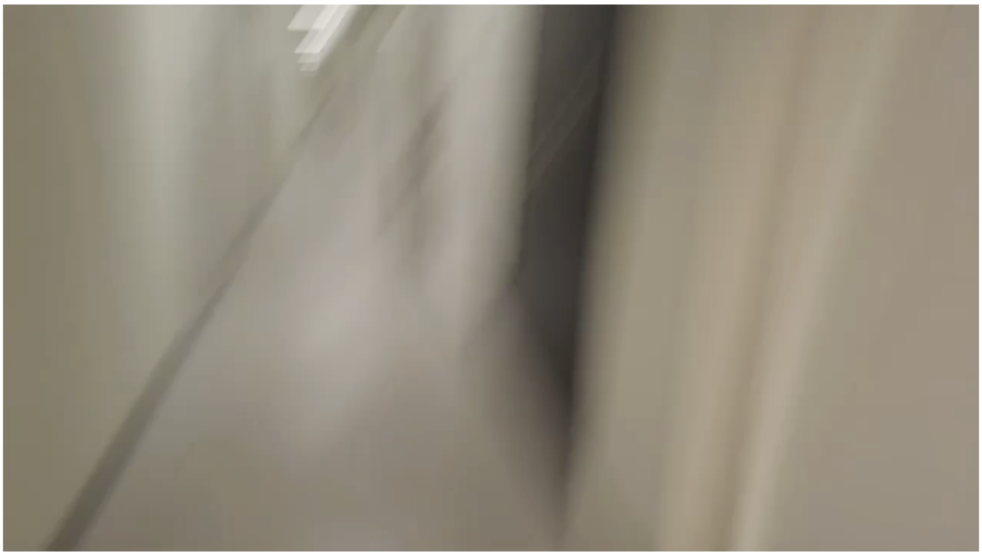

Figure 26: Test 2A: Worst case

Figure 27: Test 2B: Best case

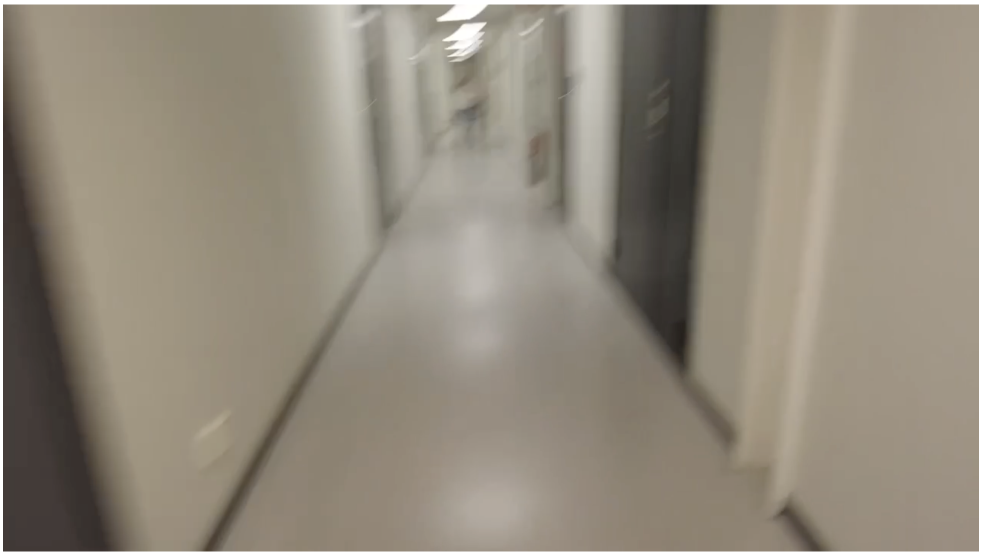

Figure 28: Test 2B: Worst case

Figure 29: Test 2C: Best case

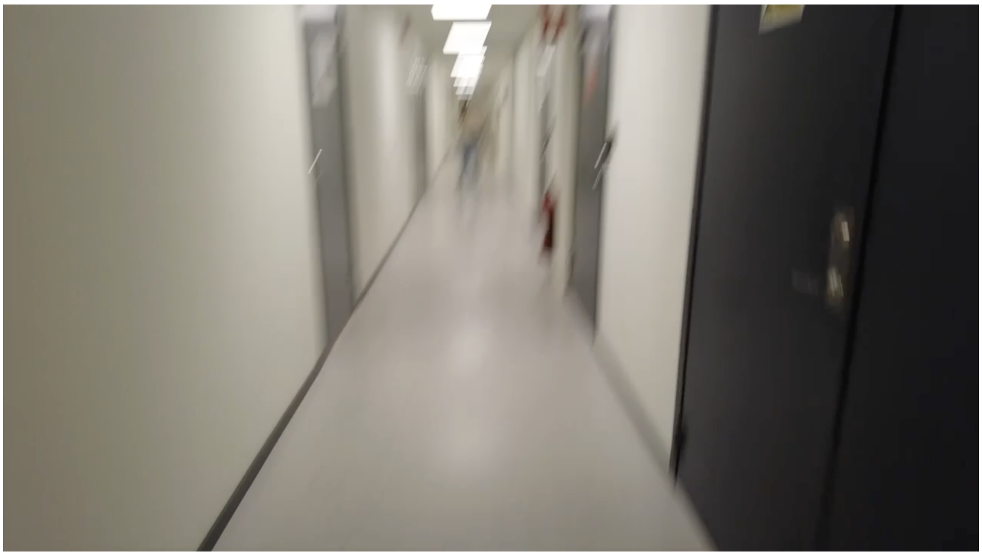

Figure 30: Test 2C: Worst case

Figure 31: Test 2D: Best case

Figure 32: Test 2D: Worst case

4.3.3 Iteration 2

The second iteration was made to investigate the different impacts of a shaky image on different lighting conditions. The previous results from test 1 and 2 had major differences in still image details and the tests were not directly comparable due to the different cameras used(Axis body-worn and a third-party camera). Test 3 was set up to compare the impact of the lighting conditions for each camera previously tested. The conductions of the tests were made the same way as for Test 1 and two, the only difference was that the Axis body-worn camera was tested in indoor lighting(same used in Test 2), and the third-party camera was tested in bright sunlight(similar to the condition used in Test 1). The holistic setup for Test 3 can be seen in Table 8.

Table 8: Test 3

Test version	***Test setup***
A	Axis body-worn camera attached to the upper chest with a magnet mount tested in bright sunlight.
B	Axis body-worn camera attached to the upper chest with a magnet mount tested in indoor lighting.
C	Third-party camera with disabled stabilization attached to the upper chest with a magnet mount tested in bright sunlight.
D	Third-party camera with disabled stabilization attached to the upper chest with a magnet mount tested in indoor lighting.

The results were measured by comparing the best and worst cases for a frozen image between A, B, and C, D. The results can be seen in Figure 33 to 36 where the image has been cropped to visualize the details that were able to be gathered from a frozen image. When analyzing the images, the details of the images taken in bright sunlight outperform the corresponding ones from indoor lighting. The results from these tests indicate that EIS might not be sufficient enough when details of the image were of importance. EIS can stabilize the footage but can not bring back details lost by motion blur captured by the camera.

Figure 33: Test 3: Best case compared between Test A(left) and B(right)

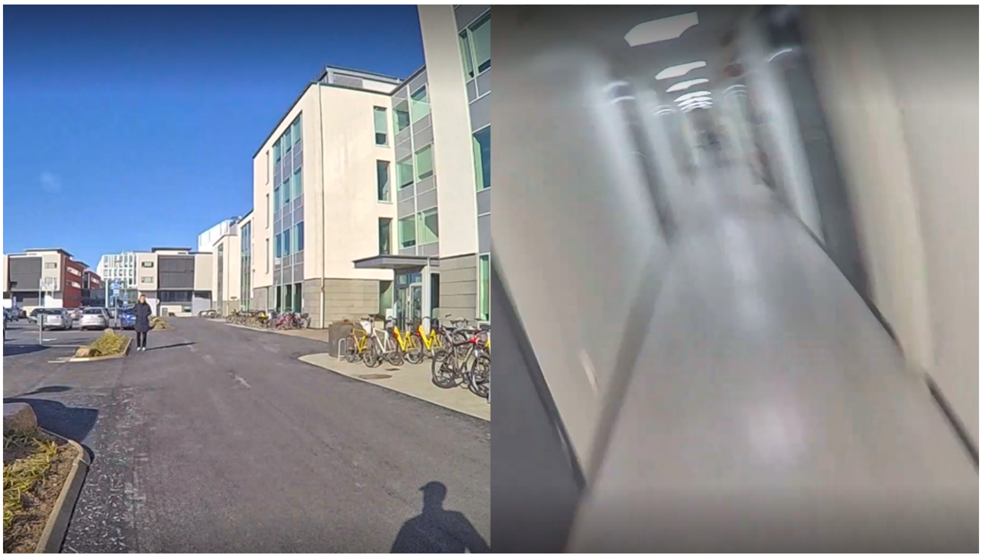

Figure 34: Test 3: Worst case compared between Test A(left) and B(right)

Figure 35: Test 3: Best case compared between Test C(left) and D(right)

Figure 36: Test 3: Worst case compared between Test C(left) and D(right)

4.3.4 Iteration 3

A third iteration of the potential areas of improvement is made to compare the rotational movements for each axis. The coordinate system in relation to Axis' body-worn camera is illustrated in Figure 37. The movements of interest are illustrated as blue rotational arrows around the z, y, and x-axis. The two axes perpendicular to the front of the camera, namely x and z, have the biggest impact on the direction of the image when rotations occur around the axes. The phenomenon can be explained by looking at Figure 17 and focusing on the distance a, where rotations around the x and z axes(seen in Figure 37) correspond to the theta angular deviation. By making rotations around x and z, the center of the image deviates from its original position. By rotating around the y-axis the center of the position remains the same and only the horizontal changes.

Figure 37: Axis' body-worn camera with a coordinate system.

4.3.5 Clarifying the Problem

All the tests have confirmed that the problem specifically relates to the axial rotational movements of the camera. Especially rotations made around the x and z-axis seen in Figure 37. EIS can not compensate for such movements in reality, making so further focus was made on mechanical and electromechanical solutions. The rotational movements that are introduced as shake were caused by a faulty fixation, a mounting solution with difficulty to be attached to and moving together with the body(introducing unreliable shaking), or the natural movement introduced by the body(reliable shaking). The tests have also shown that big rotational movements can be reduced significantly by a better mounting solution and/or a gimbal.

4.4 Develop Phase

With the knowledge gathered from the previous phase, the thesis group would start with developing one or several solutions. This should be done with a broad attitude and with an agile approach. The thesis group explores both physical concepts but also a way of working for the company as a part of a potential solution.

Since it was acknowledged that 3 parts of the body-worn setup affected the result of the image, a concept developed around these three. They included the mounting solution, the fixture in between the mounting solution and the camera, and then the camera itself. The focus was to reduce the unwanted movements that occur around two different axes that were mentioned previously. With the combined information and knowledge gathered, the group proceeded with generating, testing, and refining concepts.

4.4.1 Generate conceptual sketches

- **Concepts to counter irregular shaking**

The mounting solution to the body that the thesis group focused on developing is the magnetic mount, even though there are other mounts to look at. The magnetic mount was said by customer contact was the most used in the field by law enforcement, furthermore it was one of the mounting solutions that affected the video quality the most, which is mentioned previously.

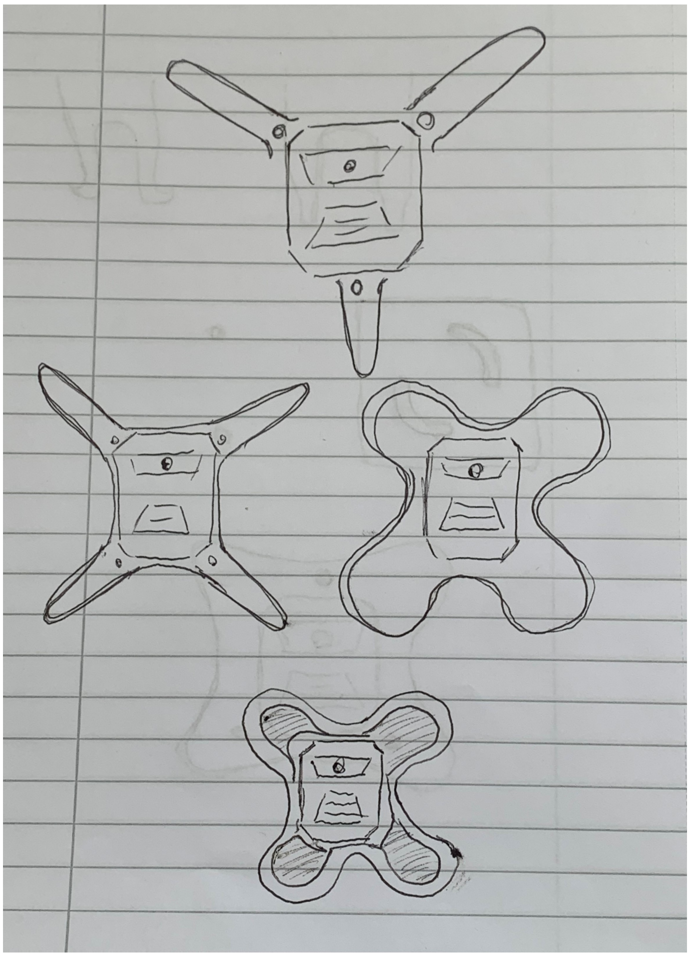

Figure 38: Early magnet mounting concepts

Early concepts that were created to counter irregular shaking can be seen in Figure 38 and the idea was to create mounts with good leverage in order to reduce the unwanted axial movements while not being uncomfortable to wear and relatively lightweight. The idea behind the rounded edges is to not hurt nor harm the wearer. The longer arms were meant to be the leverages in order to reduce the axial movements that occurred before.

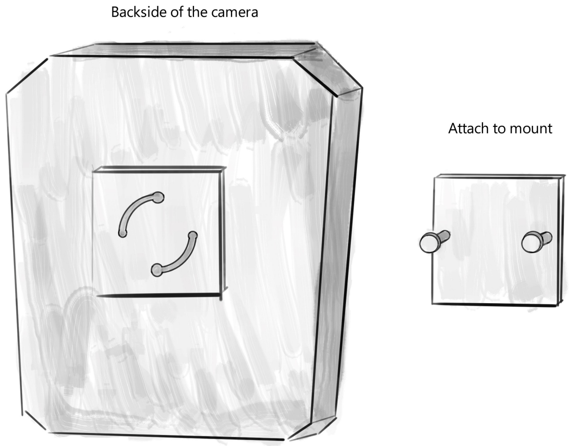

Figure 39: Fixture concept

The fixture that attach the mounting solution to the camera was also looked at. The current Klickfast solution as a fixture had some flaws. For example not being stable and also allowed an unwanted distance between the camera and mount. Ideas about implementing a new fixture with the camera were considered and sketches were made. In Figure 39 a bayonet fixture concept is shown. It works by inserting the backside of the camera in the two plugs that were attached to the mount. The plugs are fitted in the bigger holes on the camera, the camera was then turned 90 degrees in order to be locked in. When the camera is turning, it fastens at the end because it tapes before the last holes. The idea was that this can potentially sit more securely than the current solution since it has two fastening points instead of one. It was also possible to make this fit tighter to the body than the current Klickfast solution, however, this is not convincing in the sketch since the sketch is made to describe the solution more than being an exact version or a prototype.

- **Concepts to counter shaking introduced by the movement of the body**

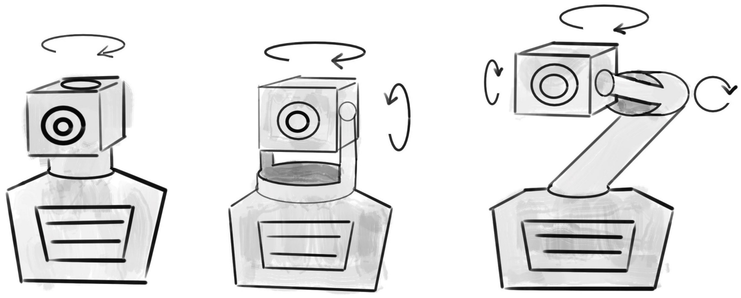

Figure 40: Rotional options for a gimbal solution

To counter rotational movements that were introduced by movements of the body a gimbal can be used. By using the already existing gyro in order to send signals to axial-placed motors the shakiness can be reduced. In figure 40 three different rough sketches of different alternatives were shown. The difference between them was what rotational movement they can compensate for. The rotational movements that can be handled by the camera are illustrated by the circular arrows above and beside the sketches. The upside of choosing fewer motors to compensate for rotations, less battery power will be used.

4.4.2 Test the concepts

New tests were made with the magnetic mount on the body worn camera. One as is and the other attached to a cardboard plate underneath the shirt. The cardboard plate allowed for a greater contact area with the body itself. The two videos were recorded while running the same distance in the same amount of time. A clear improvement could be seen in the video recorded by adding a cardboard plate. This showed that it was a clear and easy improvement just to increase the surface area of the magnet mount to the chest. Important to note that the increased area was only inside the shirt and not on top of it, this is because it is only necessary to have it on one side of the shirt, it allows it to be held more steadily between the body and the shirt furthermore does not occupy unnecessary space on the wearers' shirt, which was an argument that was brought up by the customer contact.

A third-party fixture was also tested which locked more tightly than the Klickfast solution. This showed a small improvement but not a significant one.

The thesis group bought a third-party gimbal camera in order to test this feature. The thesis group considered it take too long time of the project to build their own gimbal and it would be easier and quicker to buy a working one. The camera the group bought was a DJI pocket 2 and was fitted with three gyro motors and therefore would represent the third alternative in figure 40. The other two options were not tested because there were unfortunately not possible in these circumstances.

4.4.3 Refining concepts

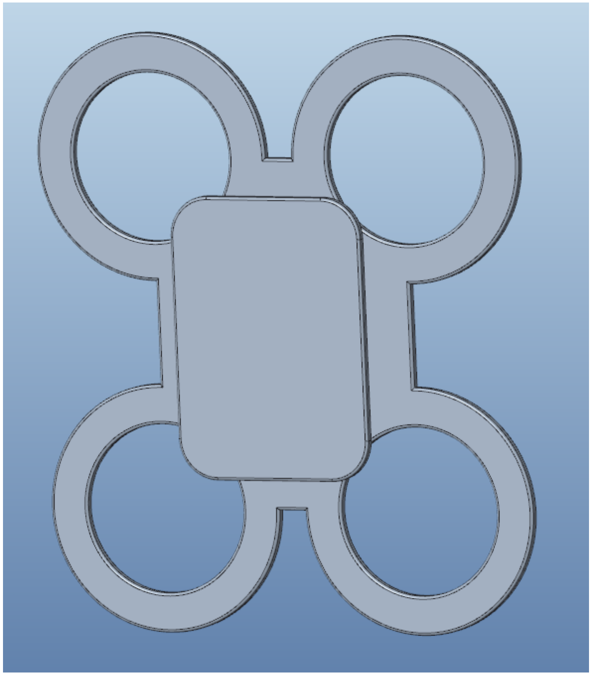

Figure 41: Refined magnet mount

A realization from the tests made from the different fixtures was that the better fixtures had more contact area with the body. A new magnet mount was designed which included a bigger contact area with the body simultaneously as it roughly remains the same weight.

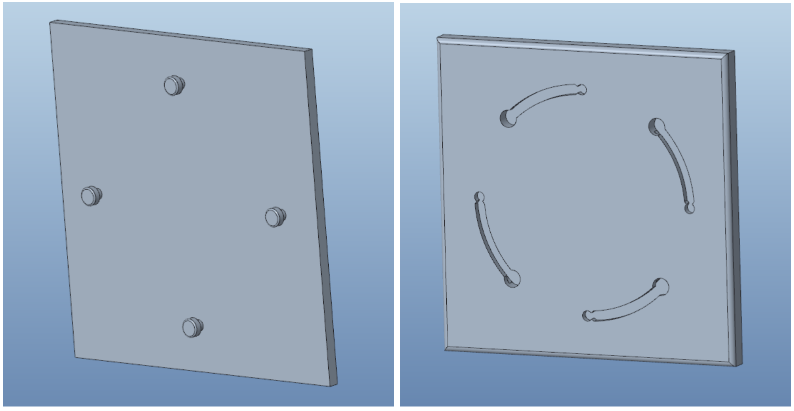

Figure 42: Refined fixture

The Klickfast solution was overseen and redesigned to another bayonet fixture solution. The refined version has 4 fastening points instead of the 1 from Klickfast and the 2 from the previous iteration of the bayonet fixture, which makes it more secure. This fixture is meant to give the camera an opportunity to sit tighter to the body which also is beneficial in order to reduce the shakiness of the image.

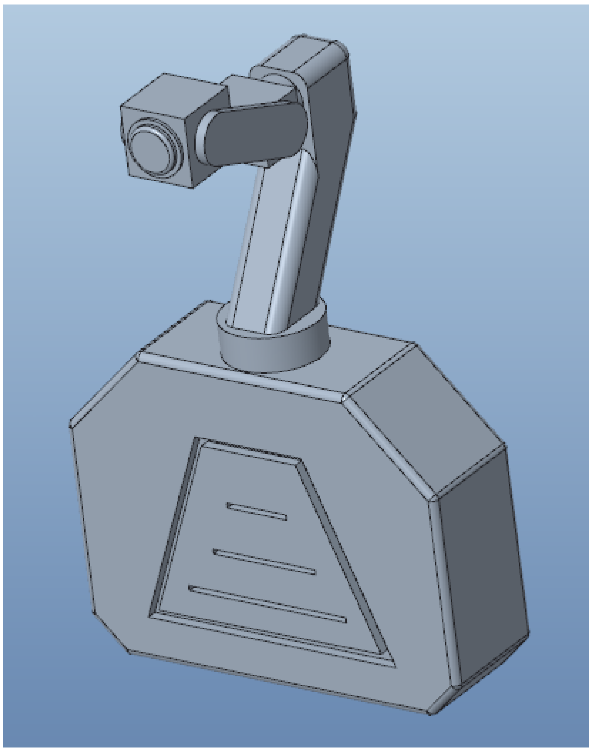

Figure 43: Refined Gimbal

A Gimbal is the third and final part of the overall solution. A gimbal as rendered in figure 43 is possible to rotate and therefore compensate for movements in all three axes. Worth noting is that a two-axial compensation could also be a viable alternative.

4.5 Deliver Phase

Continuing onwards after concepts had been explored and refined a more conclusive suggestion was collected. The group explored mounting, fixture, and camera stabilization alternatives.

4.5.1 Select Product Concepts

The thesis group came to the conclusion which implied that in order to get as stable an image as possible, all of these factors needed to be considered and handled. An important reminder is the limitation of a magnetic mounting solution as it is the most relevant one. The best overall solution in order to stabilize the image is to combine all three solutions for the different parts. Increasing the surface area of the body-connected part of the magnetic mount, changing the fixture to that of a more tightly secured bayonet, and applying a gimbal stabilization will be the best way to increase the image quality and reduce the shakiness of the image.

4.5.2 Refining concepts

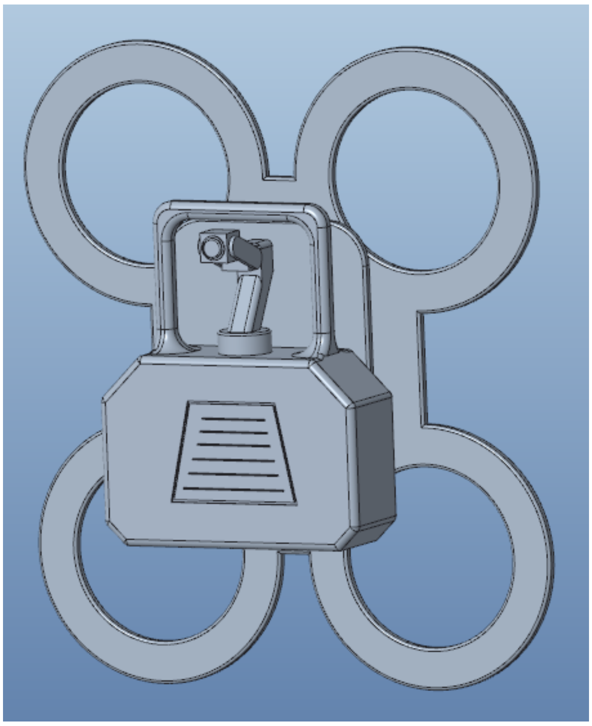

Figure 44: Assembly

In figure 44 the refined complete assembly can be seen. What is changed from before is the gimbal protection which can now be seen on the camera. Worth noting is that the Bayonet fixture is in between the camera and the mounting solution and therefore can not be seen in the image.

4.6 Design of Experiments

The design of experiment measurements relates to the tests made by the different areas of impact on the image quality and are used to get a measurable result. In a subjective area such as image quality where the shake and possibility to identify details are in focus, the ”design of experiments” is introduced to compare these measurable results. The test handled under the Design of experiments is Test 2, made in the define section to investigate the mount versus gimbal functions.

4.6.1 Identify controlled and uncontrolled factors

The factors of the problem were specifically related to feature sets and functions rather than design parameters. The factors are related to the environment and the prototype.

- **Controlled factors:**
  The controlled factors of the problem were the design of the mount to the body and the active stabilization present in the form of a gimbal.
- **Uncontrolled factors:**
  The uncontrolled factors were the movement of the body(in this case jogging) and the lighting conditions. Another uncontrolled factor was the fit of the clothing, this factor was not modified during the test otherwise than to use the right size of a police shirt.

4.6.2 Determine the objective function

The objective function was made to present the difference in factors. All uncontrolled factors were made to be as consequent as possible, by determining a controlled light condition and a certain speed of movement during the test. The controlled factors of different cases used in the test can be seen in Table 9.

Table 9: The parameters and their levels

Parameters	***Level 1***	***Level 2***
A - Active stabilization	Off	On(Gimbal)
B - Mount alternative	Magnet mount	Harness mount

4.6.3 Determine the testing procedure

The testing procedure was described in Table 10 and describes how the different combinations of the test were set up.

Table 10: The test procedure followed in Test 2

Test	*Setup*
Test 2A	No stabilization, attached to the upper chest with a magnet mount.
Test 2B	No stabilization, attached to a harness.
Test 2C	Gimbal is enabled, attached to the upper chest with a magnet mount.
Test 2D	Gimbal is enabled, attached to a harness.

4.6.4 Execute the experiment

The test results were taken from Figure 21 to 24 and were measured by looking at the percentage in the horizontal and vertical direction of the image that was covered by the red deviation area in regards to the entire image size. The results can be seen in Table 11.

Table 11: Test results from Test 2

Test	*Results(Width)*	*Results(Height)*	*Results(Average)*
Test 2A	55%	75%	65%
Test 2B	20%	22%	21%
Test 2C	22%	30%	26%
Test 2D	9%	8%	9%

4.6.5 Statistic analysis of the results

The results for each factor and its corresponding influence can be seen for factor A in Figure 45 and factor B in Figure 46. The influence of each factor was similar to the initial setup A even though factor B influence the result greater. The best result can be seen in Figure 47 where both factor A and B were set to level 2.

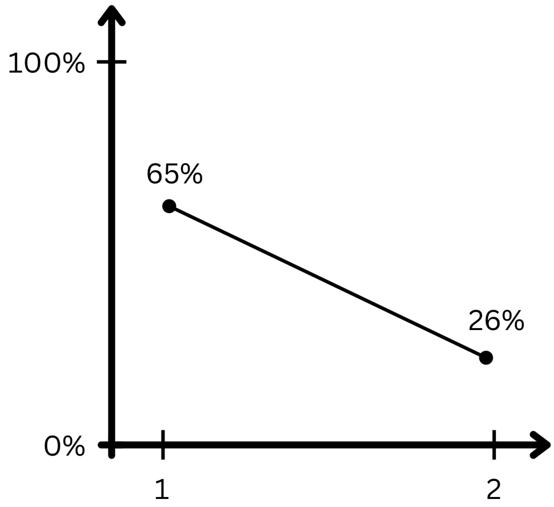

Figure 45: Factor A

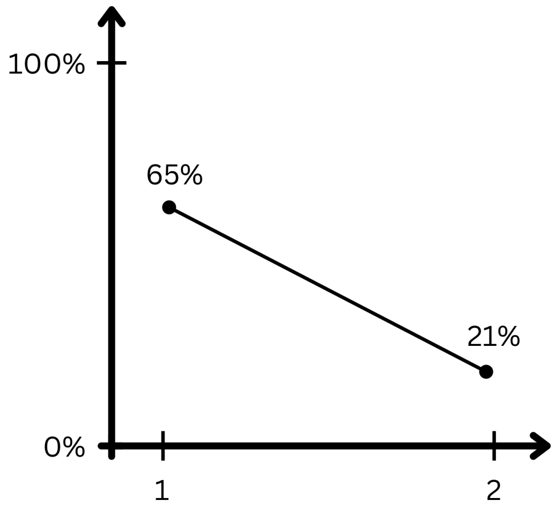

Figure 46: Factor B

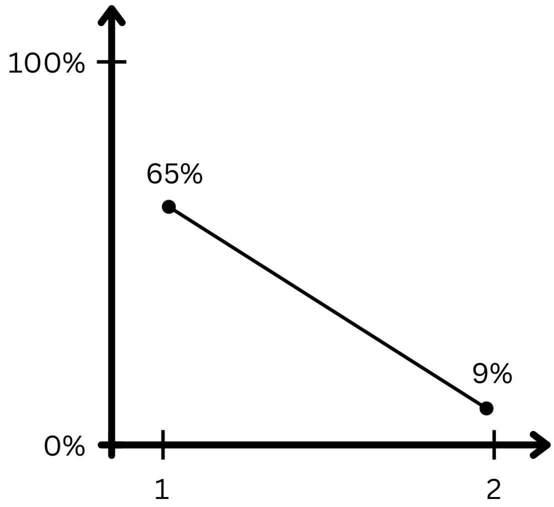

Figure 47: Combined for Factor A and B

4.6.6 Conclusions of the result

The results from the Design of experiments were an indication of the importance of both factors second level to accomplish the best possible result. Both factors can also deliver a similar much-improved result on their own.

5 Results

5.1 What problems are specifically related to poor image quality when recording video with a body-mounted camera?

The problems specifically related to body-worn cameras were that they were mounted differently to the body. The mount to the body usually introduces more movements to the camera than anticipated in the shape of unreliable movements. The movements of the body also introduce shaking captured by the camera. In the case of the first-hand users, the movements of the body and the lighting conditions used when filming are areas that can not be controlled due to their working in law enforcement.

5.2 Which solutions can be viable to solve the problems with the specifically body-worn poor image quality video?

In order to solve the full problem of stabilizing the image for the body-worn camera, 3 areas need to be addressed and solved. A mounting solution to the body that eliminates unwanted movements that could potentially be introduced by the garment it was attached to. A fixture in between the camera and the mounting solution that does not introduce unwanted movements by being unstable or weak and thirdly a camera that can counter the unwanted movements that were introduced purely by the body of the person it was attached to. A camera with a gimbal to reduce axial movements was a good alternative to solve this problem.

5.3 What problems can arise when developing a new kind of product for a new set of first-hand users?

The problems that can be faced when working on a new product for a new customer segment are many. In the thesis problems regarding the availability to first-hand users that will use the product every day have been limited. It is important to consider how the product is received by customers and not to waste resources developing solutions that never will be used.

Problems regarding the development of a new product and the feature sets to improve different areas can be overlooked by using guidelines made for products with different use cases. A new customer base can introduce new environments for the products, therefore these environments need to be considered early in the development phase not to miss any important customer needs or design decisions.

6 Discussion

6.1 Development Process

The product development phase started with the use of Ulrich & Eppinger's product development process. Early customer needs and target specifications were established with the steps given by Ulrich & Eppinger. When the generation of product concepts was to start, the difficulty to understand the problem and decompose in relation to the specifications made was met. Therefore the concept generation was stopped and the product development process was questioned.

The introduction of the Double Diamond process was made and a combined process between Ulrich & Eppinger's product development process and the Double Diamond was developed.

6.2 Approach

As the thesis group worked on the thesis, employees at Axis worked parallel with the body-worn camera. Since Axis has an established way of working for their stationary surveillance cameras, they applied that strategy for the body-worn camera as well, however, the body-worn camera differs from their other line of cameras because it is mounted on an actual person instead of a ceiling or perhaps a wall. User cases and test that Axis does to their regular line of cameras is somewhat relevant for the body-worn camera but needs to be broadened. No test was made with the camera by running it with different mounting alternatives that actually were used by customers. In hindsight this felt odd but since they never had made tests like that before they simply followed the same procedure and workflow as for other products. This meant that the actual problem with the stability of the camera was not properly explored. When exploring relevant tests for the body-worn camera and thereafter getting conclusions, Axis themselves took part in this information and actually decided to look into a new fixture, mount, and gimbal stabilization alternative but divided into the relevant work teams at Axis.

6.3 Specifications

The specifications were developed during the course of the project. The specifications were not able to be attached in a good way to the development of concepts. They started as specifically focusing on the camera enclosure but during the course of the project developed further. They gained new needs and metrics due to shifts made by newly discovered areas of the thesis. The specifications were never tested and thus only a guideline made by the thesis group when brainstorming concepts. The specifications could have a bigger impact on the project if more time and first-hand users were available for the time.

6.4 Discover

Testing and internal research highlighted different aspects of the stabilization of the body-worn camera. Initially, the problem description by people at Axis focused on a mechanical method that could optimize and improve video quality. As we ran tests ourselves we realized that the problem is broader than first anticipated. It was assumed by Axis that the current setup is only affected by movements that are caused by the pure movement of the body. In fact, it was shown by the tests that there were more disturbances that affected the quality immensely. The fixture and mounting solution introduced even more chaotic movement and disturbances than initially believed. Showing new test results would spark a new realization and the people at Axis would be convinced of new areas that needed to be improved. By filming different tests with accurate clothing and movements, it could be shown much clearer what the problem actually was and thereby convincingly changing the focus to the more relevant problem at hand. Initially, the people at Axis assumed that the vertical movements were the main issue but with the new and more accurate real-life tests it could be shown that rather than the vertical movements, the rotational contributed substantially more to poorer image quality and shaky video. The new test also highlighted the impact that the garment to which the mount and fixture are attached plays a vital role in video stability. Since the body-worn camera is a fairly new product at Axis, they have not put the time in and done the required research in order to understand the problem of mechanical stabilization fully, and quick assumptions were made from tests that didn't reflect reality in its entirety.

Interviews were an important part of the thesis since they made us a much greater understanding of Axis' knowledge, what the problem was thought to be, and what customer thoughts were about the current product and its setup. The interviews were a crucial part of the thesis however it would be optimal to gather more interviews with other people at Axis as well. The intention was to also interview another employee with customer contact but unfortunately, this was not made possible since the lack of reply from this person. It would have broadened our understanding of the customer and is something that could be looked into in the future.

6.5 Define

The tests made by the thesis group were considered to reflect real-life usage and more so when compared to the ones made before by Axis. The video test made by Axis prior to this thesis had not focused on image stability solely since the conditions and goals were different from the thesis group. The tests made by the thesis group were trying to replicate real-life usage by having the same type of clothing, the actual mounting solutions that were preferred by customers, and movements that would be done in situations where this camera would be used.

6.6 Develop

The goal was to replicate real-life use, however, there were limitations that are important to consider. The test were made in a corridor with indoor light conditions and in real life the camera would be used both indoors and outdoors, in broad daylight and in the darkest of night. The movements of the wearer in the tests were filmed by running slowly/jogging and walking compared to the many different movements made and at different speeds in real usage. The tests were made only at these conditions to more easily compared the videos since it's easier to analyze a few tests than many. Running was chosen since it is more controlled and could be duplicated easier by running the same distance at the same time by the same person. Other movements are difficult to replicate and therefore would be difficult to precisely compare.

6.7 Deliver

In the thesis delivery phase, a concept or solution was presented that was a result of the previous step. However, delivering a product can be viewed differently and the opinion may differ on what delivery actually implies. One might reasonably believe that a delivered product is a product that is evaluated in every way that it should and is ready to be introduced to the market. Since this thesis had limitations which meant that budget was not a parameter, nor was IP rating a part of the solution. This meant an actual finished product was not a part of the delivery phase, but instead, a concept that included the parameters that were a part of our scope.

6.8 Design of Experiments

The Design of the experiments was a good method to use to analyze the results from Test 2. The test was not too complicated, but the structure of the Design of the experiments made the testing itself and the results from the test more structured.

7 Conclusion

The aim of this thesis was to investigate and develop image stabilization for Axis body-worn cameras. With several interviews conducted and different relevant tests made with the camera and different mounting solutions, a better understanding of the stabilization was made. The movements that were crucial for the stability of the image were the rotational around the camera's own axis and not movements purely horizontal or vertical. The problem was broader than first anticipated and several factors were realized as being part of the issue. 3 main areas were acknowledged which were the mounting, the fixture, and the camera itself. There were several mounting solutions for the camera, however, the most used by customers was a magnetic mount which in the meanwhile resulted in a lot of unwanted rotational movements when attached to the shirt of a person who was running. Because of this, the magnetic mount was the main mounting option to be improved. Concepts for improving the three main areas were tested and concluded. The magnetic mount was improved by increasing the surface area of the body which significantly reduced rotational disturbances. The fixture was improved by changing it to a bayonet fastening solution resulting in a shorter camera distance to the body and also increasing the number of fastening points to the magnetic mount. The solution for the camera was to introduce a gimbal solution that could compensate for the rotational movements that remain after the improved mounting and fixture reduced the other.

7.1 Future work

This thesis explored the problems and concepts for a solution to the problems regarding body-worn camera image stabilization. Areas that should be continued in order to get a finished and final solution is to develop prototypes of the three areas of improvement. Other problems regarding developing a finished product, that the thesis was limited to not explore, were the strength and rigidity of the camera which would be needed to be addressed and taken into account. Another limitation was the cost and economic impact that such a solution would have on the company. A proper cost estimation should be made in order to assess how viable it is for the company to introduce. A customer review is also important to collect for a new solution since this was unclear with the current setup and is important in order to actually understand what the final customer actually wants.

A Appendix

A.1 Meeting with Axis supervisors: 2023.01.16 - 10:00-11:00

- How does the camera work currently?
  - Axis Body-worn camera is meant to be placed on a person's body for surveillance. It is meant to stay on the body for the duration of a day's work by the wearer which often is law enforcement.
- What is the current issue regarding stability?
  - As one might reckon, the video image from a body-worn camera is very shaky and it would be good to find a solution to this problem.
- Do you have any thought about what such a solution might be?
  - We are really not sure. Perhaps some sort of dampening that will reduce the up and downward movements of a person running or perhaps some compensation from electronic motors, but if they are placed inside the camera or as an attachment we're not really sure about. You may explore what is most relevant.

A.2 Meeting with engineer: 2023.01.24 - 14:00-15:00

- Which limitations are connected to an inbuilt stabilization?
  - It should be able to last for 12 hours. The space inside the camera is quite limited.
- Can test videos be made?
  - Yes, you can make test recordings. Contact X on Axis, he can lend you a camera. You can contact Y to get a walkthrough of the camera.
- What is the framerate of the camera?
  - The camera is capable of 25 to 30 fps recording.

- Is there a possibility to take apart the camera and connect it to a microcontroller?
  - Maybe, but it might be tricky.
- Can we borrow a camera and take it apart?
  - Yes, there should be cameras to pick apart for this project.

A.3 Meeting with product owner: 2023-01-26 – 09:15-09:45

- Is there any image stabilization that can be used on the camera today?
  - There is a possibility to use software stabilization (EIS).
- What are the biggest problems with a shaky image?
  - The biggest problem is related to running and walking. When the footage is investigated this will be quite uncomfortable to look at for a longer period. The significance of the problem with a shaky image is mostly based on feeling.
- What are the limitations of the current camera?
  - The size and weight are ”on the edge”, and those aspects are important, although weight is more significant. The search for small, lightweight, and cheap image stabilization is also a limitation as of now.
- How does the camera feel when worn by first-hand users?
  - The camera can be stuck on other things due to its size. It is also uncomfortable to use different on-body fixations when some of them can cause strain on the body and clothes over time.
- How is the battery life of the camera and can this be reduced if an implementation of image stabilization uses battery?
  - After three years, the camera should still be able to hit 12h run time. Although there is some wiggle room with the battery, it all depends on the solution's significance and impact on the final result.
- Which of the movements do you see as affecting the image quality the most and that you want to reduce?
  - We would want to cancel out the motion made by running and walking.
- Any other comments? - A more stabilized camera, sensor, or optical system will result in a lower bitrate when handled by the EIS.

A.4 Meeting with customer contact: 2023-03-1 – 15:00-15:30

- What are the biggest complications regarding the product?
  - Technical deployment requires an on-prem server. A cloud is an option, but a lot of the customers were working with can't afford the cloud. The deployment is not very user intuitive when pairing with any VMS including ACS. This can be addressed by developing an ACS component that is being worked on. Lack of segment knowledge by all. Not having a demo mode which helps in not locking up cameras. The video getting stuck: has already been addressed
- What is the product good at?
  - Customers are very happy with the overall solution. They like the big button. It's overall easy to use once it's set up. The biggest thing is cost. BWS and ACS are very affordable.
- Is the image quality a big concern?
  - No. With the image quality we have today, people are pretty happy.
- Is the image too shaky to look at?
  - I have not received 1 complaint about the shaky video.
- Is image quality/shake affecting the possibility to identify details in a bad way?
  - I have not received a complaint, so I can't say yes or no. In my opinion, it could.
- Is the camera too heavy?
  - People have said the camera is too BULKY. Once I dig into it, they are really referring to the mounts / old-style magnet mount TW1104. However, for non-law enforcement, the answer is yes. But this will be resolved with the W110.
- Are there any practical issues introduced by wearing the camera?
  - I have heard that the camera gets stuck on seat belts. But overall, not many.
- How is the camera often worn?
  - The camera is often worn on the center of the chest or on the right or left side of the chest.
- Do you see any areas where the camera might be improved?
  - All of the areas of concern are being addressed in the W120, such as mic placement. Also, we get complaints that the cameras don't fit in the docks with their mounts on. I am getting more and more negative feedback on the Klickfast mounts. Customers don't like Klickfast and the studs are starting to snap more often.

- Would you mind a heavier camera?
  - Yes. Heavier is not good.
- Would you mind a bigger camera?
  - Yes. Bigger is not good.
- Does the camera often experience stresses or impacts?
  - A lot. A majority of our customers are in law enforcement roles and the camera can take a beating. Durability is key.
- What are the most important attributes when it comes to using the recordings for evidence or surveillance purposes?
  - User experience on how to find the video, export video, image/audio quality, ability to redact video, ability to search and categorize video, and how easy it is to share video with those who need to view it.
- How important is it for the image to be comfortable to look at?
  - Not sure what this means.
- Do you have any concerns about the pricing of the product?
  - Not at this time. We seem to do well in pricing.
- Is the camera uncomfortable to wear?
  - Not that I have heard of. Nor that I have experienced and I have worn it all day sometimes.
- What are the biggest flaws with the fixture?
  - Klickfast stud and system are not well-liked. The 2 magnet mounts have not been well received but people use them because that's what we have.
- Which fixture is considered the best by first-hand users?
  People use the magnet mounts the most because their the most flexible when it comes to clothing, however, Law Enforcement uses a lot of different clothing styles so having a variety of mounts is critical.
- What are the opinions about the Klickfast solution?
  - We need to work with Klickfast to create mounts for the American market. Customers are asking for mounts like AXON. Especially the magnet mount. That's what our market is used to and wants to see. The stud on the back does not seem to be well-liked. Or do we need to evaluate which mounts we are OEMing from Klickfast?

A.5 Meeting with Axis supervisors: 2023-03-09 – 09:15-09:45

- This meeting was focused on the result of three test videos we made with a magnet mount fitting poorly to the stomach, a magnet mount fitting better on the chest and the camera fitting to the harness fixture. The results were shown and discussed.

- Can you reason which video belongs to the different setups?

  - ”One video is obviously more shaky than the other two, the second video is evenly in between the first and the last. The last video is significantly more stable than the first two. I would guess that the first video is of the magnet attached to the stomach, the second with the magnet mount attached to the chest, and the third with the camera attached by the harness fixture” - Maiko

  - ”I agree, it is obvious” - Victor

- How much would you say that the fixture, and how it is mounted, affects the final video by looking at these examples?

  - ”It looks to me as the fixture affects significantly the result of the image” - Victor

  - ” Now it seems obvious that the fixture itself is something that is really important to take into consideration when looking at a solution to mechanically stabilize the image” - Maiko

A.6 Meeting with the product owner and Axis supervisor: 2023-03-21 – 11:00-12:00

- We are thinking about the possibilities of applying a motorized gyro solution, is there any thoughts about that kind of solution?

  - ”One direct issue that we would see is the acquired cost for such a solution, as it stands now the Bodyworn camera is on a narrow budget” - Olof

- How does EIS currently affect the captured image?

- ”It approximately crops up to 10 percent of the image” - Olof

- Bodyworn cameras are often worn on or over different kinds of clothing with a variety of fixtures, what clothing would be best for us to look at?

  - ”One of the frequently used garments is a regular police shirt, in Sweden, they are called M90 shirt. Those would be good garments to analyze the body-worn camera attached to since they are used so often by law enforcement around the world. Other than a shirt it would also be good to investigate a tactical vest. Those are also used by law enforcement. Contrary to the shirts, the vests have a possibility to attach molle mounts which is a good idea to look into” - Olof

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