Department of Precision and Microsystems Engineering

Design of the future bird repelling laser aiming device

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TU Delft Precision and Microsystems Engineering

Bird Control Group

Challenge the future

Design of the future bird repelling laser aiming device

A 2DOF laser aiming solution

by

B.H.F. van Haren

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An electronic version of this thesis is available at `http://repository.tudelft.nl/`.

Summary

The need for bird control has always existed, and even grown in recent years. More and more airplanes are taking off from runways that need to be kept free of birds; otherwise, the risk of a so called bird-strike is far larger and large damages can be incurred. These damages can include but are not limited to engine damage, breaking of windows and damage to flaps or ailerons. All of these damages can lead to the plane becoming uncontrollable and possibly crashing, leading to loss of life in the worst case.

A less dramatic scenario where bird control is required: A blueberry farmer is losing about 10% of his crop to birds eating or infesting the berries. Large farms can lose in the order of tens of thousands of euros/dollars per year solely through birds spoiling their crop. More examples; a car dealership might have problems with birds on the roof and bird droppings are creating a high cleaning bill on a daily basis. Large industrial buildings with flat rooftops have their roof drainage clogged by birds nesting, resulting in water damage inside the building. An oil drilling platform can have problems with birds on the helicopter pad, and the amount of droppings can make it hard for incoming helicopter pilots to see where the pad is, making weekly cleaning of the pad a necessary and expensive ordeal.

The demand for new bird control techniques has grown significantly due to habituation of birds in relation to traditional bird control techniques. Birds are habituating to the classic scarecrow or propane cannon and thus cannot be controlled through these methods anymore. Poisoning or shooting of birds is not an animal friendly solution, and whilst it may help in some cases, it is not always safe to apply and can influence the image of a company using these methods.

A new way to control the birds has been developed by Bird Control Group, a Dutch company specialized in the repelling of birds by means of a moving laser spot on the ground. A specific laser beam characteristic has been developed to repel birds without the birds habituating to it. The laser system developed by Bird Control Group works by utilizing the bird's instinct to avoid objects it is not familiar with. The birds are not harmed by the laser, making this method of bird control favorable over shooting or poisoning of birds.

The laser developed by Bird Control Group can be used as a hand-held device, much like a flashlight would be used. An automated system, in which the human does not have to aim or turn on the laser anymore, called the Autonomic® can repel birds autonomously. The laser will cover a designated area with certain patterns setup during installation. Patterns consist of waypoints on the ground where the laser will pass through. These waypoints are created after an assessment from an installer and feedback from the customer on the specific area where birds are likely to appear. The patterns are repeated with a certain interval, and can be setup to operate during specific timeslots. With this lasersystem, birds are repelled autonomously and continuously without intervention of humans. A new generation of the Autonomic® will incorporate bird detection and active repelling of the detected birds within the designated repelling area.

A major concern with the automated system is safety. The laser poses a hazard to the human

eye when viewed directly because of its power and wavelength. The current, state of the art steering and aiming solution is not designed to aim a laser; it is designed to steer CCTV cameras with an operator and a joystick controlling it. In that case, the operator provides feedback and is essentially the feedback controller of the system. On top of that, the cameras normally used on top of this aiming device have a wide field of view, making high amounts of accuracy unnecessary. This solution then is not accurate or reliable enough to be used autonomously for aiming a laser spot.

Airfields do not buy the current automated systems because of the afore mentioned safety issues. There has previously been an experiment on airfields with a more high performance, commercially available pan-tilt aiming device, however this turned out not to be a success due to high costs and disappointing performance. Farmers currently have to apply large safety margins in order to make sure the system does not aim the laser spot on pedestrian zones or other areas where people are likely to be. Sometimes, this safety margin is so big, the farmer cannot cover his entire stretch of land and birds are still creating problems around the edges of the field. An accurate and precise way of aiming the laser, combined with additional safety features and improved reliability will increase the market for this product dramatically and make the automated laser system a much safer to use product overall.

The goal of this research is to develop a laser aiming solution which is accurate and thus contributes to safety of operator and surrounding environment. The first question that comes to mind is: how accurate is accurate enough? Since there was no answer to this question readily available, a more detailed set of requirements needed to be setup. The product expert knows the limitations of the system, which come down to a minimum intensity of the spot on the ground in order for the birds to be scared. From experience, this was estimated to be at an oval spot length of 5m. A detailed analysis revealed that the device must be positioned at a height of 1% of the projection distance. This then lead to a maximum allowable angular error of 6×10^{-3}deg in the tilt axis when the laser is on and it is positioned 5m above the ground, in order to have a maximum error on the ground of less than 5m. Some species of birds need the laser spot to be closer to them then other species; 5m is a worst case scenario as most species of birds will fly away when the spot is within 10m of them.

Besides the required accuracy, precision and resolution, the price of the aiming solution is an important requirement. The current, state-of-the-art aiming solution costs around 500 euros. The maximum price of the new aiming solution is 600 euros. It is ok for the solution to be slightly more expensive than the current state-of-the-art solution as long as the performance meets the new requirements.

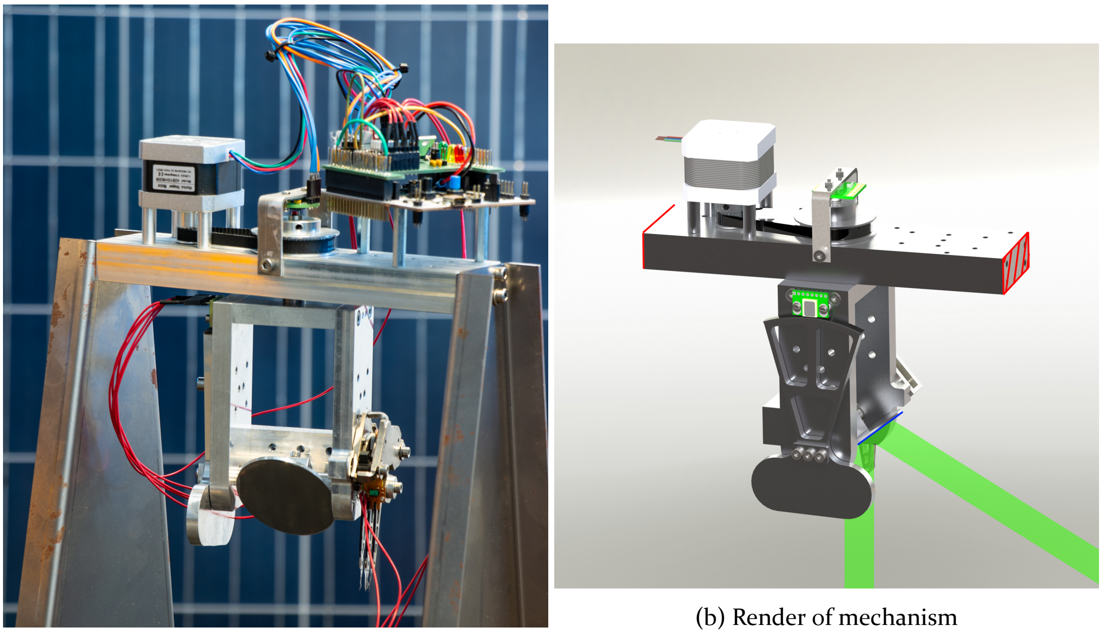
The aiming solution can be implemented using multiple concepts; these concepts were compared on different aspects such as accuracy, longevity and price. The concepts differentiated themselves from others by using different ways of actuation, sensing and aiming principles. A concept that reflects the laser beam was chosen over a concept that moves the laser source, as this saves weight and thus increases performance and decreases wear in the mechanical parts. It also decreases the range of motion of the actuator and sensor, but increases required accuracy and resolution because of the effective doubling of the outgoing angle through reflection.

After choosing a general concept, methods of actuation, sensing, constraining motion and controlling the device are important decisions to be made. Starting with the actuation, many different types of actuators were considered, ranging from linear to rotational and from direct drive to geared options. Different actuation principles such as electrical and pneumatic were devised to split the large amount of actuators into manageable groups. The same thing was done for the sensing, constraining motion and controlling the device categories. Each category was then analyzed by looking at the state-of-the-art technology in each category and selecting or rejecting certain options. From all these categories, the most promising options were chosen to produce a final concept.

In the final concept, the choice was made for a magnetic encoder over other ways of position feedback. Different ways of acquiring position information were considered and compared for prototype use and also for mass production. The same was done for actuators and bearings, resulting in the use of radial deep-groove ball bearings and a rotational voice coil motor in the prototype device. This type of actuator is used in hard-disk drives for computers, where a high amount of precision and speed is required. The direct-drive nature of this type of actuator removes the need for any gears, belts or other forms of power transmission where potential backlash and position errors could occur. Position feedback sensors are placed on the output shaft to prevent errors between the actuator and actual, crucially moving parts.

With the components selected, a design was made and manufactured. This prototype will provide a testing platform to test if the design can meet the specifications setup in the early phase of the project. However, a mechanical prototype is only the first step in a mechatronic device; the electronics and controller implementation need to be robust and stable in order for the prototype to function properly. A 32-bit microcontroller was used to control the prototype in conjunction with assisting electronics designed and manufactured specifically for this purpose.

In figure 1, a picture and a render of the final concept are shown. Red areas in the render (figure 1b) are connected to fixed world. The reflective face of the mirror is colored blue. The laser comes from the bottom, hits the mirror and is reflected in the desired direction.



(a) Assembled prototype

(b) Render of mechanism

Figure 1: Final concept. The two axes can make the mirror pan and tilt all around the unit.

After verifying the functionality of the hardware, a feedback controller was designed and implemented after extensive model identification of the mechanical setup. The controller uses a standard PI controller expanded with a low-pass filter and added feed-forward from a smooth, 2nd order input trajectory. The bandwidth of the system was determined to be around 20Hz in the system identification phase, and the controller was tuned accordingly.

With the prototype now able to follow trajectories with small reported errors from the encoders, external testing was performed to validate the encoders and reported errors. These tests were successful and the device passed the most critical requirements: accuracy and precision in the tilt axis. For reference, the new prototype was compared with the current state-of-the-art laser aiming device used in the Autonomic®; the results showed a speed of 71 times the currently in-production solution, with the same accuracy as the current state-of-the-art, or an improved accuracy from around 8.7×10^{-3}rad to around 8.7×10^{-5}rad, or about 100 times the accuracy of the current state-of-the-art.

Preface

Over the course of about one year, doing this master thesis was a great experience. Getting to know a company, seeing what their problems are and addressing an important issue while learning new things was not only helpful, but also very enjoyable for me. Having friendly and helpful people around me really helped, and for that I would like to thank:

Jo Spronck

Jo has been my supervisor at the TU Delft, asking me questions to start the thinking process and guiding me through the project.

Tim Sprang and Erik Vlasblom

Tim and Erik have been my supervisors at Bird Control Group. Even though I got through this project mostly on my own, it was nice to have Tim or Erik around to discuss various parts of a design problem.

Hassan HosseinNia

When I ran into a controller issue, Hassan pointed me in the right direction which allowed me to create a controller that did work.

Bird Control Group

I would like to thank Bird Control Group as a company in general for offering an exciting project. The support from the company for this project was great! There were always colleagues to have a cup of coffee or tea with around me so we could have a chat.

Suppliers for this project

Paul Peters from MTPP allowed me to use the CNC machines at my weekend job to produce my prototype. Thank you Paul!

I would also like to thank Kevin Flanagan from Renishaw encoders for supplying the encoders for this project.

My fellow MSD students, PHD students and other monday-morning meeting attendees

Thank you for listening to my problems, asking me difficult questions during the monday-morning meetings and making me think about the formulation of my answer. The problem of bird repelling

laser aiming mechanisms is not something you were familiar with, nor will my committee be, so formulating my answers correctly and giving you the correct introduction has really helped me during this project.

My family

Hans, Petra, Max, and Duc, thank you for supporting me not only during this project, but throughout my studies. Fixing, upgrading and detailing the cars, playing some games and enjoying the food along with the great atmosphere really made me want to come home every weekend.

Contents

Chapter 1

Introduction

In this chapter, the topic of this thesis project is introduced. First, an introduction into bird control in general is made in section 1.1. Here, the classic techniques to deter birds from certain areas are explained. In section 1.2, the company which proposed this thesis project is introduced, along with their current range of products and vision of the future with regards to bird control. Their most important and best-selling product, the Autonomic® is explained in subsection 1.2.1. The Autonomic is the main application of this thesis project. The problems that lead to this project are explained in section 1.3. Along with this problem comes a set of requirements, which section 1.4 discusses. Finally, because the current requirements were not sufficient, a new set of requirements was setup. These new requirements are explained in subsection 1.4.2.

1.1 Introduction to Bird Control

Put simply, bird control is a way to solve the problem where humans are experiencing nuisance from birds. Bird control has previously been described as: 'people and/or products that control the bird population in a specific area' [3]. Because birds and humans often occupy the same space on earth, nuisances are guaranteed to be experienced somewhere. Humans experience these nuisances in various different ways, some examples of which are below:

- Farmers' crop is eaten or infected by birds, and thus cannot be sold anymore.
- Airplanes encounter birds, mostly during takeoff and landing, and can become subject to bird strikes.
- Public places are unhygienic because of bird droppings.
- Industrial buildings with flat roofs have their drainage clogged because of birds nesting.
- Offshore platforms have helipads which are full of bird droppings, making it difficult for incoming helicopter pilots to land their helicopter.

The above problems require a bird control solution in order to be solved. Bird control has many different forms, with specific strategies for certain situations. Birds can be scared, removed or killed, but there can also be changes to the habitat of the birds, so that it becomes less attractive for birds to settle in that area. A problem with many bird control techniques is the habituation of birds to that specific technique. For example: a relatively animal friendly way of bird control can be shooting to miss. The sound of gunshots will scare the birds, making them leave the area.

However, if the birds notice that none of them are getting killed, they will continue to occupy the area and a new method of bird control must be used.

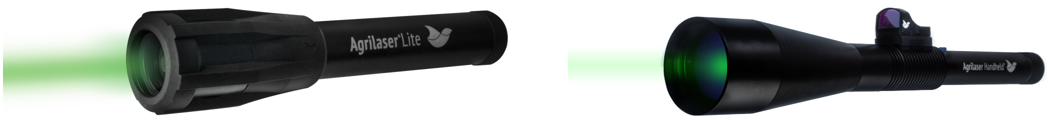
High intensity lasers have been used to scare and cause pain to birds if they get hit by the laser. This bird control technique is not animal friendly, but has benefits such as no habituation by the birds and a good effectiveness overall.

1.2 Bird Control Group

Bird control Group is a company specialized in the controlling of birds by means of a lower intensity laser light. The company was started in 2009 and quickly grew because of the high demand in this new bird control technique. This new technique is different from the previously mentioned, high intensity laser technique because the used laser has a maximum output power of 500mW spread out over an area of at least $22cm^2$, which means the intensity per surface area is not high enough to cause pain to birds when the laser hits them. Instead, the birds get startled from the approaching laser spot projected on the ground, and will move away from this spot before it hits them. The wavelength of light that the laser emits is of high importance; this wavelength has been tuned to maximize the perception by the eyes of birds.

Bird Control Group has applied this new laser 'formula' in a few different forms meant for different markets. On the lower end of the scale, the Handheld Lite is a product that fits in ones back pocket and has a short effective range because of the limited intensity of this product. This product is limited to 50mW of output power, and with that the effective range on overcast days is around 100 meters. The product runs off of a battery, and has the form factor of a small flashlight. This product is meant for both indoor and outdoor use.

One step up on the product ladder, Bird Control Group has the Handheld: a product available in three different output powers, ranging from 100mW to 500mW, and with ranges on overcast days up to 1300 meters. The Handheld is marketed as a device mainly for outside use, but can be used indoors as well. This product is also powered by a battery, but unlike the Lite is not a small, compact device. It is still portable though, unlike the next product in the range: the Autonomic®.



(a) the Lite (b) the Handheld

Figure 1.1: products by Bird Control Group

1.2.1 The Autonomic

The Autonomic is, as the name implies, an autonomous bird repelling device. The Autonomic is the state-of-the-art bird repelling device that is sold and used in over 70 countries. This device can be equipped with the same output powers as the Handheld: 100mW, 200mW and 500mW. The Autonomic is not operated by a human, but can be setup with specific patterns to move the laser spot, and with certain time slots in which the repelling is active. The Autonomic is depicted in figure 1.2.

During installation of the device, an assessment is made by an experienced installer to reveal the needs of the customer. The customer might want to get rid of birds in a specific area, but leave

(a) the Autonomic

(b) the Autonomic in a typical, agricultural application

Figure 1.2: the Autonomic by Bird Control Group

birds in another area. Or, the customer might want to use the laser only between 6AM and 8AM so that employees can enter the area after that time without the risk of exposure to the laser. The installer will setup patterns and time slots to meet the requirements of the customer, after which the device will continue to play the patterns during the assigned time slots until told otherwise. The ease of use, reliability and effectiveness of this device is what makes it such a success.

The Autonomic can be used in a host of different situations, which is why it is available with different options to suit specific situations. For example, the Autonomic can be used with solar panels and a battery to power the unit. This is useful for a lot of agricultural customers, as they do not have power available in the middle of their field, where the Autonomic would be ideally positioned for maximum coverage.

In future generations of this product, bird detection and active repelling will be possible. The current device can be extremely simplified, and split into two basic functionalities:

- Create laser spot on the ground.
- Move laser source to move laser spot on the ground.

Creating the laser spot is done using a very similar laser module as those found in the Handheld. The laser source is in an enclosure, on top of a commercially available Pan-Tilt Unit (PTU) which allows the source and thus the laser spot to be moved. There are however some problems with this PTU, on which section 1.3 will elaborate.

1.3 Problem Statement

The Pan-Tilt Unit is not designed to be used with lasers, it is designed to move cameras. Cameras and the lasers used by Bird Control Group are fundamentally different in the sense that the laser has virtually no divergence (less than 0.05mrad) and a camera has a wider field of view. That means the camera can be slightly off the target, but the target can still be inside the image that the camera creates. PTUs designed for cameras do not have to be precision machines for this very reason, whereas the aiming module for the laser should be a precision machine both to be effective and to be safe.

Another problem with the currently in-use PTUs is that the speed range is very limited. The minimum speed is slow enough to repel birds, but because of the gearing the maximum speed is quite low. The minimum speed needs to be low, so the laser projection is visible and noticeable to the birds. This does influence the maximum speed in the current PTU, which makes moving from one side of the range to the other a rather slow affair.

The PTUs have been tested according to a strict testing protocol which is added in appendix A. These tests revealed big problems with the accuracy and precision of the PTU. These problems are so big in fact, that safety margins around the area where the laser is used are over two times larger than the actual covered area. In many situations, it is simply not possible to maintain such a big safety margin and thus the covered area needs to be decreased. That in turn reduces the effectiveness of the product sold by Bird Control Group.

The errors in positioning of the aiming module start at the backlash of the PTU; the backlash lies between 0.4deg and 0.7deg, or between 6.9mrad and 12.2mrad depending on the unit tested and whether or not the unit has been used already. Wear on the mechanicals of the PTU will increase the backlash. Furthermore, the units have no internal feedback and can thus suffer from missed steps in the motors. This has a big negative impact on the accuracy of the unit, as these type of errors are steady-state errors which appear at every movement and cannot be compensated for because of the lack of feedback.

The problems with the current, state-of-the-art solution do not end at poor accuracy and precision however. The PTUs prove to be hard to protect from the environment, with water coming into the units being a regular occurrence, causing increased wear or even outright failure of units. The lowest speed of the unit is slow enough to repel birds, but when traversing from one position to another position further away, the maximum speed of the unit is too slow. The birds have plenty of time to eat a few berries from the bush before the laser arrives. The power consumption of the units lies within the specifications set by Bird Control Group (more on the current requirements in section 1.4.1), but a lower power consumption is desired so the complete system can operate longer on battery power.

1.4 Requirements

The requirements for an aiming module that is suitable for this kind of application must contain at least the requirements for accuracy, precision and resolution, as these are requirements that are applicable to any positioning device in general. Besides these requirements, the minimum and maximum speed of such an aiming module are important factors to consider, especially since the minimum speed is important to repel birds effectively. If the minimum speed is not low enough, the laser spot on the ground will move with a too high speed, giving the birds not enough time to perceive the spot and as a consequence not repelling said birds. The maximum speed should have a lower limit, but a higher speed is always desirable to increase system performance.

The range of motion is another important aspect of any positioning system. The required range of motion of the laser spot should be mentioned in the requirements.

More general requirements include the ingress protection of the aiming module, along with the electrical specifications such as maximum power consumption. The service life of the module is another important aspect to consider to keep servicing costs low.

Since the goal is to develop a solution that will be put on the market, price is perhaps the most important requirement of all, and should not be forgotten.

1.4.1 Current Requirements

The current requirements set for the aiming device are specifically set for the purpose of an aiming Pan-Tilt Unit. A few of the requirements were actually changed to accommodate manufacturer's capabilities, which is a compromise with respect to safety and effectiveness. Furthermore, some important requirements are missing such as accuracy and precision. These requirements are not enough to start the project with, and thus some new requirements were setup.

Table 1.1: Current Requirements for pan-tilt units used to aim laser

Parameter	**Value**	**Unit**	**Comment**
Payload capacity	>5	kg	
Home position	[0,0] $\pm$ 1	deg	
Range of motion			
Pan [MIN, MAX]	[-180,+180]	deg	(continuous)
Tilt [MIN, MAX]	[-50, 30] $\pm$ 1	deg	(0 is horizontal)
Range of speeds			
Pan [MIN, MAX]	[0.5, 6.0]	deg/s	
Tilt [MIN, MAX]	[0.5, 3.5]	deg/s	
Resolution			
Pan	<0.1	deg	
Tilt	<0.02	deg	
Mechanical play			
Pan	<0.2	deg	
Tilt	<0.2	deg	
Operational hours	>10000	hours	
Supply voltage range	[18,32]	VDC	Optimized for 24VDC
Power consumption			
During movement	<20	W	With maximum payload
Idle	<3	W	
Weatherization	>IP66M	IP rating	
Temperature range	[-20, 50]	deg C	
Price	<500	Euros	
Installation height recommended	$\frac{1}{100} * x$	m	1m for 100m of projection distance

The current requirements are listed in table 1.1. The requirements were tested with a testing procedure specified in appendix A. The results of the test are in appendix A.2. These results show that the current aiming device cannot meet the requirements set by the Bird Control Group, which were already adjusted negatively.

1.4.2 New Requirements

As mentioned in the previous subsection, the current requirements are not detailed enough to design a solution for the problem. The requirements need to be setup again with the real-world consequences in mind. Because the birds need a combination of the correct intensity, speed and proximity of the laser spot to be effectively repelled, those will be the main requirements. Besides the main requirements, there are additional requirements such as range of motion and power consumption.

Intensity

The intensity of the laser spot is mainly determined by the distance it is projected from the unit. Each laser unit is tuned to give out just shy of the maximum 500mW and the beam characteristics differences between different units is negligible. Therefore, the only variable that remains is the projection distance; the laser spot grows as the aiming mechanism aims the laser further away.

Initially, the laser spot is a circle 50mm in diameter, which is transformed into a large oval as the spot reaches its maximum projection distance.

This projection distance can be calculated by using an estimate of the maximum spot size. This corresponds to a certain intensity of the spot on the ground, which just barely startles the birds. The product expert at Bird Control Group estimates this maximum spot size to be 5m in length. With this information, a simple calculation reveals the height to distance relation necessary to keep the spot length within this 5m (all symbols are declared in figure 1.3):

$$\tan\alpha = \frac{x}{h} = \frac{x+\Delta x}{h+s} \tag{1.1}$$

$$x(h+s) = (x+\Delta x)h \tag{1.2}$$

$$x = \frac{\Delta x * h}{s} \tag{1.3}$$

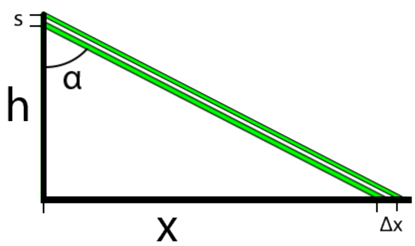


Figure 1.3: Size of the laser spot on the ground. Illustration of variables

The above calculation combined with the estimation by the product owner reveals that the maximum projection distance is related to the height of the device in the following fashion:

$$\frac{x}{h} = \frac{\Delta x}{s} = \frac{5}{0.05} = 100 \ \rightarrow \ x = 100 * h \tag{1.4}$$

Using this relation, the requirement for the maximum included projection angle of the aiming device is equal to:

$$\alpha = \arctan\frac{x}{h} = \arctan 100 \approx 1.56\text{rad} = 89.43\text{deg} \tag{1.5}$$

Speed

The speed of the laser spot has to be able to slow down to the speed of a fast runner, around $20\text{km}\,\text{h}^{-1} \approx 5.56\text{m}\,\text{s}^{-1}$. If the spot moves much faster, the bird might not notice it and is not startled at all. This minimum speed of the spot on the ground is hardest to achieve at maximum range of the device. Since there are two axes available to move the spot, both of the axes were analyzed to find a minimum speed requirement for one of the axes.

On the other hand, the maximum speed the device needs to be able to achieve is dictated by the maximum amount of time a bird can spend on the exact opposite side of the range of the machine. The move from one side of the range to the other can be done with less tracking accuracy, as long as the accuracy at then end, when the laser turns on, is within the safe limits.

For the tilt axis, the following holds if the spot is moved from the maximum range towards the device with the desired speed (see figure 1.4a for a schematic overview):

$$\alpha = \arctan\frac{x}{h} \tag{1.6}$$

$$x = 100h - 5.56t \rightarrow \alpha = \arctan\frac{100h - 5.56t}{h} \tag{1.7}$$

Taking the derivative with respect to time will result in the required angular velocity:

$$\frac{\mathrm{d}\alpha}{\mathrm{d}t} = \frac{1}{1 + \left(\frac{100h-5.56t}{h}\right)^2} * (-5.56) \tag{1.8}$$

Since the speed is highest at the maximum range, $t = 0$ describes the highest speed case:

$$\frac{\mathrm{d}\alpha}{\mathrm{d}t} = \frac{-5.56}{1 + 100^2} \approx -0.556\mathrm{mrad\,s^{-1}} = -0.032\mathrm{deg\,/s} \tag{1.9}$$

The speed in the pan direction can be calculated as follows (see figure 1.4b for a schematic overview):

$$s = x\beta \rightarrow \beta = \frac{s}{x} \tag{1.10}$$

$$\frac{\mathrm{d}\beta}{\mathrm{d}t} = \frac{\mathrm{d}s}{\mathrm{d}t} * \frac{1}{x} \tag{1.11}$$

It becomes obvious that this time, the projection distance cannot be ignored and a reasonable value for this must be assumed. After analyzing use cases of the systems in use by customers (see appendix B), a good assumption for the maximum projection distance is 500m. Filling this out:

$$\frac{\mathrm{d}\beta}{\mathrm{d}t} = \frac{\mathrm{d}s}{\mathrm{d}t} * \frac{1}{x} = \frac{5.56}{500} \approx 0.0112\mathrm{rad\,s^{-1}} = 0.637\mathrm{deg\,/s} \tag{1.12}$$

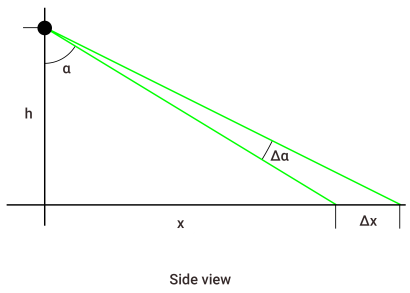
This minimum speed is easier to achieve than the previously calculated minimum speed that would be required from the tilt axis. The pan axis should be used to repel birds while the tilt axis can be used to position the laser spot at the correct distance away from the system.

The maximum speed achievable by the aiming device is dictated by the maximum amount of time a bird is allowed to stay in the area before being repelled. This time is set to 5s. That means the pan axis should be capable of moving at a speed of:

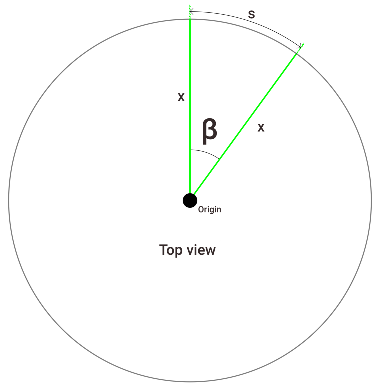
$$\omega_{\text{pan}} = \frac{\Delta\beta}{\Delta t} = \frac{180}{5} = 36\mathrm{deg\,/s}. \tag{1.13}$$

The tilt axis should be capable of moving from within 5m of the device to its maximum range in 5 seconds, and with a height of the device of 5m that means:

$$\omega_{\text{tilt}} = \frac{\Delta\alpha}{\Delta t} = \frac{89.43 - 45}{5} \approx 9\mathrm{deg\,/s} \tag{1.14}$$



(a) Side view



(b) Top view

Figure 1.4: Schematical views of the laser projection system

Proximity

The proximity of the laser spot to the bird is of critical importance to the effectiveness of the system. The laser spot should be roughly within 5m of the bird in the worst case scenario: some birds will leave when the laser spot is within 20m while others are more stubborn and will not leave until the laser spot is within 5m of them. This distance to the bird needs to be translated into specifications for the aiming module such as accuracy, precision and resolution. A graphic representation of these three terms is found in figure 1.5. The crossing of the black lines in figure 1.5 indicate the target of the system. The red dots indicate locations where the system has moved to. The resolution is the smallest step the system can make in terms of positioning.

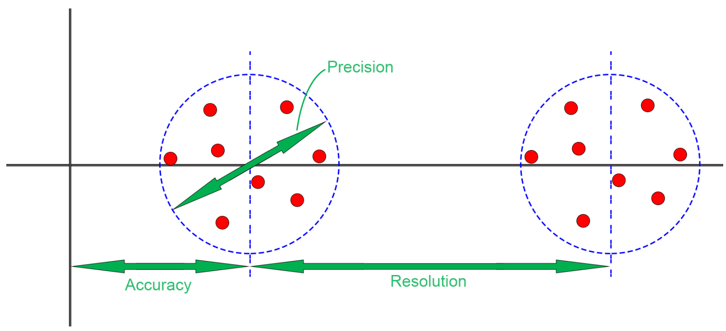


Figure 1.5: Precision, accuracy and resolution graphically illustrated

Since the origin of the laser is fixed, and the laser spot comes from this point when moving across the field, the aiming solution has only rotational degrees of freedom. This means the accuracy, precision and resolution should be expressed in either radians or degrees.

In figure 1.6a, a schematic aid is displayed. This figure shows the "Scaring radius" of a bird, which as previously mentioned is estimated to be 5m, and the accuracy, precision and resolution.

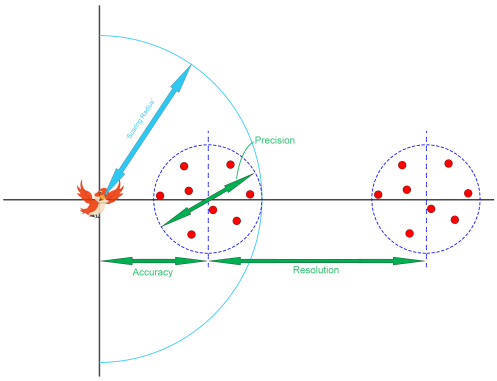
Because the birds need to be scared even in the worst case scenario, the following is true:

$$\text{ScaringRadius} = \text{Accuracy} + \frac{1}{2}\text{Precision} \tag{1.15}$$

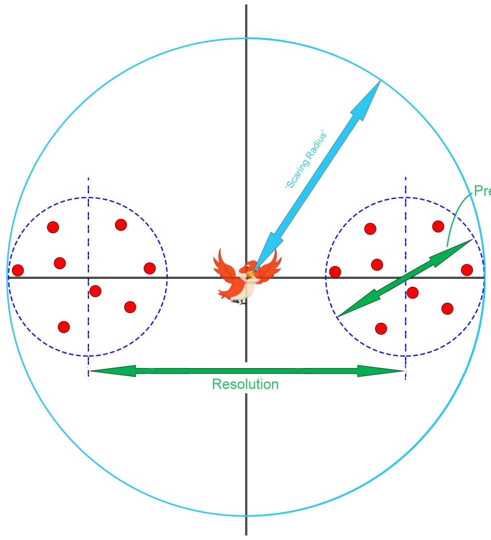
This equation leaves us with two unknowns. The resolution is also not determined yet.

Another equation can be setup with the aid of figure 1.6b. Here, it is assumed that if the worst case position falls just outside the radius, a new step from the aiming system brings all possible new projection points within the scaring radius:

$$2 * \text{ScaringRadius} = \text{Resolution} + \text{Precision} \tag{1.16}$$



(a) Situation one



(b) Situation two

Figure 1.6: Accuracy, precision and resolution with scaring radius

The formulas above do not deliver a concrete answer. Three unknowns remain with only two equations to solve them. Looking at the equations, precision has its place in both equations. Clearly, a smaller precision will benefit both the resolution and accuracy constraints. With all the previous in mind, a precision was estimated and the accuracy and resolution were determined:

$$\text{ScaringRadius} = 5\text{m} = \text{Accuracy} + \frac{1}{2}\text{Precision} = 4\text{m} + \frac{1}{2} * 2\text{m} \tag{1.17}$$

$$2 * \text{ScaringRadius} = 10\text{m} = \text{Resolution} + \text{Precision} = \text{Resolution} + 2\text{m} \rightarrow \text{Resolution} = 8\text{m} \tag{1.18}$$

Using the same equations as before, and assuming the same 500m maximum projection distance, these distances can be translated into angular values for the tilt and pan axis. This delivers table 1.2 and table 1.3.

From the tables 1.2 and 1.3, it becomes clear that the tilt axis needs a much higher precision, accuracy and resolution for this application.

Table 1.2: Tilt axis accuracy, precision and resolution with $h = 5$m

Tilt Axis	Distance (m)	Angle (deg)	Angle (mrad)
Accuracy	4	0.0045	0.079
Precision	2	0.0023	0.040
Resolution	8	0.0090	0.157

Table 1.3: Pan axis accuracy, precision and resolution with $h = 5$m

Pan Axis	Distance (m)	Angle (deg)	Angle (mrad)
Accuracy	4	0.46	8
Precision	2	0.23	4
Resolution	8	0.92	16

Range of motion

In the current requirements, a range of motion for the tilt axis of -50deg to +30deg is mentioned. These requirements do not fit in the schematic pictures shown, and should be interpreted as follows: 40deg<α<120deg. Also, the results from the performed use case study (see appendix B) show that a decreased range of motion will not impact the usability of the product. A new range of motion requirement is setup using the same 10m scaring radius and 5m height of the device. The range of motion for the tilt axis proves to be: 45deg$\leq \alpha \leq$89.43deg (89.43$\approx$90deg) $\rightarrow$ 45deg$\leq \alpha \leq$90deg.

From the use case study (see appendix B), the current range of motion requirement for the pan axis was confirmed: many customers use the product with the pan axis rotating all the way around. That means: -180deg$\leq \beta \leq$180deg

Energy consumption

Because the system can be powered off of a battery system, recharged by solar panels, the power consumption of the aiming mechanism is an important aspect to allow customers to use the system for longer periods of time when the system has a lower power consumption. Ideally, the power consumption would be (near) zero. Two upper limits have been set for the power consumption of the aiming mechanism: a limit for an idle aiming system, and a limit for a moving system. The moving system probably has different power consumptions for different speeds; the worst case scenario should be analyzed and compared to the limits.

The limits are:

- During movement: <20W
- Idle aiming system: <3W

Table of new requirements

Summarizing the new requirements, a table was made to give a clear overview of the new requirements. See table 1.4.

Table 1.4: Table of new requirements

Parameter		Value	Unit	Comment
Speed, maximum				
	Pan	>36	deg/s	
	Tilt	>9	deg/s	
Speed, minimum				
	Pan	<0.637	deg/s	
Accuracy				
	Pan	0.46	deg	
	Tilt	0.0045	deg	
Precision				
	Pan	0.23	deg	
	Tilt	0.0023	deg	
Resolution				
	Pan	0.92	deg	
	Tilt	0.0090	deg	
Range of motion				
	Pan	[-180,180]	deg	Continuous
	Tilt	[45,90]	deg	
Energy consumption				
	Moving	<20	W	
	Idle	<3	W	
Price		<600	Euros	
Recommended height		$\frac{1}{100} * x$	m	Lower possible if Safety zone is large

Chapter 2

Concept Generation

In this chapter, the generation of concepts is discussed. The problem stated in section 1.3 is divided in multiple different smaller problems, such as moving an axis, guiding the light and other categories. With the new requirements setup in section 1.4.2, the concepts and solutions will be compared to one another and the performance will be estimated, after which a choice for a concept will be made.

2.1 Analysis of Subfunctions

To divide the complete problem into multiple different smaller problems, an analysis of the subfunctions can be performed. These subfunctions each have various different solutions. These solutions can be put into a morphological matrix to have an overview of the solutions and to form ideas for a complete solution to the main problem.

The main problem, as described in section 1.3, can be summarized as: 'What is the optimal design for a high-precision, large range-of-motion and low-cost device to aim a laser beam?'. The main design is split up, and each smaller design aspect has one of the subfunctions listed below.

Guiding the light

The (laser)light needs to be guided from the source to the destination.

Actuating an axis

Actuating axes to move the light guiding mechanism, which in turn moves the laser spot on the ground to a different location.

Constraining motion

With the movement of the axes, there is a need for the constraining of motion in other, undesired directions.

2.2 Subfunction Solutions

Guiding the light

Guiding the light can be achieved in several different ways. Two different categories are distinguished between: movement of the source and changing the beam direction. The movement of the source is self-explanatory: the source is moved to change the location of the spot on the ground. The path from the source to the ground is a straight line, without any disturbances in between. In the case of the beam direction change, the source is fixed and the direction of the beam is changed with the help of mirrors, lenses or other aids. The current state-of-the-art Pan-Tilt-Unit (PTU for short), introduced in section 1.2.1, falls into the first category.

The second category contains solutions such as using a movable or deformable mirror to deflect the light in a desired direction. Also, a set of lenses can be used to shift the light direction into the desired path. More exotic options such as using a gradient-index optic material to effectively bend the light can also be solutions here [10]. Another exotic option that can be considered is mentioned in [7], where polarization gratings where used to achieve beam steering. The resolution of the resulting PG-based beam steering concept is only 1.7deg though, and thus is not useful for this project.

In literature, there are more projects using mirrors to steer lasers. For example, in [15] a MEMS device is developed which is immersed in liquid and can aim a laser with a field of view of around 150deg. The used laser has a very small diameter, and needs to be enlarged to be used for the intended application of laser scanning. A solution like this would require a complicated (& expensive!) set of lenses all around the module to expand the beam, wherever it is steered to, to be useful for this project.

There are also hybrids between the two categories. These hybrids are, for example, a fiber guided laser. In this solution, the laser light travels through glassfiber strands which can bend and retain the light in the fibers while doing so. The source is fixed, but the set of lenses to expand the very small diameter laser beam into the desired diameter has to move with the glassfiber.

Actuating an axis

The actuation of an axis can be accomplished in a variety of ways. There is a clear division possible between different categories of actuation:

- Electric
- Hydraulic
- Pneumatic
- Others

Pneumatic actuators use a difference in pressure of a gas (usually air) to create movement. By letting the gas expand from a high-pressure storage tank into either side of a cylinder, the cylinder is pushed thus creating the actuation. The excess gas is usually vented to the environment in the case of a non-harmful gas, such as air. Pneumatic actuators are used a lot in industrial automation because of their simplicity and ease of use. A linear actuation is very easy to achieve with pneumatics, as opposed to an electric actuation where a true linear actuation requires more parts. Also, the system is less sensitive to leakage compared to the next type of actuation: hydraulics.

Hydraulic actuators work in a very similar fashion, with the main difference being the matter used to actuate. In hydraulic actuation, instead of a pneumatic actuation which uses a gas, a fluid is used to push a cylinder. The fluid is of non-compressible type, unlike the gasses used by pneumatic actuators. Hydraulic actuators find homes in all sorts of applications, perhaps the most well known are heavy machinery such as excavators and forklifts.

Electric actuators such as brushed DC motors or linear inductance motors rely on the Lorentz force created when a charged particle passes through an electric or magnetic field. Most commonly, the brushed DC motor uses a coil inside a magnetic field where the current passing through the coil generates Lorentz forces on each of the windings, which in turn create the torque needed to rotate the motor. Advantages over the other types of actuators are the lack of a pump or pressure vessel and the lack of pressurized lines which makes the system insensitive to leakage and thus more reliable. The widespread availability of electric power sources creates a system usable in many different situations.

There are many other actuation principles, or actuators that cannot be put into any of the above categories easily. One such example is the piezoelectric motor, which could be placed in the category of electric actuators since it uses an electric source. However, the actuation principle is a lot different since it does not rely on the Lorentz force like a traditional electric actuator.

Other aspects that influence the actuation of an axis are possible transmissions required to reach the speed and/or precision requirements. Each of the above mentioned actuation principles can require a transmission, especially if a rotational movement is required yet the actuator provides a linear motion, or vice versa. Direct drive actuators are actuators that do not require such a transmission, generally reducing the number of parts and complexity of a system whilst increasing performance.

Constraining motion

Conventionally, bearings are the most used item to constrain motion in a certain direction. In the field of MicroElectroMechanical Systems (MEMS for short), bearings are not used and the smart design of flexures can provide the constraining of several degrees of freedom, whilst others remain free to move. The use of flexures is common in the field of MEMS because of the relatively short travel of actuators. The limitation of flexures in terms of range of motion is usually not applicable in the field of MEMS. An application of these flexures in combination with mirrors has been done by Slagmolen [13].

2.2.1 Morphological Matrix

2.3 Solution comparison and Concept choice

Guiding the light

Moving the source has, like most solutions, some benefits and some drawbacks. For example: The effort to change a broken PTU can be fairly low in the case of a moving source solution. Also, there is a slight safety advantage because it is easy to see where the light will exit the enclosure, and since the light is intense enough to cause retina damage, this is indeed a benefit. However, the drawbacks are that the moving source solution typically has to move a lot of mass, consuming energy and decreasing performance.

The second category, where the beam is deformed or redirected during flight, has the benefit of a lower moving mass. Also, if reflecting the beam with a mirror, only half of the range of motion is required on the actuator and sensors because of the effective doubling of the angle. However, this also means that the precision and accuracy of the actuator and sensor needs to be doubled in comparison with a moving source alternative. These are trade-offs that do not negatively effect

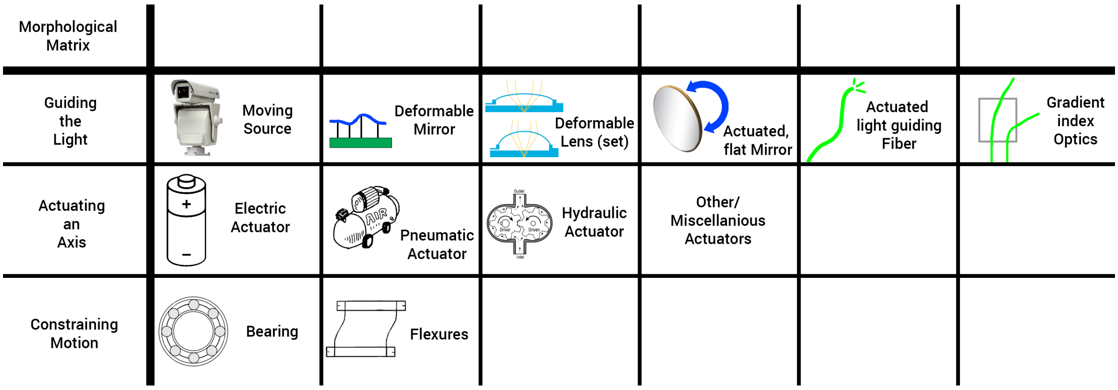


Figure 2.1: A morphological matrix of the proposed solutions to the subfunctions

the system performance, and in combination with the correct actuation and sensors the system performance is even increased.

Gradient-index optic material has many different cons, such as only giving the beam a small angular displacement from a required input linear displacement, and being hard to acquire or expensive, which makes this solution not viable.

Actuating an axis

Comparing the different actuation principles with one another, taking into consideration the application of an aiming mechanism for a laser and the power sources available on many installation sites, hydraulic and pneumatic actuators both have a big disadvantage where an additional step from electric power to a pressurized gas or fluid is required. A pump would need to be supplied with the installation, making the system less energy-efficient, more bulky and more expensive. Electric types of actuators, or actuators that use electric power but do not necessarily rely on Lorentz forces for actuation, are the most promising option. Direct drive type actuators which do not require transmissions to reduce the speed of the actuator are a nice feature to have, since they are generally more energy efficient and are less prone to having slop or backlash on the end-effector. There are solutions to both of these problems introduced by transmissions (see [5] and [8] for example), but they increase the price or decrease the performance of the system.

Constraining motion

Flexures are very energy efficient and when designed properly have near ideal properties. However, the stiffness of such a suspension combined with the limited range of motion quickly eliminated the possibility of using flexures for this system. Zero-stiffness flexure suspensions are available but have the limited range of motion issue unresolved (unless a very large design space is available for very long flexures).

Bearings are a very common solution. The problem with servicing the bearings is not an issue for this system, as bearing lifetime is much longer than the service life of the system at the relatively low speed. The friction of bearings can be overcome by the correct actuator choice. A possible issue with bearings could be the stick-slip effect, introduced when there is friction between two elements where the dynamic friction is lower than the static friction.

2.3.1 Concept Choice

With the subfunctions analyzed and compared to one another, a concept can be created by drawing a vertical line in the morphological matrix through the most promising subfunction solutions. This creates a solution where the axes are actuated by an electric, rotary actuator. Pneumatic or hydraulic actuators use additional components and are sensitive to leaks, making maintenance costs higher for the system in the long run. Also, electric actuators are relatively easy to control with simple electronics and a control loop.

The light is reflected by a mirror instead of moving the source or using a set of lenses to move the beam. Using the mirror, a relatively low weight of the axes and suspension of the axes can be achieved in comparison to the moving source solution, which is good for the performance of the moving mirror solution. The set of lenses uses the same principle of deflecting the beam instead of moving the source, but is slightly heavier and slightly more complicated than the moving mirror solution.

The concept will use bearings to constrain the motion in undesired directions instead of flexures. Flexures do not provide the system with enough range of motion, and they have stiffness in the desired moving direction as well, making constant energy consumption higher.

Chapter 3

Concept Development

In this chapter, the concept development from an idea to a prototype device design will be discussed. The concept chosen in 2.3.1 is further developed into something that can be manufactured to demonstrate the capabilities of the concept. Besides the mechanical design, the electronics required and the manufacturing aspect of the prototype will also be discussed, along with the controller design for the prototype.

3.1 Mechanical Design

In section 2.3.1, the decision for a moving mirror, actuated by electric actuators and suspended by bearings was elaborated upon. In this section, the mechanical design is developed further, creating a more detailed concept ready for manufacturing.

3.1.1 Tilt axis

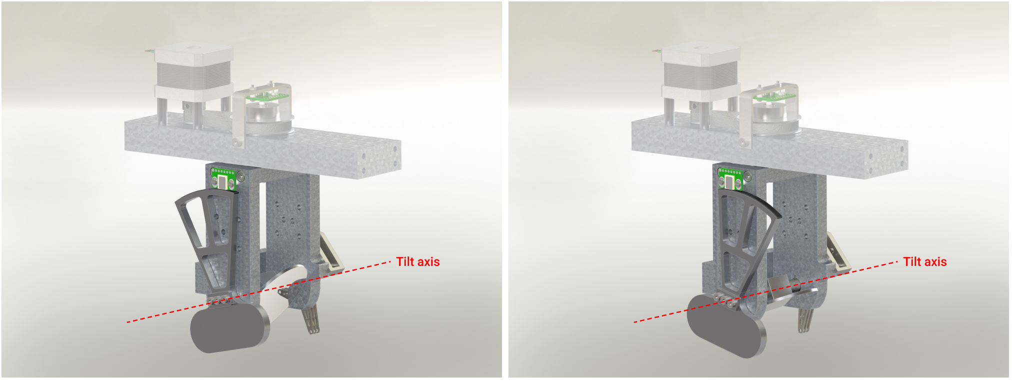
The tilt axis needs to be designed with care, since the requirements for precision and accuracy are high. Choosing parts for actuation and suspension, one must be careful of tolerances and fitments creating possible issues resulting in poor accuracy and/or precision. A render of the prototype tilt axis is displayed in figure 3.1.

Actuator

Starting with the actuator, ideally a direct drive actuator is used. By using a direct drive actuator, backlash in the transmission can be avoided and the requirements for precision and accuracy are easier to achieve. Direct drive electric, brushed or brushless DC motors with low minimum speeds are generally quite big, and this option was quickly discarded.

Another option is to use piezo steppers, which use piezoelectric material to 'inchworm' to a new location. These actuators are generally quite slow, and also quite expensive. They are however quite precise when combined with a high resolution sensor. The big issue with piezo stepper actuators for this project however is the price. The price of piezo stepper motors is very high, as they are relatively new in the field. As these get used more often, the price might decrease and the piezo stepper might prove to be an option. However, at the time of writing, the piezo steppers are simply too expensive for this application.

Conventional stepper motors are a good option, as these are able to provide very small rotational steps in microstep modes. Most regular steppers have 200 distinct steps per revolution.



(a) Tilt position 1 (b) Tilt position 2

Figure 3.1: The tilt axis construction in two positions

With a good stepper driver, microstepping up to 1/256th of the full 1.8 deg step is possible, creating a 0.007 deg step. Stepper motors with 400 steps per revolution are available, and this would increase the resolution to 0.004 deg. Positives include a low price and good availability. Also, stepper motors can be driven with or without microstepping, creating a nice balance between speed and resolution. A downside to stepper motors is their weight: they are relatively heavy in comparison to a piezo stepper or the next option, a galvanometer type actuator. Also, microstepping can introduce accuracy issues as described in [9] due to the torque curve of the stepper motor in relation to the position. When a stepper is used with an optional encoder, the accuracy issue can easily be resolved.

The galvanometer is originally used as an instrument for current in an electric circuit. Two types of galvanometers can be distinguished between: the moving magnet type, and the moving coil type. The moving magnet type is used frequently for laser scanning systems. By attaching a mirror to the moving magnet, a lightweight beam steering mechanism is created. These mirror galvanometers can be used in applications where a high frequency response is required, as the actuator has a low mass and therefore a fast response. Galvanometers with a moving coil can be found in a hard disk drives used in computers for storage. The galvanometer in this application controls the reading arm of the hard disk, which in turn reads the ones and zeros from the spinning disks. This is however not a 'true' galvanometer, as the spring is missing in this application. The actuator in a hard disk drive is therefore most often referred to as a voice coil actuator [2][11].

Unfortunately, mirror galvanometers with large diameter mirrors are not easily available. They are either very expensive, or the mirrors are much smaller for use with a narrow diameter beam. However, hard disk drive actuators are easily obtained by disassembly of a hard disk, and as the price of hard disks has become so low, even considering that the rest of the drive is thrown away, the actuator is still quite cheap. The range of motion of such an actuator fits the requirements, the weight of the actuator is relatively low and controlling the actuator can easily be achieved with a simple DC motor driver connected to a microcontroller. This solution is chosen for the actuation of the mirror, as it fits the requirements with a low price and good availability to build a prototype with. In figure 3.3, the actuator is schematically drawn. In blue, the iron cage is drawn to keep the flux leakage to a minimum. The red arrows indicate the flow of magnetic flux, the black crosses or dots indicate the current flow in the coil. Using the formula $\vec{F} = i\vec{L} \times \vec{B}$, it is derived that the force on the coil will be to the right of the figure.

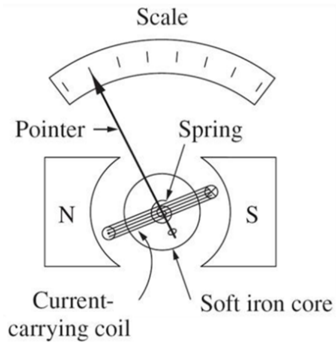


Figure 3.2: Moving coil galvanometer, *Image from: Dux College*

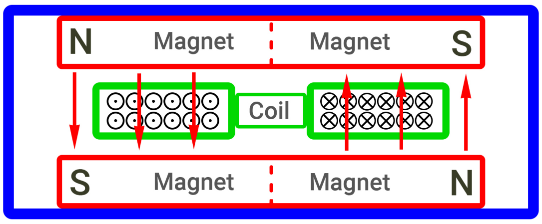


Figure 3.3: Hard disk drive, rotary voice coil actuation principle. Force on the coil is to the right. Image derived from [4]

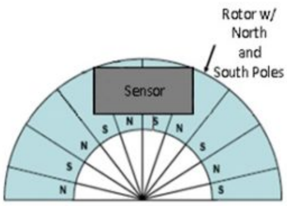
Sensor

The sensor for the tilt axis needs to be a high-resolution position sensor, capable of differentiating between the different steps at the smallest required resolution. A speed sensor in combination with fixed references is also an option, although utilizing this could introduce drift in the measurements, requiring a second sensor for sensor-fusion purposes, or frequent homing to combat the drift. These options are more complicated than using a good position sensor, while not necessarily being any cheaper. The option to go for a high-resolution position sensor is the best option for this application; there are however many different types of these position sensors such as different types of encoders, different types of laser sensors and potentiometers.

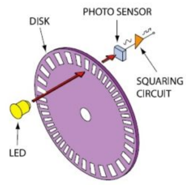
Encoders can be either absolute or relative. These two types differ in the signals they are picking up: absolute encoders pick up a different signal at every position, therefore they are able to extract an exact position from their readings from the moment they are powered up. Relative (or incremental) encoders pick up only an incremental signal every time the position changes a certain amount. These types of encoders need to be used with a homing sensor and a homing sequence is required on power-up of the device to find the absolute position.

An interesting proposal for an incremental rotary encoder is made in [14], where the optical sensor of a computer mouse is used as a rotary incremental encoder. The disadvantage to this approach is the effort required to make this work, along with the relatively low resolution of up to 1900 counter per revolution (or 0.1895deg per count). An off-the-shelf encoder has a higher resolution and is simpler to implement, making it favorable in this scenario.

After selecting an encoder type, the selection is not done yet. A measurement principle needs to be selected; most commonly the choice is either magnetic or optical. Both of these types are non-contact sensors, which do not have the disadvantage of mechanical wear over time. See figure 3.4 for a simplified representation of both types. Magnetic encoders pick up changes in magnetic flux as they pass along strips of magnets. Optical encoders have light shining through discs or strips with thin slits. Detectors behind the slits can detect whether or not light is passing through, thus indicating whether or not there is a slit in front of it.



(a) Simplified representation of a magnetic encoder. *Image from: Anaheim Automation*



(b) Simplified representation of an optical encoder. *Image from: Encoder Products Company*

Figure 3.4: Two types of encoders

In the case of this prototype, an angular tilt range of only 22.5deg need to be sensed. This means a circular encoder does not have to be completely circular, and only needs to span the 22.5deg mentioned. A smaller range saves some cost, as either the disc with slits (optical encoder) or the magnetic strip (magnetic encoder) can be shorter.

Laser sensors such as laser triangulation sensors are primarily used as distance sensors. To use these on a rotational axis, they have to either be compatible with slanted faces, or a mechanism that convert the rotational movement into a linear movement needs to be designed which should be an ideal mechanism: no backlash, play or any other disturbances can be present in this mechanism or the measurement will be wrong.

Laser triangulation sensors work on slanted surfaces, however units that have sufficient resolution are expensive. Usually, additional hardware is also required to transform the analog current signal into a digital signal for the microprocessor.

Potentiometers are widely used in all sorts of electronics, from consumer toys to very high-tech equipment. They are widely used as volume adjustment knobs on audio equipment for example. Also, trim potentiometers are used in electronics to fine-adjust voltage coming out of a dc-dc converter for example. Potentiometers are variable electrical resistances where the rotation of the knob influences the amount of electrical resistance the potentiometer has.

Potentiometers have multiple common types: carbon composition, cermet, resistive polymer and wire wound. Most of these types are continuous variable electrical resistances, with the wire wound potentiometer being the exception: this is discrete in the sense that the resistivity changes in discrete steps. These steps are usually very small though, so this does not have to be a problem. To read the potentiometer, an analog to digital converter (ADC) in combination with a Wheatstone bridge is commonly used. The resolution of the ADC determines the resolution of the measurement if a continuous potentiometer is chosen.

The major downside to using a potentiometer as a position sensor that is continuously used is the longevity. Since the potentiometer relies on mechanical contact, wear occurs between the wiper and the contact material reducing the lifetime every use. See figure 3.5 for a schematic representation of a potentiometer, showing the wiper and the resistive material which wear away. Frequent replacements are not allowed for the design, making the potentiometer not eligible.

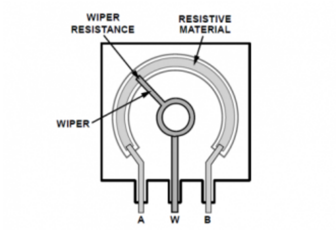


Figure 3.5: Potentiometer construction, *Image from: EEWeb Electrical Engineering Community*

Taking the positives and negatives of each sensor option into account, the encoder is the most promising option. Encoders have the resolution required, or have an even higher resolution. Since the range of motion is not completely circular, having an encoder with that range is not necessary and an encoder with a smaller range of motion can be chosen, which reduces the cost of the solution. Either a magnetic or an optical encoder can be used; in the prototype, a magnetic encoder is used because of the availability and the cost saved by going with a small strip of magnetic material instead of the full circle.

The chosen magnetic encoder has 8192 pulses per 2mm of travel. Since the required range of motion for the mirror is only 22.5deg, and the minimum bend radius for the magnetic strip is 75mm, the resolution of the chosen solution is calculated as follows:

$$s = CR = 22.5 * \frac{2\pi}{360} * 75 \times 10^{-3} = 29.45 \times 10^{-3}\text{mm} \tag{3.1}$$

$$N = s * \frac{8192}{2 \times 10^{-3}} \approx 120637 \tag{3.2}$$

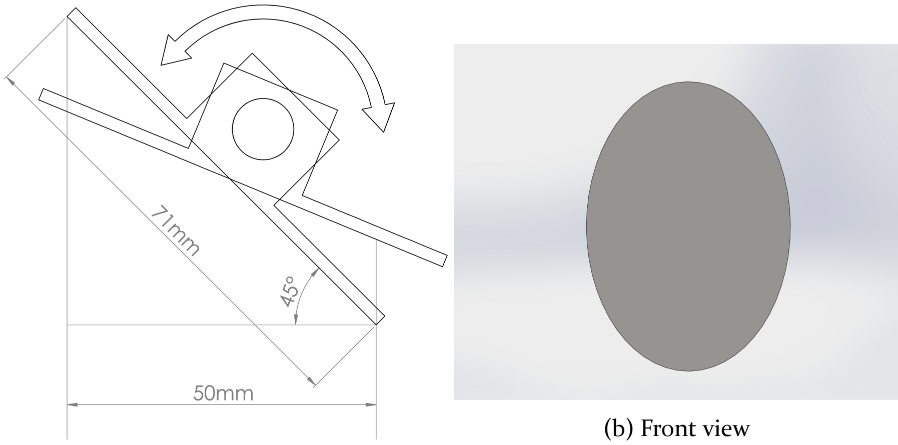
$$\text{Resolution} = \frac{22.5}{120637} \approx 0.1865 \times 10^{-3}\,\text{deg}\,/\text{pulse} \tag{3.3}$$

The calculated resolution is around a factor 10 higher than the required precision (see table 1.4). This is good, as the control loop has more information and a larger number of pulses which deliver a result that is within spec. If the resolution of the sensor is only slightly higher than the required precision, accuracy or resolution, the system can be hard to stabilize, jumping between two values of the encoder.

Mirror

Because the diameter of the beam that the mirror needs to reflect is 50mm, the mirror required can either be a circle with a diameter of 71mm, or an ellipse with a major axis of length 71mm and a minor axis of length 50mm. The additional step in diameter is needed so that the circle shaped laser output always falls inside the mirror, even if it is at an angle of 45 degrees. See figure 3.6 for a graphical interpretation. Making the mirror ellipse shaped saves some rotational inertia and weight, making this an obvious choice.

The material of the mirror then has to be chosen. For the prototype, the mirror is manufactured out of aluminium. Polished aluminium has a high reflectance for the wavelength of the light used. Polished aluminium is not the best choice for the mirror surface however; as aluminium does oxidize where oxygen is present, protected silver would be a better choice for the surface of the mirror [1]. Usually, a mirror would be made out of one material and receive a coating of another, in this case silver. This makes the mirror cheaper as the materials with high reflectance are expensive, and should be used as little as possible.



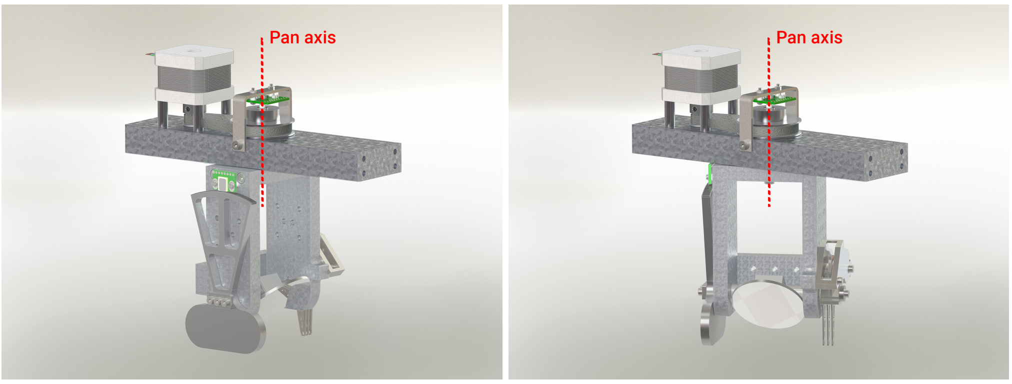
(a) Side view

(b) Front view

Figure 3.6: Ellipsoid shape of mirror illustrated

3.1.2 Pan axis

The pan axis is located above the tilt axis, supporting it and locating it as well. The pan axis is fixed to the surrounding world on the two short sides, pictured in figure 3.7.



(a) Pan position 1

(b) Pan position 2

Figure 3.7: The pan axis construction in two positions

Actuator

If the pan axis is chosen to be the first axis, i.e. it actuates between the fixed world and the system, the weight of the fixed part does not matter. In that case, looking at the above options for actuators, a stepper motor is a good option which combines a high resolution with low cost.

Sensor

The same considerations as above, for the tilt axis, can be made now for the pan axis. The sensor options remain the same, with the same wear issues for potentiometers and the same additional

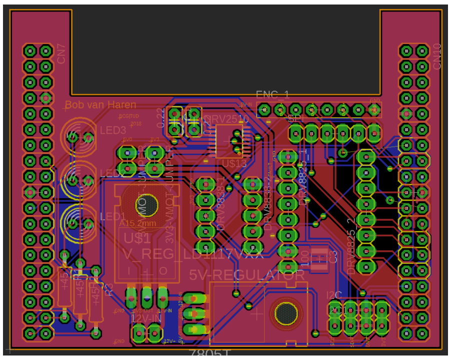


Figure 3.8: The custom PCB board design. This board houses all components such as stepper drivers and the voice coil driver.

hardware for laser triangulation sensors. Therefore, an encoder is again the preferred option. In the case of the pan axis though, the range of motion is 360deg, or a full rotation. The required resolution is lower, and a lower-end encoder is selected to keep the cost of the solution low. This lower end encoder is of the magnetic type, and consists of only a single 2-pole magnet and an IC to differentiate between 4096 positions, or 12-bit resolution.

3.2 Electronics Design

For the design to be complete, an electronics design needed to be added as well. The electronics selected consist of a microcontroller from ST Microelectronics, the STM32F091RC to be precise, and additional hardware to read the sensors and control the motors. Since the design uses stepper motors, a stepper motor driver is needed in order to have control over the microstepping and offload some of the computation required to drive a stepper from the MCU. Besides the stepper, the voice coil needs a motor driver: this driver can be the most basic H-bridge as this gives control over the direction of the motor. The speed of the motor is controlled by sending the H-bridge pulse-width modulated (PWM) signals. When the used frequency is high enough, these PWM signals appear to the motor as a linear voltage signal, while the signal actually turns on and off with a certain duty cycle and frequency.

With the required electronics selected, a platform to reliably use and connect these different electronics is required. Designing a custom PCB is the preferred method for doing this, as a prototyping breadboard can be confusing with many different components. Also, the breadboard is quite sensitive to errors like loose wires. A custom PCB design is superior, and thus this prototype was fitted with one. Designing a custom PCB is made easier with software tools like Autodesk's Eagle, where it takes only a few hours to design a custom PCB once you have all the components required already prepared. A preview of the finished PCB is displayed in figure 3.8.

Details of the components on the additional PCB are as follows:

- Texas Instruments DRV8825 stepper motor driver. Controlled by two GPIO's and one PWM channel.
- Texas Instruments DRV8838 DC motor driver. Controlled by two GPIO's and one PWM channel.

- Texas Instruments LM1086-3.3 Linear voltage regulator. Supplies 3.3V.
- ST Microelectronics L78S05CV Linear voltage regulator. Supplies 5.0V.
- Headers for the encoder and I2C devices (also an encoder).
- Selector for selecting the Voice-Coil-Motor voltage. This can be either 3V3 or 5V.
- Debugging LEDs (3x), for simple situations this is quicker than USB debugging. These can be lit up in sequences to show Morse code, binary numbers for error codes and many more applications.

3.3 Realization of the prototype

Mechanically, the prototype is mostly manufactured using a CNC milling machine. The parts need to fit together with great precision to allow the bearings to function optimally, without any play. Play in the system makes it hard for the controller to control the system, and will most likely decrease system performance. Since the prototype consists of multiple parts that need to fit together with great precision, these parts were first milled with material left in the critical areas. The parts were then fixed together, and milled a final time in only one setup. The precision of the parts can reach the precision of the CNC milling machine in this case, which lies in the order of a micrometer.

To remove even more play from the system, the bearings are pressed onto the shafts, removing any internal play they have. Looking at the manufacturer's specifications, the internal clearance is specified and the corresponding fits for removing this internal clearance are indicated.

After creating the mechanical prototype, the task of programming the microcontroller remains. The microcontroller can be programmed with various languages, of which the standard C language was used in this project. Programming in C for the large count encoder is tricky since some timers (which record the encoder input) feature only an 8-bit or 16-bit counter, which will over- or underflow because of the high pulse count. Programming around this can be problematic but is not impossible.

3.4 Controller Design

In order for the system to move according to the input, a controller is necessary. The control system handles the incoming signals and controls the motor output signal to make them match. Before designing the controller, the system needs to be either modeled or identified from the physical system. Identifying a system can also be combined with an estimated mathematical model, to make the system identification process take less time.

3.4.1 Modeling of the system

To model the system, the decision was made to first model the tilt axis, and then model the full system. Modeling the tilt axis separately decreases the degrees of freedom to a single one, and this makes the modeling a lot less complicated to start with. The tilt axis can be compared to a standard mass-spring-damper system: the mass represents the inertia on the axis where the mirror is mounted, the spring acts as the gravity since there will always be a slight imbalance on the axis, and the damper represents the bearings on either side. This is a simplified system, not taking into account stick-slip effects in the bearings or any other nonlinear effects. A schematic representation of this mass-spring-damper system is found in figure 3.9. The external force shown in figure 3.9 is supplied by the voice-coil actuator.

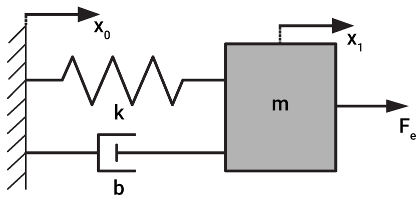


Figure 3.9: Schematic representation of the tilt-axis

Converting this system into a set of equations, the first action is to take the free-body diagram of the mass, and setup the equations:

$$F_e - F_k - F_b = m\ddot{x_1} \tag{3.4}$$

Filling in $F_k = k(x_1 - x_0)$ and $F_b = b(\dot{x_1} - \dot{x_0})$, the following can be stated:

$$F_e = m\ddot{x_1} + b(\dot{x_1} - \dot{x_0}) + k(x_1 - x_0) \tag{3.5}$$

Converting this to the Laplace domain, and setting $\dot{x_0} = 0$ and $x_0 = 0$, the following is true:

$$F_e(s) = x_1(ms^2 + bs + k) \tag{3.6}$$

Since many of these parameters are unknown, but a model can be constructed with unknown values, a grey-box system identification can be performed. This grey-box identification uses estimated starting values and measured data (usually input and output, but additional measurements can improve the model) to determine the values of the unknowns in the mathematical system. The measured data is usually obtained by inputting either white-noise or a chirp signal (increasing frequency sine wave) to the system. This type of input signal contains many different frequencies, usually this frequency range can be specified. This means a bode plot of the desired frequency range can be constructed from this test. From this bode plot, a crossover frequency can be read and thus the control bandwidth can be determined.

In the grey-box identification, the gathered input and output data is compared to the starting values of the identification, which are then adjusted to match the actual, noisy bode plot as close as possible. In a black-box identification, the system will be identified without prior knowledge of the system, and this usually results in a complicated but accurate system description because of the many parasitic influences that are not modeled in the grey-box approach.

For the purpose of controlling the real-world system, the system identification does not need to be perfect. A comparable system from identification is a perfectly acceptable starting point for the controller design in many cases.

3.4.2 Controller implementation

Controlling the system is done using a combination of the following controllers:

- Feedforward
- PI(D)

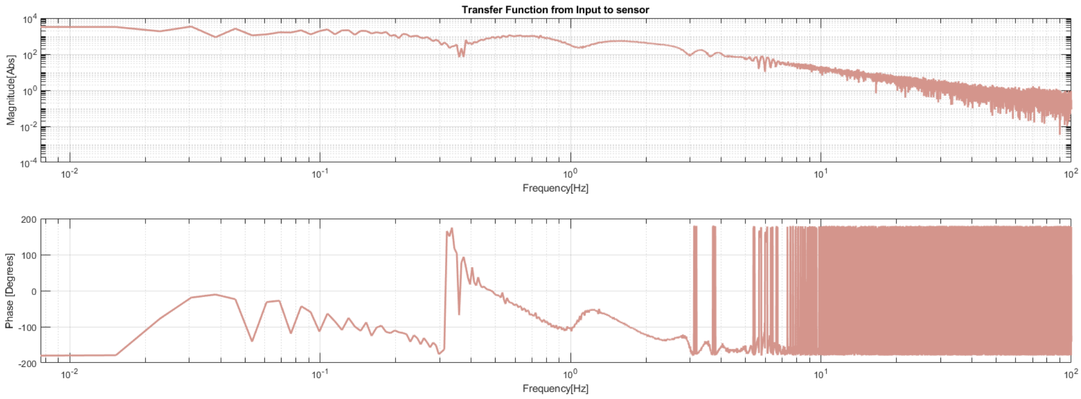


Figure 3.10: Chirp signal system identification bode plot. Transfer function from input chirp to output encoder counts.

- Second order low pass filter

These controllers, combined with input smoothing, make sure the system performance is optimal and robust.

Input smoothing

Input smoothing creates a smooth but slower reference trajectory that the system needs to follow. Sharp jumps like a step input are smoothed out to first, second or larger order inputs which describe the derivative of the position to the order of smoothing. In this case, a second-order input smoothing is performed, describing maximum acceleration values.

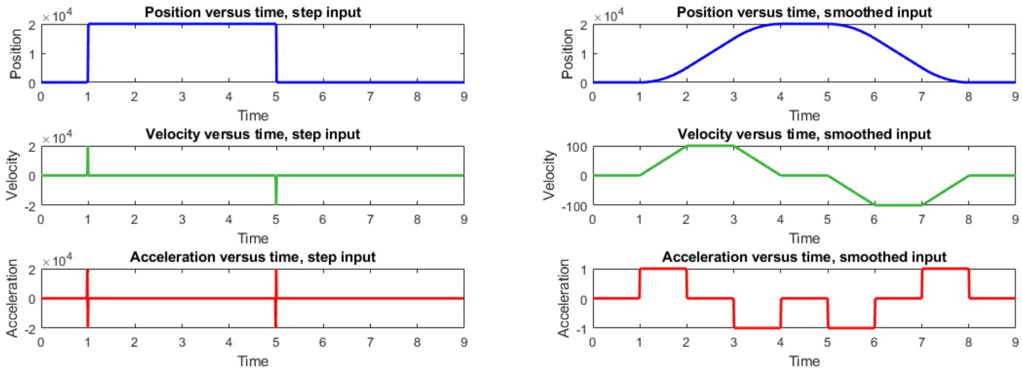
In figure 3.11, the effect of this input smoothing is clearly visible: the reference is slower but missing the sharp velocity and acceleration peaks. Because these graphs were made with a discrete-time program, the peaks have a finite value. In reality, a step input has an infinitely high velocity and acceleration peak. Making a physical system with any mass follow this trajectory is not possible (as this would require infinite force, as per Newton's second law $F = ma$), and input smoothing is a way to limit either velocity, acceleration, jerk and/or even higher order derivatives from position.

With this new, smooth input, the controller now comes into play.

Feedforward

A feedforward controller or a feedforward addition can be used to reduce the delay introduced by a purely feedback controller. The feedback controller needs to receive sensor information first, construct an error signal, calculate the output value with different gains and only then can the signal be sent out to the motors. If, however, the reference is known and there is some known system information to tune the feedforward controller to, an output signal can be created without the feedback controller active.

Controllers consisting of only feedforward can have trouble following an absolute reference, as the output can drift without the controller noticing. That's why a feedforward addition to a feedback controller is used: there is compensation of the delay without the side effect of drift being a problem. A schematic representation of a structure like this is represented in figure 3.12.



(a) Step input

(b) Second order smooth input

Figure 3.11: Position, velocity and acceleration of different reference position signals

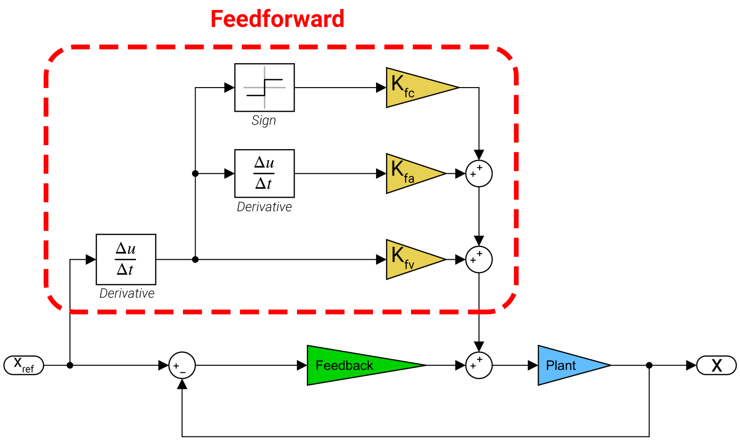


Figure 3.12: Feedforward portion of control loop

In figure 3.12, the total feedforward addition to the loop would be:

$$F_{\text{feedforward}} = K_{\text{fa}}\ddot{x}_{\text{ref}} + K_{\text{fv}}\dot{x}_{\text{ref}} + K_{\text{fc}} * sign(\dot{x}_{\text{ref}}) \tag{3.7}$$

PI(D)

PID Feedback controllers are a well-known way to control systems with relatively low time-delays. Fortunately, this system does not have a large time delay and thus a PID controller can be applied. Most systems in industry are controlled with PID control, a good percentage of these PID controlled systems is unfortunately also poorly tuned [12].

There are generally two ways to tune a PID controller: with or without the frequency response of the system. If the frequency response of the system is not known, a system can be manually tuned: set K_i and K_d to zero, and keep increasing K_p until the system oscillates. Then set K_p to about half and increase K_i. The system might have a lot of overshoot now, which is where K_d comes in. By raising K_d, the overshoot can be minimized. Having a K_d value larger than zero is not required however, and thus the derivative part can be 'turned off' effectively. The derivative part was not required in this system, and so the differential action gain was left at zero.

Another way to tune a PID controller without a frequency response of the system is with the Ziegler-Nichols method. This method also relies on finding the oscillation point with just proportional gain, but describes the other gains from there. This method is described in more detail in [6].

If, on the other hand, the frequency response is known (in practice, usually from a system identification), the PID can be tuned in many different ways. An easy way can be to use one of the many tools designed for this purpose, where the open-loop system identification data is loaded and the closed loop bode plot is represented as the parameters of the PID controller are changed. The close loop Bode plot can be shaped by adding different controller components while keeping an eye on gain- and phase margin to ensure stability. The Bode plot of a PID controller alone is represented in figure 3.13.

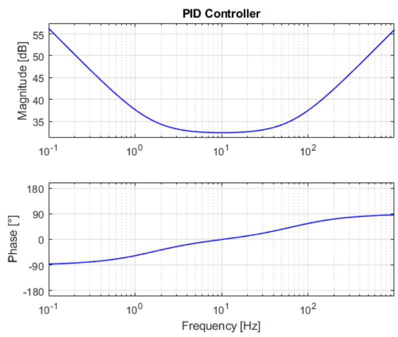
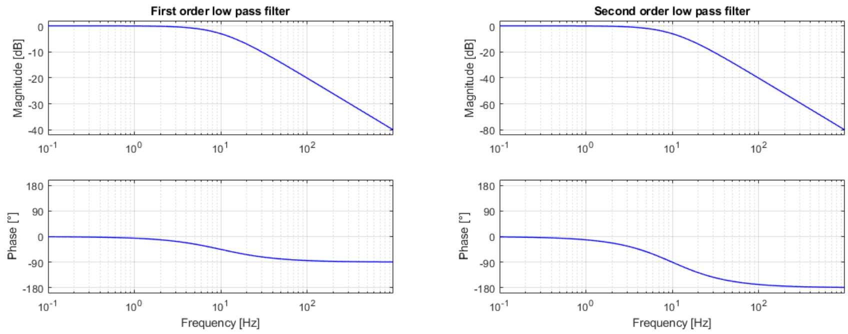


Figure 3.13: Bode plot of a PID controller

Second order low pass filter

A low pass filter is used in cases where high-frequency inputs are not desired or in situations where high frequency signal noise is present but not desired. A second order low pass filter increases the attenuation of these high-frequency disturbances with respect to the first order low pass filter, but also decreases the phase more. See the bode plots in figure 3.14.



(a) First order low pass filter (b) Second order low pass filter

Figure 3.14: Bode plot of first and second order low pass filters

3.5 Prototype overview

In this section, an overview of the prototype is presented.

In figure 3.15, the center of rotation of the mirror is illustrated by the black and red dot. Ideally, the mirror center would be coincident with this center of rotation, however for the prototype, it was easier to manufacture with a slightly offset mirror surface. Because the mirror is mounted slightly off-axis, the mirror also needs to be slightly bigger, as the effect described previously and depicted in figure 3.6 is accentuated even more.

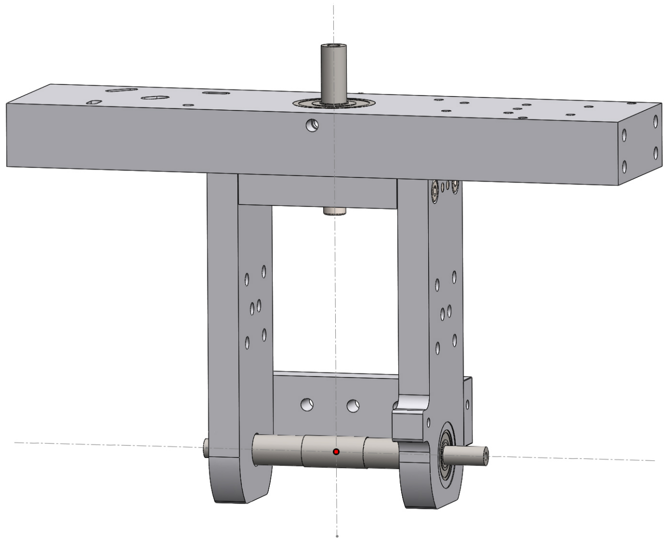


Figure 3.15: The center of rotation of the two axes

In figure 3.16, the complete prototype is presented and the primary components are highlighted. The motors are both circled in purple, the encoders in yellow and the other primary components in green.

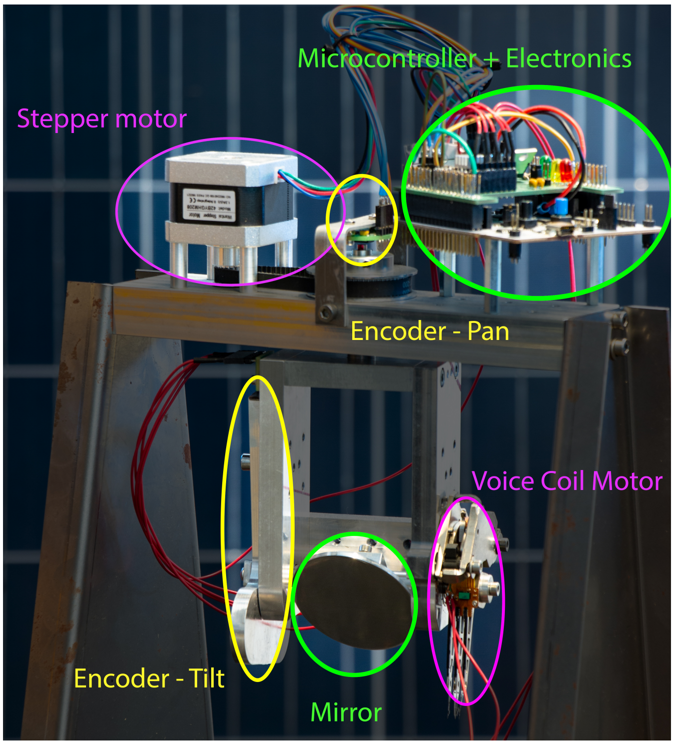


Figure 3.16: Overview of concept with labels added to the primary components

Chapter 4

Concept Testing

In this chapter, the process of testing and verifying the concept is explained. First, the process of testing is explained together with the conditions under which the tests were performed. Then, the testing parameters are further explained with their relation to the bird repelling problem. Lastly, at the end of this chapter, the results from these tests are presented and analyzed.

4.1 Testing parameters, conditions and testing process

After tuning the system's controllers, as described in section 3.4, the testing procedure can begin. The tests were all conducted under room-temperature, inside an office, over the coarse of a week. The signals were all collected by the microcontroller and logged, so the results can be analyzed afterwards.

The testing process is described as follows:

1. Determine a suitable input profile
2. Determine the desired speed
3. Program this profile into the microcontroller as reference
4. Execute the program and start logging data

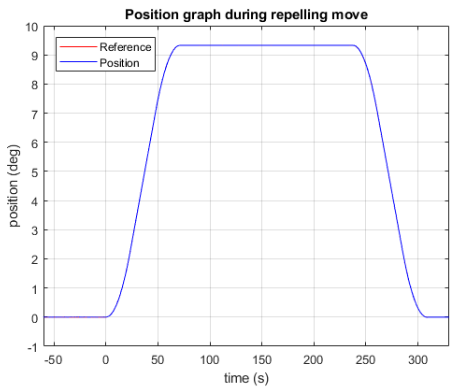
The logged data includes a time signal, reference signal, encoder position and the control signal that is output to the voice-coil motor. With this data, the error signal is easily constructed by subtracting the position from the reference signal.

4.1.1 Testing patterns

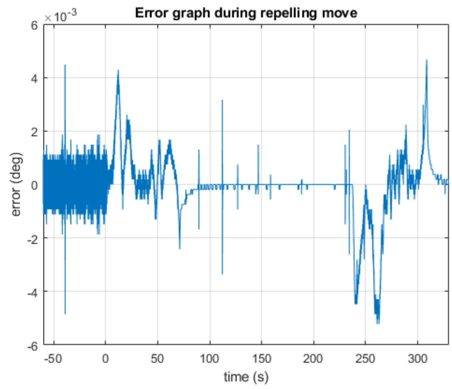
There are two important testing patterns for the application of bird repelling: a fast, traversing move where the laser can be turned off and thus a larger error during movement is allowable, but the settling time should be as low as possible. Another testing pattern is the bird repelling pattern: the speed is set much lower but the tracking error should be minimized because the laser is on and should project as close to the reference as possible to avoid exposure to laser in undesired areas.

4.2 Positioning and tracking Results

Below, some figures show the results of both test patterns. In figure 4.1, the figures display the position and corresponding error when a repelling move is issued. In figure 4.1a, the reference and position graphs overlap almost exactly, making it hard to see the red line showing the reference.

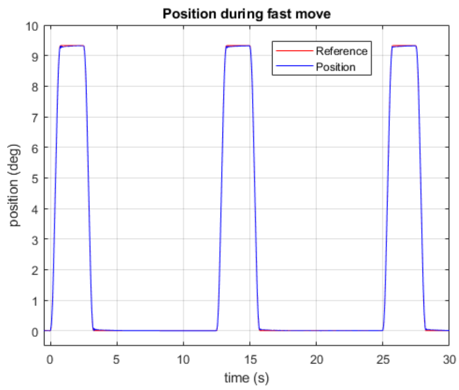


(a) Position during repelling movement ($v_{\max} = 0.4\text{deg}\,/\text{s}$)

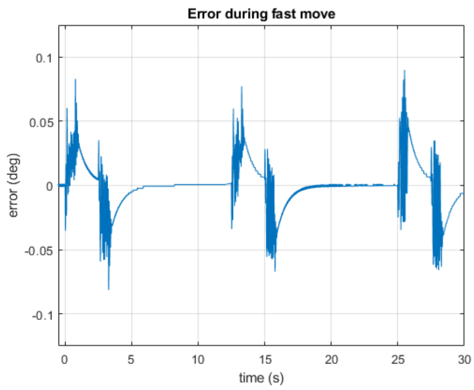


(b) Error during repelling movement

Figure 4.1: 'Repelling movement' test in tilt axis, showing tracking performance of the system



(a) Position during fast movement ($v_{\max} = 37.2\text{deg}\,/\text{s}$)

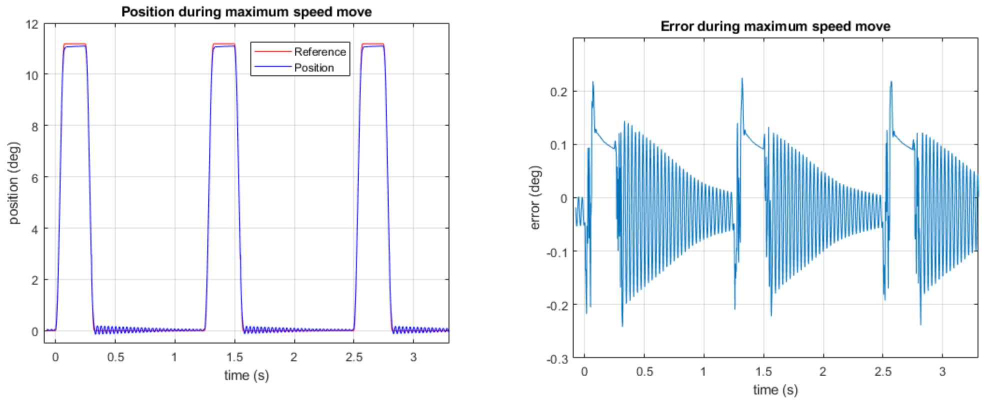


(b) Error during fast movement

Figure 4.2: 'Fast movement' test in tilt axis, showing higher frequency input performance.

The current, state-of-the-art bird repelling laser aiming device has, for the slow, repelling move, a maximum error of around 0.5deg. This was tested with a new unit; wear over time due to mechanical contact will increase this error. Comparing the two solutions, this prototype shows an error over 100 times smaller. Also, the current aiming device has a maximum speed of $3.5\text{deg}\,/\text{s}$. That means this prototype is showing speeds over 10 times larger, while still keeping the error very low in comparison with the current aiming solution.

Pushing the speed even further, the speed reached $250.01\text{deg}\,/\text{s}$, around 71 times as fast as the current-state-of-the-art solution provides. This did however result in a larger error and oscillations on the output, as the control loop is not tuned for speeds this high. The error reached a maximum value of 0.24deg. These results can be seen in figure 4.3.



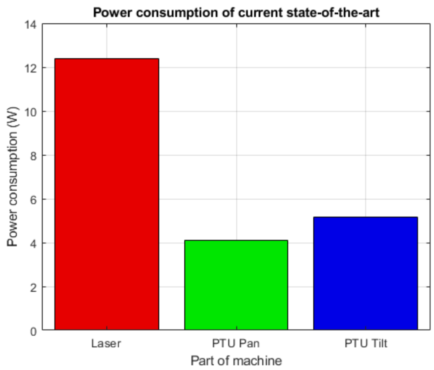
(a) Position during maximum speed movement ($v_{\text{max}} = 250.01\text{deg}/\text{s}$)

(b) Error during maximum speed movement

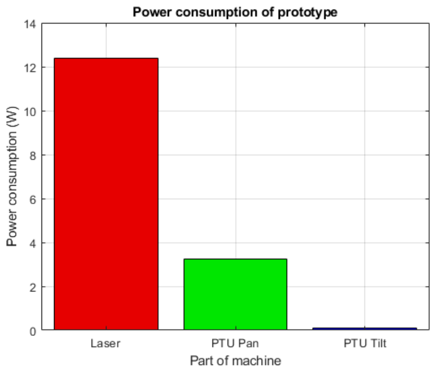
Figure 4.3: 'Maximum speed movement' test in tilt axis, showing the limits of the controller

4.3 Energy consumption

Since the system is often used where mains power is not available, and off-grid power systems power the unit in that case, energy consumption is an important aspect of the module (see section 1.4.2). The current state-of-the-art aiming solution uses 9.30W when in use and both axes are moving. The prototype uses 0.11W when only the tilt axis is used. This number is very low, especially compared to the rest of the system. When the pan axis is used, 3.24W is used. This is considerably more power consumption than the tilt axis, as the stepper motor driver is not very efficient. In total, this makes the prototype consume 3.35W, less than a third of the current-state-of-the-art solution.



(a) Power consumption by current state-of-the-art solution



(b) Power consumption by prototype design

Figure 4.4: Power consumption of laser and aiming mechanism

Chapter 5

Conclusion

For an automated laser projection device to deter and control birds, a solution was required that upgraded the current, state-of-the-art aiming device. This new solution has been developed and tested over the last nine months. A prototype of the design has showed improvements in the range of 40 times better performance in both speed and accuracy.

Possible negative aspects of the new solution compared to the state of the art solution are:

- Slightly higher cost, the new concept has a price of roughly 120% of the current aiming solution. However, the cost of a total system will decrease when this solution is implemented because only one housing is required to house the complete system.
- New design of complete system is required. It is not a plug and play, drop-in solution for current systems. Many of the old components such as the laser source are still used though, thus reducing the amount of design work required to finish the system.

However, compared to the state of the art solution, the new concept has several notable advantages, which outweigh the possible negative sides of the concept:

- The required angular range of motion is half the size of the current device, resulting in faster traversing from one position to another.
- The maximum speed is more than 10 times higher than state-of-the-art laser aiming devices used for this purpose.
- The accuracy is improved with a factor of more than 100. This means the safety zones can be considerably smaller and areas with smaller safety margins such as airports can also use this new solution.
- External moving parts are removed, and the option to externally block laser output is added for customers with particularly tight safety regulations.
- Power consumption has been reduced by a factor of 3, meaning the unit can aim the laser and scare birds for longer when used in combination with photo-voltaic panels or other off-grid solutions.
- The full system can be better weather-sealed in a single, larger enclosure.

The experimental results show that the prototype can meet the requirements for position accuracy and trajectory following. Minimum and maximum speed are achieved, as well as the desired range of motion. This means that the mechatronic design, including the mechanical design but also the controller and electronics design, functions as intended.

With all the previous in mind, the new solution is shown to be a good solution which solves the problem focused on in this research.

Appendix A

Pan-Tilt Unit testing

A.1 Pan-Tilt Unit specification tests

The current state-of-the-art Pan-Tilt Unit used by Bird Control Group is tested in-house to ensure a level playing field across the aiming solutions researched by Bird Control Group. The PTUs go through several different tests:

- Accuracy & precision test
- Resolution test
- Minimum and maximum speed test
- Range test
- Mechanical play test (if applicable)
- Ingress Protection test

A.1.1 Accuracy & precision test

The accuracy and precision test is described as follows: there are 6 measuring points along the range of each axis. Each measuring point is touched upon multiple times. Every time the PTU moves and stops at a measuring point, the angle is measured and stored by an inclinometer, type HPS-60-1-485 manufactured by Level Developments. This sensor has an accuracy at room temperature of 0.05deg and a resolution of 0.002deg. These values are compared to the command given to the Pan-Tilt Unit and the difference between these values then indicates the accuracy & precision by looking at the average difference and the spread of the results respectively.

A.1.2 Resolution test

In the resolution test, the smallest possible step the PTU can make is tested. A relative movement command is sent with a very small angular value. Either the machine responds, or an error is returned as the angular difference is too small. Once the smallest step that is actually executed is found, several measurements are done around the zero point of the axis, so that the mechanical play in the gears has minimal effect on the resolution.

A.1.3 Minimum and maximum speed test

Much like the resolution test, the minimum and maximum speeds are found by commanding movements with very small and very big speeds, and logging angular measurements while moving. It is then a case of calculating the speed, which is easily done with the formula:

$$\omega = \frac{d\theta}{dt} \tag{A.1}$$

Although since the data is in discrete time, the formula used is:

$$\omega \approx \frac{\Delta\theta}{\Delta t} \tag{A.2}$$

With a sufficiently high data-rate, the approximation is very close to the exact speed, if not exactly if the movement speed is linear (which in most cases, it is).

A.1.4 Range test

This test is fairly straight forward: starting with large relative movements in one axis and one direction only, go until it will no longer accept the command. Decrease the relative movement amount in the command and try again. Do this until the range of the PTU has been found in both directions, in both axes.

A.1.5 Mechanical play test

Only if applicable to the PTU, a mechanical play test is performed. Some PTU designs may not be accessible to outside influences such as wind gusts which trigger mechanical play. This type of PTU must be controlled by a sensor on the output to eliminate mechanical play completely, and in that case a measurement of the mechanical play is not necessary.

A.1.6 Ingress protection test

This test does not focus on the performance and speed of the device, but focuses on the field application where rain on the device and high-pressure cleaning of the device may occur. A device must be protected to meet an IP-rating of IP66 or higher.

A.2 Current Pan-Tilt Unit testing results

Out of many tested PTUs, an average PTU has a mechanical play of 0.83deg in the tilt axis, and 0.47deg in the pan axis. This comes on top of the accuracy, which in tilt is 0.26deg on average and in the pan axis, this is 0.09deg. The combination of both mechanical play and accuracy can deliver errors of more than 1.0deg. In a typical application of 200m range and an installation height of 2m (and thus the projection angle is 89.43deg), this can lead to dangerous projections in the sky as the angle comes above 90deg.

Below are the testing results of some of the PTUs currently in use. As can be seen, quite a few of these PTUs do not meet either the current or the new specifications.

Serial No	Standby power supply < 3W(0.125A)	Maximum load <20W(0.83A)	Vertical initial position $H_{TILT}0$ ° ±1 °	M_{TILT} ≤0.20 °	$R_{TILT, MAX}$ 30 ° ±1 °		$R_{TILT, MIN}$ -50 ° ±1 °		Vertical reset $H_{TILT}0$ ° ±1 °	Vertical accuracy	Horizontal initial position $H_{PAN}0$ ° ±1 °	M_{PAN} ≤0.20 °	Horizontal reset H_{PAN} 0 ° ±1 °	Horizontal accuracy
				Actual value	Measure ments	Actual value	Measure ments	Actual value				Actual value		
100001312	0,06	0,51	0,00	0,82	30,51	30,51	-50,73	-50,73	0,34	-0,34	0,95	0,54	1,00	-0,05
100001313	0,08	0,50	0,34	1,15	30,55	30,21	-50,59	-50,93	0,32	0,02	0,27	0,47	0,27	0,00
100001314	0,08	0,52	0,82	0,76	31,63	30,81	-49,50	-50,32	1,33	-0,51	0,96	0,37	0,96	0,00
100001315	0,06	0,50	0,61	0,56	30,97	30,36	-49,83	-50,44	0,59	0,02	0,86	0,41	0,82	0,04
100001316	0,08	0,51	0,88	1,13	31,87	30,99	-49,62	-50,50	0,84	0,04	0,89	0,45	0,90	-0,01
100001317	0,07	0,51	0,98	0,55	31,95	30,97	-49,44	-50,42	2,21	-1,23	0,39	0,56	0,27	0,12
100001318	0,07	0,52	0,78	1,30	31,46	30,68	-50,18	-50,96	0,22	0,56	0,97	0,68	1,07	-0,10
100001319	0,08	0,52	0,09	0,55	29,94	29,85	-50,42	-50,51	0,09	0,00	0,97	0,51	1,11	-0,14
100001320	0,08	0,51	-0,24	0,45	30,01	30,25	-50,68	-50,44	-0,27	0,03	0,52	0,44	0,88	-0,36
100001321	0,08	0,57	-0,44	0,59	31,08	31,52	-49,88	-49,44	0,70	-1,14	1,13	0,51	1,36	-0,23
100001322	0,06	0,50	0,08	1,08	30,67	30,59	-50,68	-50,76	0,82	-0,74	0,50	0,43	0,58	-0,08
100001323	0,07	0,51	0,66	0,98	31,12	30,46	-49,79	-50,45	0,84	-0,18	0,79	0,46	0,81	-0,02
100001324	0,06	0,50	0,11	0,76	30,36	30,25	-50,51	-50,62	0,11	0,00	0,59	0,37	0,49	0,10
100001325	0,07	0,51	0,03	1,08	31,08	31,05	-50,36	-50,39	0,43	-0,40	0,40	0,27	0,32	0,08
100001326	0,06	0,50	0,87	1,04	31,84	30,97	-49,42	-50,29	0,85	0,02	0,31	0,35	0,33	-0,02
100001327	0,07	0,51	-0,01	0,90	30,63	30,64	-50,40	-50,39	0,22	-0,23	0,19	0,56	0,15	0,04
100001328	0,06	0,51	0,34	0,56	31,09	30,75	-50,28	-50,62	0,58	-0,24	0,30	0,34	0,33	-0,03
100001329	0,08	0,50	-0,14	1,42	30,93	31,07	-50,66	-50,52	0,03	-0,17	0,19	0,56	0,21	-0,02
100001330	0,12	0,70	-0,06	0,83	30,44	30,50	-50,39	-50,33	0,22	-0,28	0,21	0,30	0,27	-0,06
100001331	0,06	0,54	0,60	0,52	30,89	30,29	-49,78	-50,38	0,85	-0,25	0,90	0,54	0,90	0,00
100001332	0,07	0,51	-0,22	1,06	30,28	30,50	-50,65	-50,43	-0,04	-0,18	0,46	0,75	0,42	0,04
100001333	0,07	0,54	0,86	0,68	31,39	30,53	-49,66	-50,52	1,08	-0,22	-0,34	0,49	-0,40	0,06
100001334	0,09	0,58	-0,30	0,70	30,23	30,53	-50,45	-50,15	0,03	-0,33	0,78	0,30	0,79	-0,01
100001335	0,05	0,51	0,08	0,60	30,53	30,45	-50,49	-50,57	0,19	-0,11	0,36	0,53	0,34	0,02
100001336	0,07	0,53	0,20	0,52	30,40	30,20	-50,50	-50,70	0,12	0,08	0,26	0,40	0,25	0,01
100001337	0,08	0,53	0,00	0,66	30,52	30,52	-50,39	-50,39	0,31	-0,31	0,82	0,46	0,84	-0,02
100001338	0,08	0,54	-0,11	0,95	30,75	30,86	-50,64	-50,53	0,46	-0,57	0,56	0,59	0,47	0,09
100001339	0,07	0,51	-0,12	0,49	30,25	30,37	-50,52	-50,40	-0,15	0,03	0,97	0,58	0,99	-0,02
100001340	0,06	0,51	-0,06	1,18	30,28	30,34	-50,51	-50,45	-0,15	0,09	-0,06	0,04	0,06	-0,12
100001341	0,07	0,54	0,51	0,51	30,44	29,93	-50,08	-50,59	0,43	0,08	0,74	0,39	0,79	-0,05
100001342	0,06	0,50	0,51	0,57	31,58	31,07	-49,93	-50,44	0,85	-0,34	0,74	0,49	0,96	-0,22
100001343	0,08	0,58	0,13	0,69	30,93	30,80	-50,20	-50,33	0,33	-0,20	1,09	0,24	1,20	-0,11
100001344	0,07	0,52	-0,37	1,32	29,95	30,32	-51,15	-50,78	-0,22	-0,15	0,83	0,58	0,87	-0,04
100001345	0,08	0,53	-0,78	1,04	29,46	30,24	-51,34	-50,56	-0,79	0,01	0,21	0,64	0,21	0,00
100001346	0,07	0,51	0,10	0,72	30,72	30,62	-50,33	-50,43	0,47	-0,37	0,98	0,46	1,09	-0,11
Maximum	0,12	0,70	0,98	1,42		31,52		-49,44	2,21			0,75	1,36	
Minimum	0,05	0,50	-0,78	0,45		29,85		-50,96	-0,79			0,04	-0,40	
Average	0,07	0,53	0,19	0,82		30,57		-50,48	0,41			0,46	0,63	

Appendix B

Use-cases study

To define a useful set of requirements, the demands of the customers need to be taken into account along with the safety aspects of the solution. The customer demands were gathered primarily in two ways: by asking the sales employees of Bird Control Group what their customers require and by going through the location assessments created by installers over the past years. These location assessments provide useful information regarding the wishes of customers such as the maximum projection distances, possibility of human exposure right next to the bird repelling zone etcetera.

By reviewing 161 different assessments, a good overall idea of the customer's wishes was gained. A summary of the reviewed assessments can be found in figure B.1.

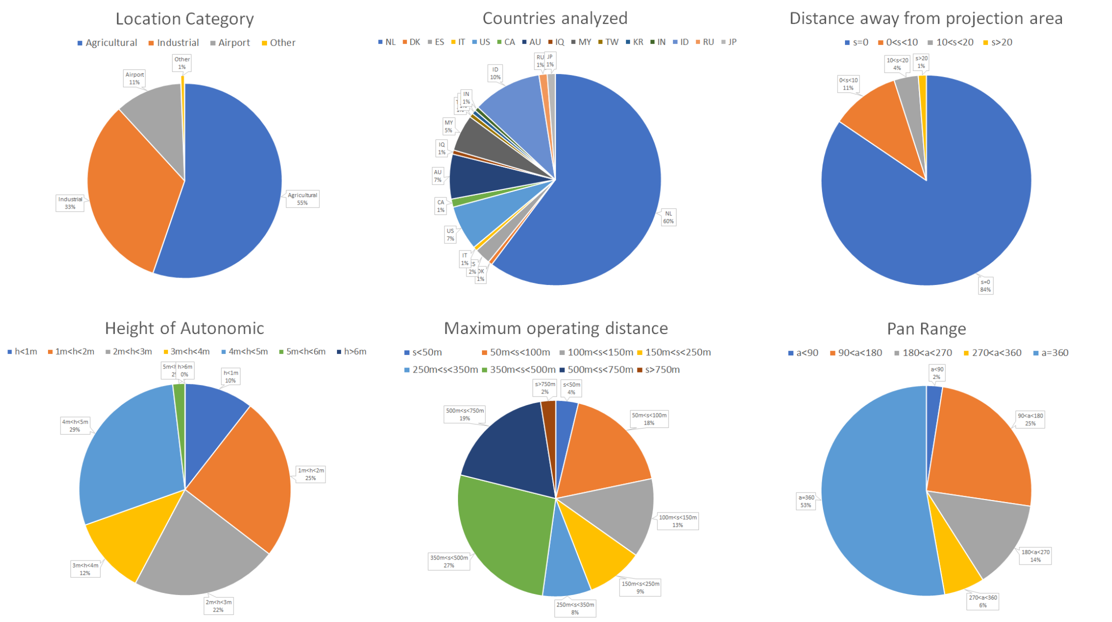


Figure B.1: Pie graphs showing the results of the assessment analysis

From the pie graphs in figure B.1, some of the requirements can be easily distilled. For example, 84% of customers want to be able to repel birds at a distance away from the projection area $s = 0$, meaning they need the laser to come within 5m of the device (5m since this is the 'scaring radius' of the birds). This leads to the requirement of the tilt axis to go from -45deg to 0deg when looked at in combination with the height of installation pie. The height of installation pie indicates that 98% of devices are installed at a height of 5m or less, thus creating the need for the -45deg tilt range. This situation is represented in figure B.2.

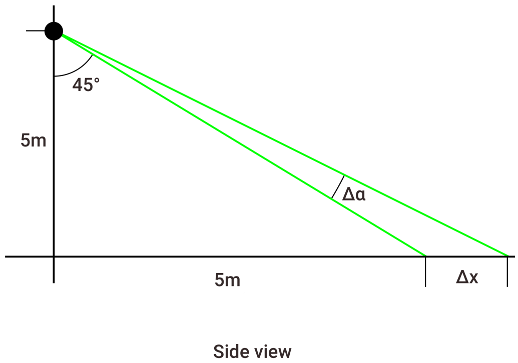


Figure B.2: Schematic view of the tilt requirement distilled from assessments

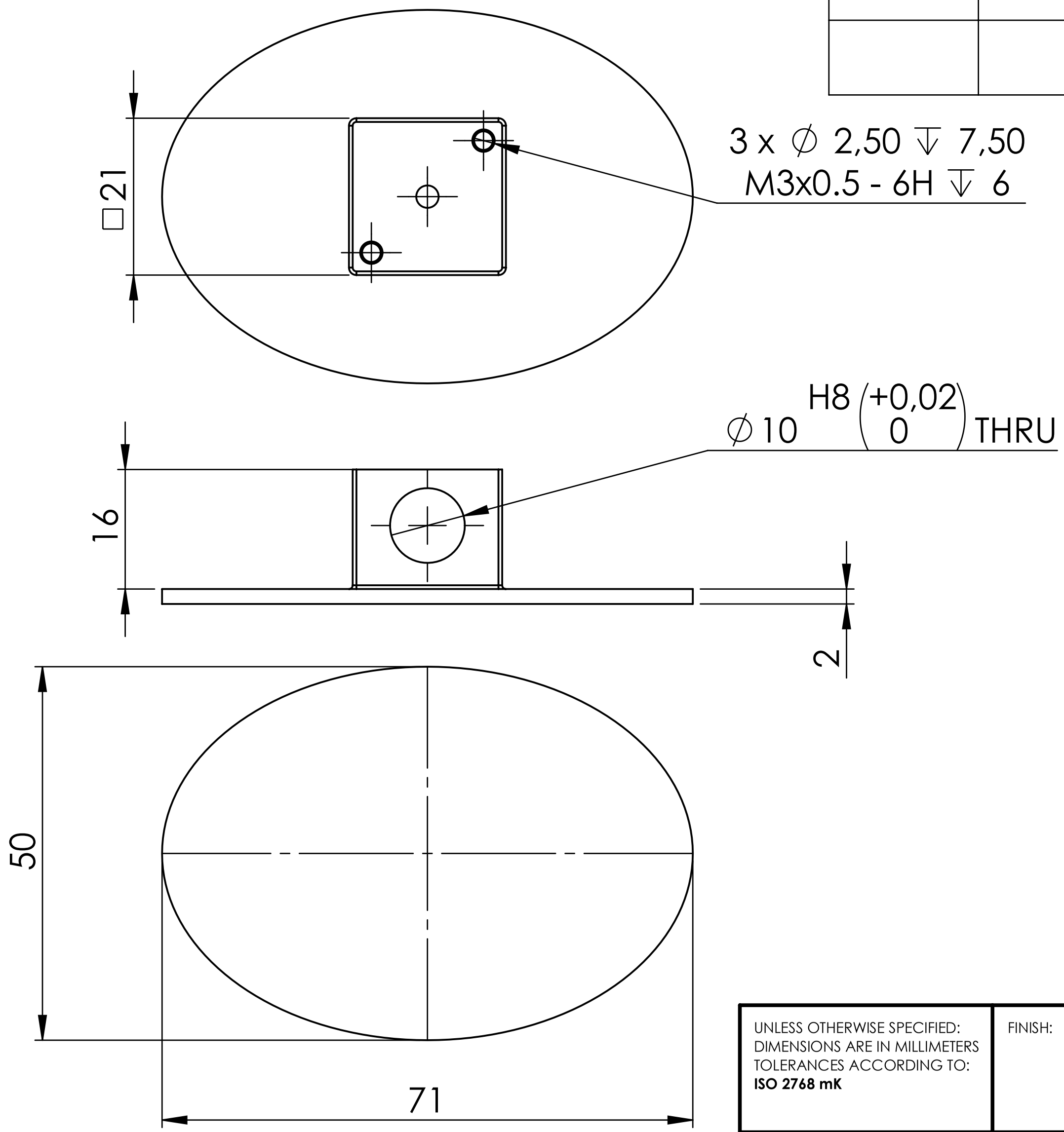
Also, from the 'pan range' assessment analysis, the 360deg range is required by slightly more than half of the customers. This means that the pan range of 360deg is a requirement that cannot be lowered, or more than half of the customers will be disappointed or will not even be interested in this product.

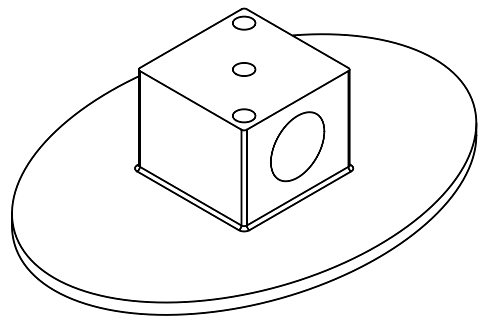
Appendix C

Technical Drawings

Below are some of the technical drawings used to manufacture the prototype. As discussed before, the prototype was manufactured using high-end CNC milling equipment, and thus accuracy and precision of parts can be less than 0.01mm. Some of the drawings have been left out for confidentiality purposes.

Rev	Description	Date	Approved





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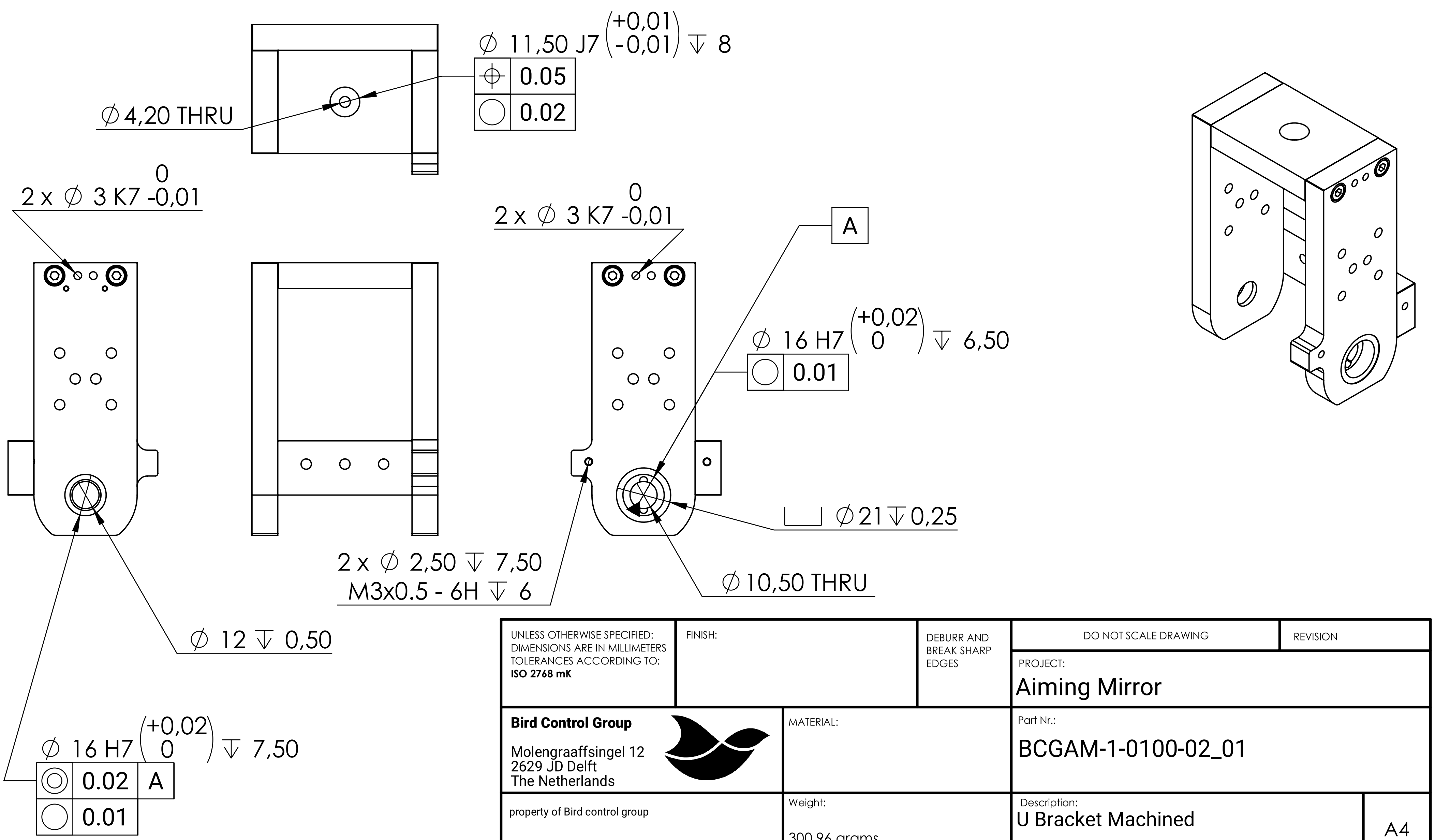
			PROJECT: Aiming Mirror	
Bird Control Group Molengraaffsingel 12 2629 JD Delft The Netherlands	MATERIAL: 6082-T6		Part Nr.: BCGAM-1-0100-01_01	
property of Bird control group Confidential/VERTROUWLIJK	Weight: 27.77 grams		Description: Mirror	A4
	Drawn by: BvH			
Date Created: 15-10-2018 / Last Saved: 15-10-2018	Units: mm/deg		SCALE:1:1	SHEET 1 OF 1

BCGAM-1-0100-01

Rev	Description	Date	Approved



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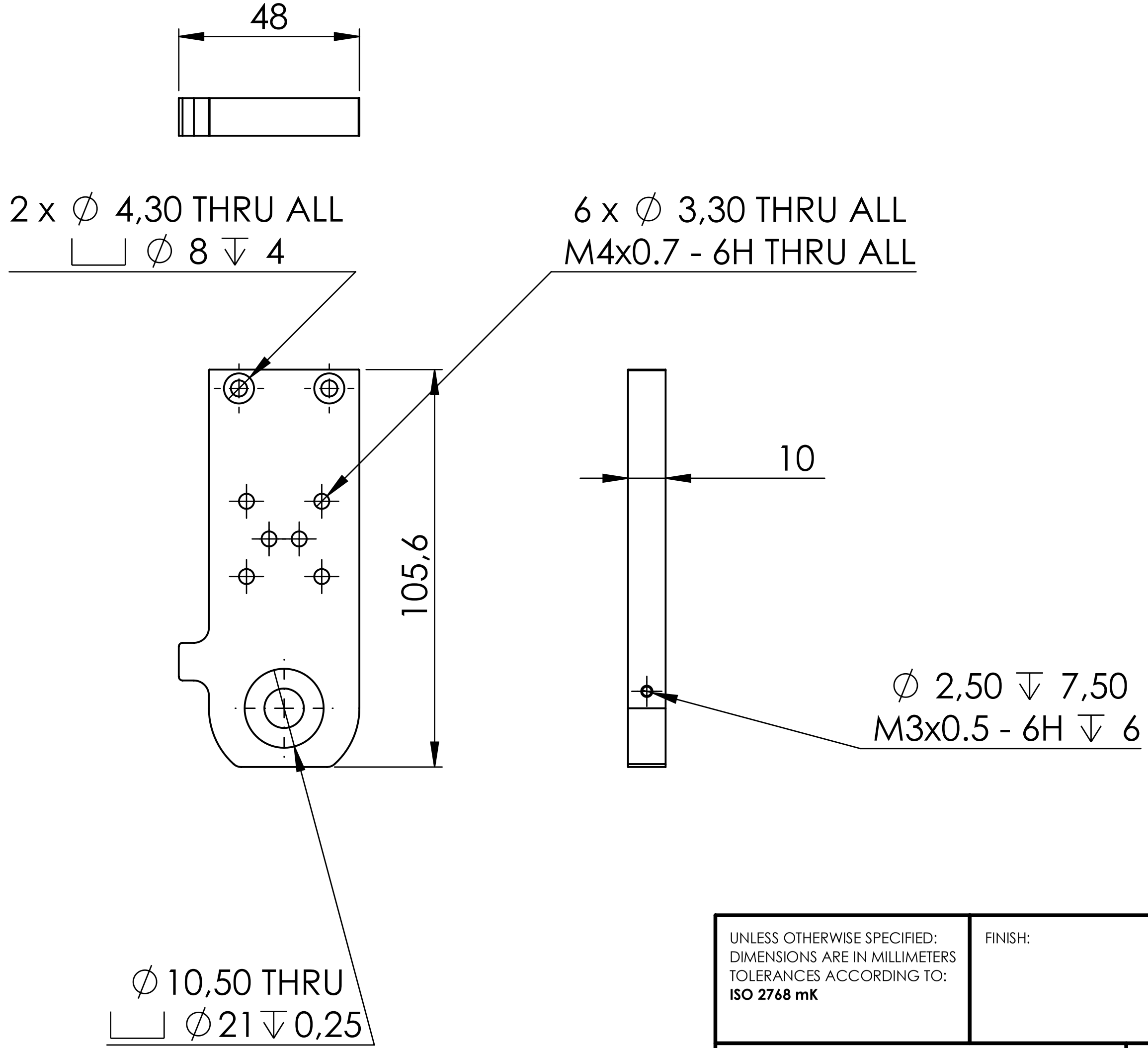
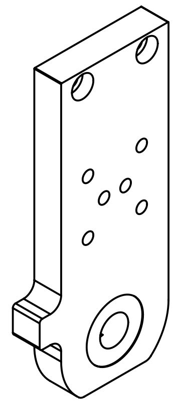
			PROJECT: Aiming Mirror	
Bird Control Group Molengraaffsingel 12 2629 JD Delft The Netherlands	MATERIAL:		Part Nr.: BCGAM-1-0100-02_01	
property of Bird control group Confidential/VERTROUWLIJK	Weight: 300.96 grams		Description: U Bracket Machined	A4
	Drawn by: BvH			
Date Created: 15-10-2018 / Last Saved: 15-10-2018	Units: mm/deg		SCALE:1:2	SHEET 1 OF 1

BCGAM-1-0100-02

Rev	Description	Date	Approved





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ISO 2768 mK

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

PROJECT:
Aiming Mirror

Bird Control Group

Molengraaffsingel 12
2629 JD Delft
The Netherlands

MATERIAL:
6082-T6

Part Nr.:
BCGAM-1-0100-02-01_L

property of Bird control group

Confidential/VERTROUWLIJK

Weight:
108.12 grams

Description:
U Bracket vertical L

A4

Drawn by: BvH

Date Created: 15-10-2018 / Last Saved: 15-10-2018

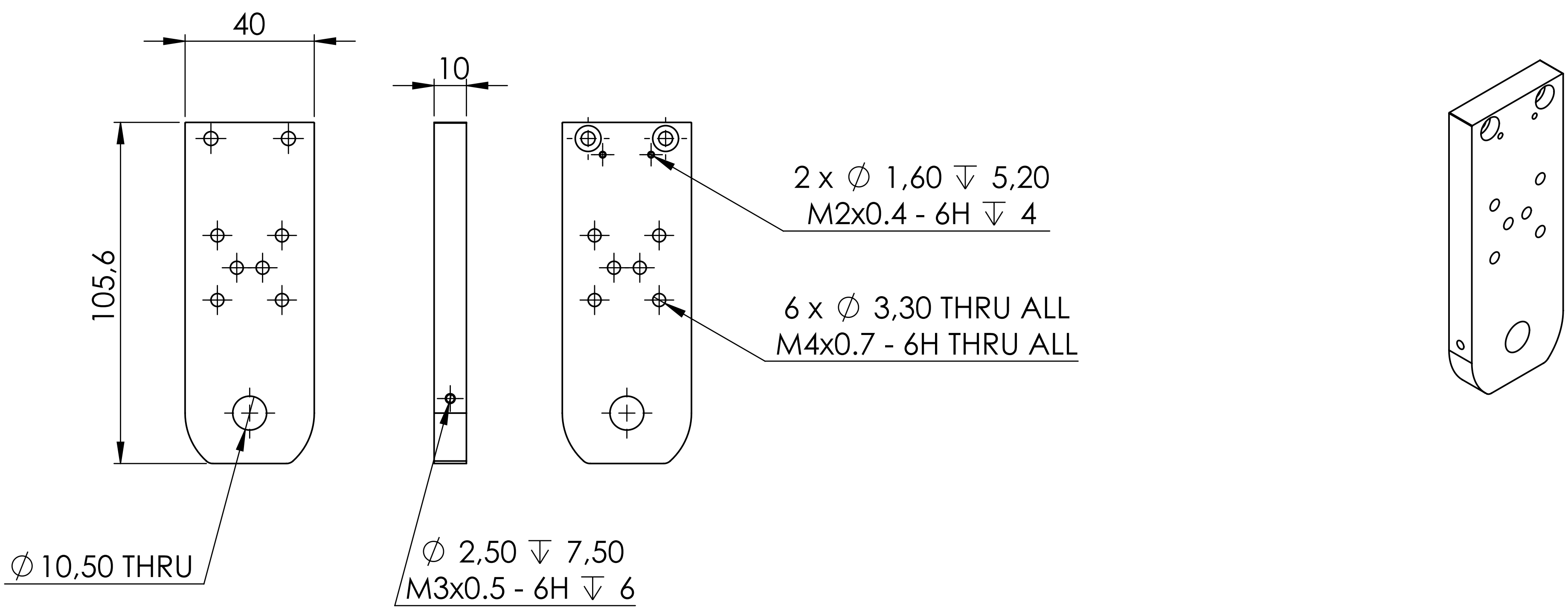
Units: mm/deg

SCALE:1:2

SHEET 1 OF 1

BCGAM-1-0100-02-01

Rev	Description	Date	Approved



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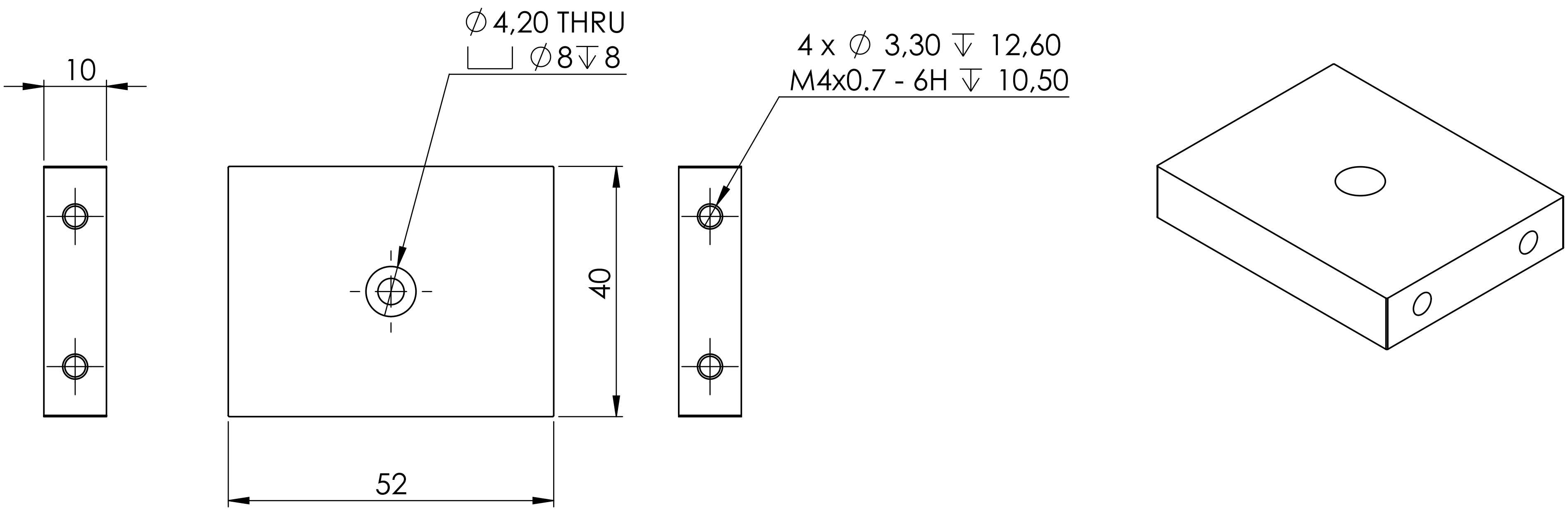
			PROJECT: Aiming Mirror	
Bird Control Group Molengraaffsingel 12 2629 JD Delft The Netherlands	MATERIAL: 6082-T6		Part Nr.: BCGAM-1-0100-02-01_R	
property of Bird control group Confidential/VERTROUWLIJK	Weight: 105.98 grams		Description: U Bracket vertical R	A4
	Drawn by: BvH			
Date Created: 15-10-2018 / Last Saved: 15-10-2018	Units: mm/deg		SCALE:1:2	SHEET 1 OF 1

BCGAM-1-0100-02-01

Rev	Description	Date	Approved



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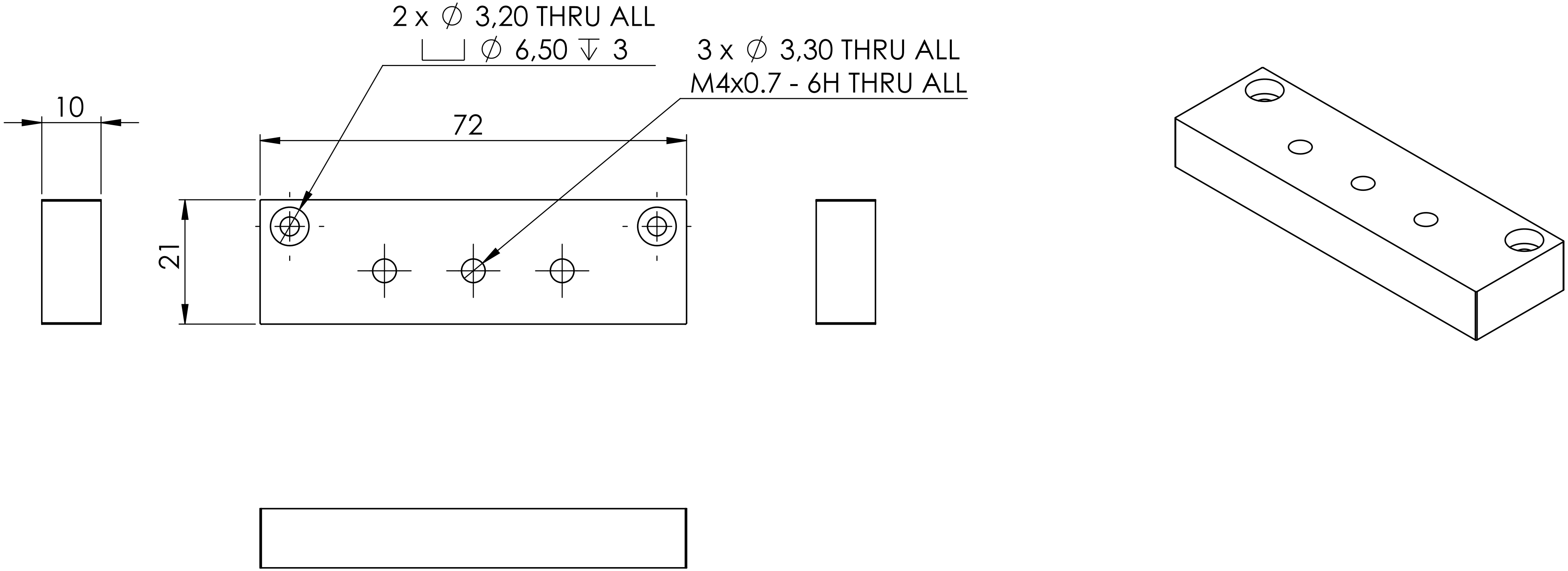
			PROJECT: Aiming Mirror	
Bird Control Group Molengraaffsingel 12 2629 JD Delft The Netherlands	MATERIAL: 6082-T6		Part Nr.: BCGAM-1-0100-02-02_01	
property of Bird control group Confidential/VERTROUWLIJK	Weight: 53.35 grams		Description: Pan axis mount	A4
	Drawn by: BvH			
Date Created: 15-10-2018 / Last Saved: 15-10-2018	Units: mm/deg		SCALE:1:1	SHEET 1 OF 1

BCGAM-1-0100-02-02

Rev	Description	Date	Approved



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			PROJECT: Aiming Mirror	
Bird Control Group Molengraaffsingel 12 2629 JD Delft The Netherlands	MATERIAL: 6082-T6		Part Nr.: BCGAM-1-0100-02-03_01	
property of Bird control group Confidential/VERTROUWLIJK	Weight: 38.96 grams		Description: U Bracket reinforcement	A4
	Drawn by: BvH			
Date Created: 15-10-2018 / Last Saved: 15-10-2018	Units: mm/deg		SCALE:1:1	SHEET 1 OF 1

BCGAM-1-0100-02-03

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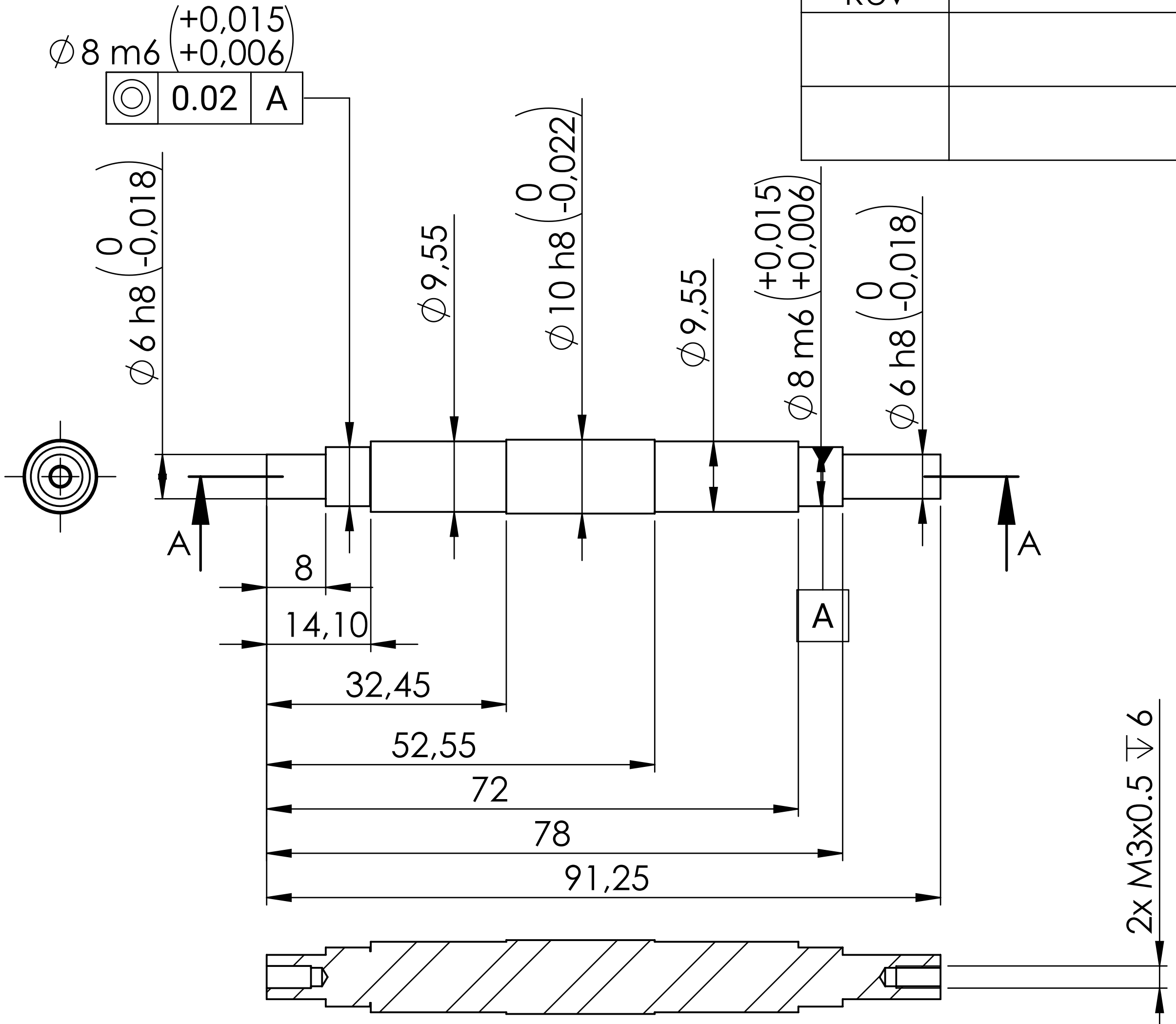

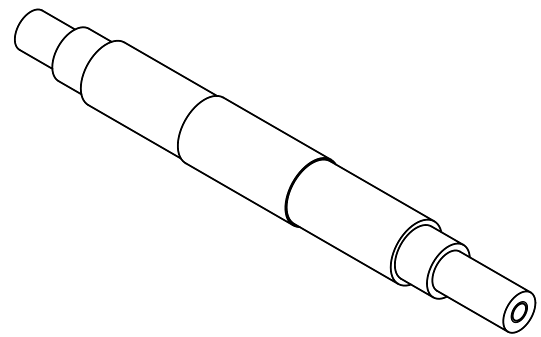

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			PROJECT: Aiming Mirror	
Bird Control Group Molengraaffsingel 12 2629 JD Delft The Netherlands	MATERIAL: AISI 304		Part Nr.: BCGAM-1-0100-03_01	
property of Bird control group Confidential/VERTROUWLIJK	Weight: 43.24 grams		Description: Shaft for tilting motion	A4
	Drawn by: BvH			
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BCGAM-1-0100-03

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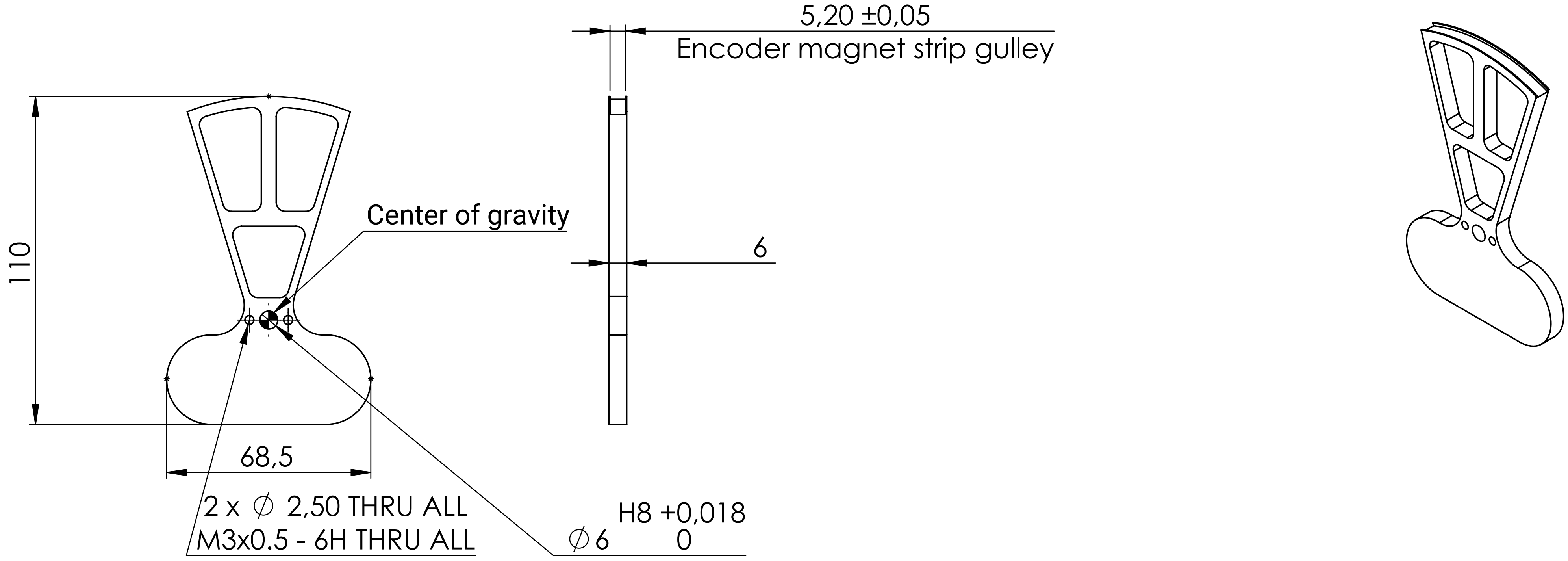

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			PROJECT: Aiming Mirror	
Bird Control Group Molengraaffsingel 12 2629 JD Delft The Netherlands	MATERIAL: 6082-T6		Part Nr.: BCGAM-1-0100-04-01_xx	
property of Bird control group Confidential/VERTROUWLIJK	Weight: 46.33 grams		Description: Measurement arm bracket	A4
	Drawn by: BvH			
Date Created: 16-10-2018 / Last Saved: 16-10-2018	Units: mm/deg		SCALE:1:2	SHEET 1 OF 1

BCGAM-1-0100-04-01

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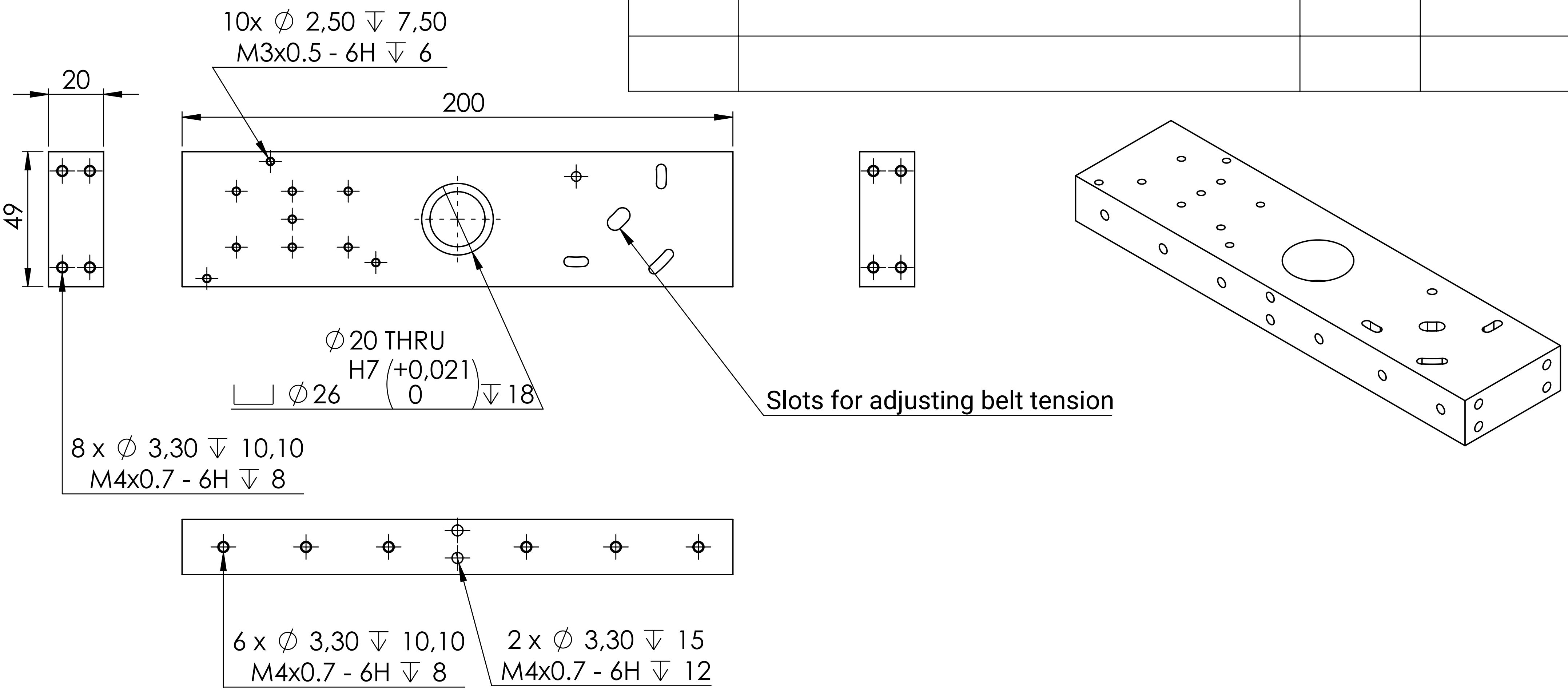

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			PROJECT: Aiming Mirror	
Bird Control Group Molengraaffsingel 12 2629 JD Delft The Netherlands	MATERIAL: 6082-T6		Part Nr.: BCGAM-1-0100-05_xx	
property of Bird control group Confidential/VERTROUWLIJK	Weight: 484.20 grams		Description: Pan Bracket	A4
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BCGAM-1-0100-05

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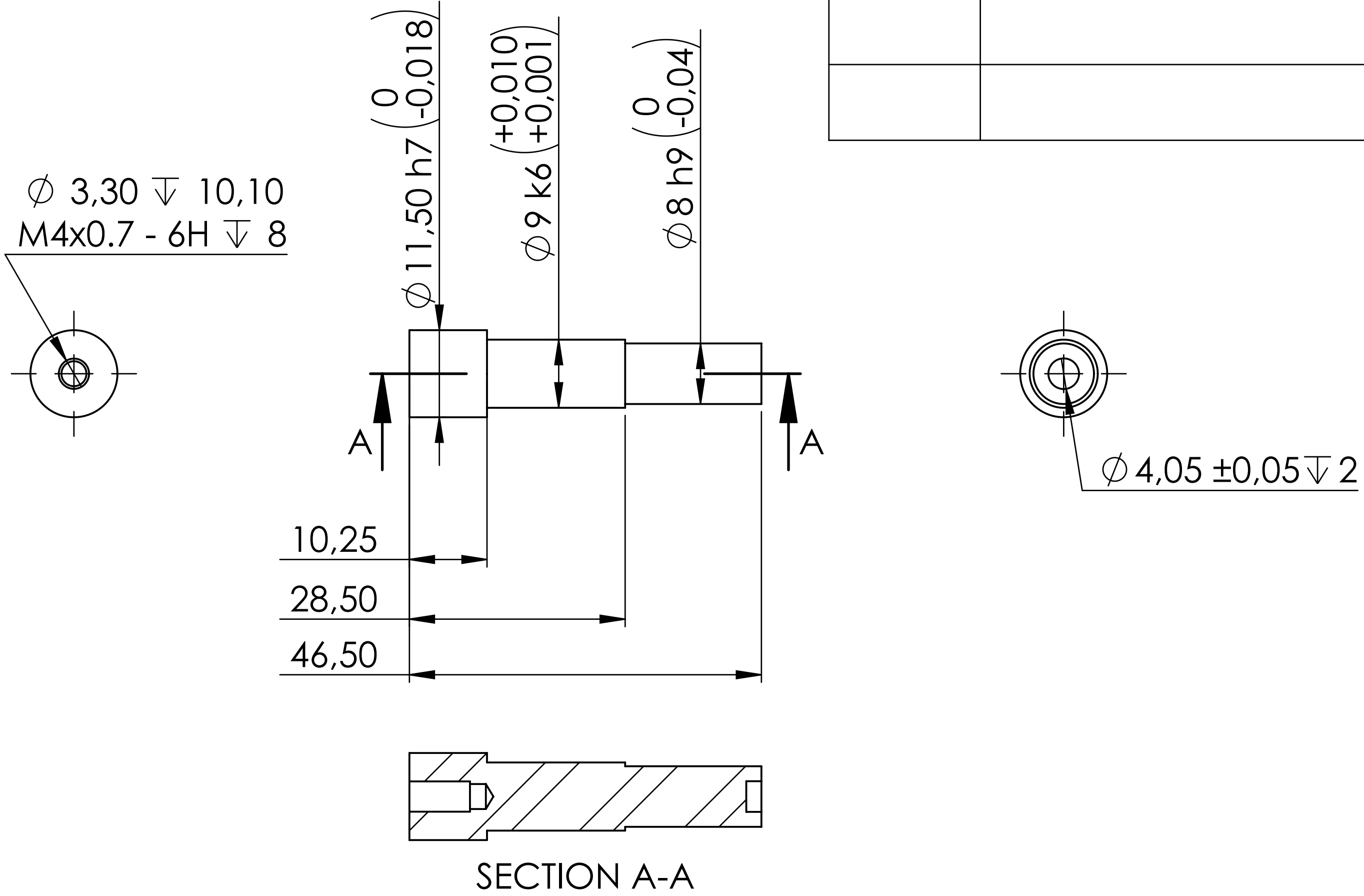

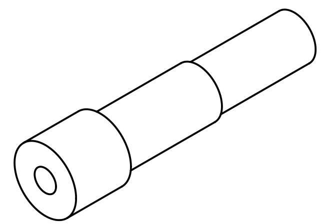

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			PROJECT: Aiming Mirror	
Bird Control Group Molengraaffsingel 12 2629 JD Delft The Netherlands	MATERIAL: AISI 304		Part Nr.: BCGAM-1-0100-09_xx	
property of Bird control group Confidential/VERTROUWLIJK	Weight: 23.87 grams		Description: Pan axis	A4
	Drawn by: BvH			
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BCGAM-1-0100-09

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