Master Thesis

Reducing the need for manual cleaning maintenance of digital surveillance cameras – A conceptual study

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Division of Machine Design • Department of Design Sciences
Faculty of Engineering LTH • Lund University • 2013

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Lund, June 2013

Alfred Ekermo & Victor Norell

Abstract

This report is the result of a Master Thesis project by Alfred Ekermo and Victor Norell. The project was carried out at Axis Communications AB at the Department for Product Concepts and New Ideas, through the Division of Machine Design at the Department of Design Science, Faculty of Engineering (LTH), Lund University.

Axis Communications AB, based in Lund, Sweden, provides high-end network video solutions and digital video surveillance to clients throughout the globe. A major challenge for Axis and its competitors is exterior cleaning maintenance, i.e. how to keep camera lens covers free from contamination. There are many different types and characteristics of contaminants and their impact on optical performance when adhering to different lens cover surfaces vary. There are also environments where active manual cleaning is not an alternative, due to e.g. elevated mounting or surveillance in hazardous areas.

Finding an efficient way of keeping the camera lens covers clean by minimizing the need for manual maintenance would provide Axis with market advantages and an edge towards competitors. The main objective of this thesis was therefore to generate, develop and test innovative concepts on both active and passive automated cleaning solutions to lower the cleaning maintenance frequency for digital surveillance cameras mounted in extremely dusty and/or inaccessible environments.

The project resulted in a deeper understanding on what mechanisms and phenomena that acts when a particle adheres to a surface, and what mechanisms that can be used to facilitate detachment and resuspension of particles. The project also resulted in a number of principle solutions of varying characteristics, one of which, a solution based on building an air barrier in front of the camera to prevent particles from adhering, was deemed to have greater potential and was therefore designed and tested in field on the Axis P5512 PTZ model. The results were satisfactory, as the lens cover of the prototype solution was significantly cleaner than the unprotected reference that was exposed to the same field test.

Keywords: Digital surveillance camera, particle adhesion, contaminants, active/passive cleaning, coatings

Sammanfattning

Den här projektrapporten är resultatet av ett examensarbete av Alfred Ekermo och Victor Norell. Projektet genomfördes på Axis Communications AB, på avdelningen Product Concepts and New Ideas, genom avdelningen för maskinkonstruktion, institutionen för designvetenskaper på Lunds Tekniska Högskola (LTH).

Axis Communications AB, baserat i Lund, Sverige, erbjuder lösningar inom nätverksvideo och digital videoövervakning till klienter över hela världen. En stor utmaning för Axis och dess konkurrenter är utvändigt underhåll, d.v.s. hur man håller linsskyddet rent från föroreningar. Det finns många olika typer av och olika karaktärer på föroreningar och deras inverkan på optisk prestanda vid vidhäftning på olika linsskydd varierar. Det finns även miljöer där manuell rengöring inte är något alternativ, på grund av t ex upphöjd montering eller övervakning i hälsofarliga miljöer.

Att hitta ett effektivt sätt att hålla kamerans linsskydd rent och att minimera behovet av manuellt underhåll skulle innebära marknadsfördelar för Axis och ett övertag gentemot dess konkurrenter. Målet med detta projekt var därför att generera, utveckla och testa innovativa koncept för både aktiva och passiva rengöringslösningar och att på så vis minska underhållsfrekvensen för övervakningskameror monterade i extrema och/eller oåtkomliga miljöer.

Projektet resulterade i en djupare förståelse för vilka mekanismer och fenomen som verkar då partiklar fastnar på ytor och vilka metoder som kan användas för att underlätta lösgörande och bortforsling av partiklar. Projektet resulterade också i ett antal konceptuella lösningar av varierande karaktär, varav en, efter utvärdering och initiella funktionstester, ansågs ha större potential och som därför konstruerades till en prototyp och fälttestades på kameramodellen Axis P5512 PTZ.

Prototypen bestod av en axialfläkt som, genom att skicka luft genom en specialdesignad, ihålig kropp, bygger upp en luftbarriär runt kamerans linsskydd och på så sätt hindrar damm från att sätta sig på ytan.

Prototypen testades i en accelererad testmiljö för att erhålla snabba resultat, då det verkliga fälttestet avses pågå under ungefär ett halvårs tid. Med rätt fläktinställningar och dimensioner på den specialdesignade kroppen som guidade luftflödet erhölls tillfredsställande resultat. Prototypen monterades i testmiljön tillsammans med en oskyddad referenskamera, som blev avsevärt mer kontaminerad än rapportens lösning.

Table of Contents

1 Introduction

This chapter intends to introduce the reader to the background of the project. This is done through a brief presentation of the company Axis Communications AB, the department at which this project was carried out along with a thorough problem formulation. Furthermore, the objective of the project is stated as well as general delimitations to narrow down the areas of focus. The chapter ends with an overview of the method used to achieve results.

1.1 Axis Communications AB

Axis Communications AB (Axis) is a network video and digital video surveillance company, based in Lund, Sweden. Axis was founded by Mikael Karlsson, Martin Gren and Keith Bloodworth in 1984.

At the startup, the main focus of the company was developing print servers, enabling connection of PC printers to IBM networks. Later on, as the Internet emerged and the concept of network access to everything accelerated, the focus was broadened to develop smart network solutions, enabling more and more hardware to be connected simply and economically to IP networks.

In 1996, Axis launched the world's first network camera. The camera featured an integrated web server, allowing video to be viewed remotely from any browser, regardless of its location. This became the starting point in the switch from analog to digital video surveillance and a modern network structure.

Today, Axis has got more than 1400 employees in 40 countries and annual sales at about 4,000 Million SEK (2012) [1].

Axis product catalog for network cameras is categorized into five different groups (figure 1-1) [2]:

1. Fixed network cameras – Traditional design cameras where the viewing direction is set once the camera is mounted.
2. Fixed dome network cameras – Compact cameras with a dome casing, making it more difficult to see where the lens is faced.
3. PTZ cameras – Dome cameras that provide **P**an, **T**ilt and **Z**oom functions, enabling wide area coverage.
4. Covert cameras – Extremely small cameras, designed to blend into various environments for unnoticed surveillance.

5. Thermal network cameras – Cameras that create images based on heat radiation from surrounding objects, making surveillance detection possible around the clock.

Figure 1-1 a) Q1604 fixed camera, b) P33 fixed dome camera, c) Q60 PTZ camera, d) P1204 covert camera and e) Q1921 thermal network camera

The department, at which this project was carried out, is called *Product Concepts and New Ideas (PCNI).* Axis follows a project plan, where upcoming projects are more or less defined over a period of time. The purpose of PCNI is to look beyond that time span and generate conceptual solutions to problems or opportunities. It is also to search for new technology trends, investigate and evaluate how they could be applied on Axis' products in the future [3].

1.2 Problem formulation

As with any other surfaces, camera lens covers attracts different types of contaminants which to different degrees affect the visibility and the optical performance, depending on characteristics and concentrations. Cleaning and maintenance of surveillance cameras today is mainly a manual chore and automated cleaning systems are not common.

Manual cleaning is a cheap and simple alternative when the cameras are easily accessible, e.g. in environments such as retail stores or public transportation vehicles. It is also an economic alternative in clean environments where the need for frequent maintenance is low. However, there are several environments, hereafter referred to as *extreme environments*, where cameras are mounted in such a way that it prevents manual cleaning. Such environments are e.g.:

- Critical infrastructure or highways surrounding major cities where cameras are often mounted with high elevation on poles or masts.
- Hazardous rooms, chambers, shafts or other areas where humans are prohibited to sojourn.
- Wind tunnels, mining shafts and other environments where the contamination is extensive and continuous, requiring a very high cleaning frequency.

Manual cleaning in such types of environments are often complex, expensive and/or time consuming, being that they require e.g. special equipment, demounting or other actions. Therefore, it has become a major challenge for the video surveillance industry to develop an automated solution or an alternative way of cleaning cameras in these extreme environments [4].

1.3 Objective

The objective of this project is to generate, develop and test (by simulating and/or field testing a prototype) one or more principle solutions of lowering the maintenance frequency for cameras mounted in extreme environments.

Note that the objective is not necessarily to provide a detailed design that can be implemented and placed into service immediately without any adjustments, but rather to investigate the efficiency of principle solutions, such as cleaning mechanisms or other possible techniques in a conceptual manner [4].

1.4 Delimitations

Because of the complexity and diversity of different particles and contaminants and how they behave when adhering to surfaces, finding a universal solution that can handle any environment without any supplies, other than electricity, is unrealistic. Being that the extent of the project is limited to 20 weeks, it is therefore necessary to narrow down and specify what environments are the most crucial to focus on.

After gathering and reviewing opinions from representatives of different departments at Axis, two specific environments were chosen as starting points for strategic reasons:

- Mining industries, mainly open pit mining, where contaminants mostly consist of mechanically quarried, dry, relatively large mineral dusts but also exhaust fumes from diesel vehicles and other machinery.
- City surveillance and surrounding infrastructure where contaminants mostly consist of combustion particles such as e.g. exhaust fumes and asphalt deposits.

It is assumed that cameras mounted for mining surveillance have access to common industrial supplies such as water- and compressed air piping, while cameras mounted in urban regions only have access to electricity. Mining industries are considered to be the primary environments, while city surveillance is secondary, i.e. the main focus will be mining industries [4].

The solution(s) should also primarily be focused on dome cameras for several reasons:

- Dome cameras are popular, meaning there are many potential units to protect.
- There are fewer cleaning solutions for dome cameras among competitors, due to its more complex shape.
- A functioning solution for a dome camera is more likely to work on a fixed camera than the other way around, again due to the dome’s higher shape complexity.[4]

1.5 Method

The course of action for the project is roughly following the steps in figure 1-2. Complete project time plans (prediction and outcome) can be viewed in Appendix B.

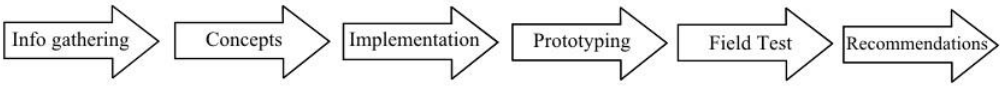

Figure 1-2 Method flow chart

The initial phase mainly consists of gathering information and getting familiarized with important aspects of the problem formulation, e.g. particle adhesion theory. A market analysis is also of great importance to understand what has been done already, how existing solutions work and to what degree of success.

The concept phase includes everything from initial brainstorming and other generative methods to evaluation and selections for further testing. To weed out less good or unrealistic ideas from good ones, the methodologies from Ulrich and Eppinger's book *Product Design and Development* (2012) [5] will be used, to create well-founded decisions through a systematic manner. This will also be done through evaluating inputs from representatives from different departments at Axis.

Simplified prototypes will then be built of the chosen principle solutions. The most successful concept will then be implemented and integrated with a subject camera model, using gathered theoretical and empirical data.

The prototype(s) will then be built, using a suitable manufacturing method, and tested in field, through mounting in a suitable environment. While the simplified prototype version from the previous step is tested to analyze cleaning abilities, the more detailed prototype version is also intended to analyze e.g. consequences on optical performance.

The results from the field tests are evaluated. Any flaws are analyzed and possible, negative short term and long term effects are also taken into consideration. The final step will be to provide final recommendations which discuss everything from necessary preconditions and supplies to potential long term effects [4].

1.6 Figures

Figure references and other information on the pictures in the report are listed in the Figure credits, pp.91-98.

2 Theory

This chapter intends to introduce the reader to some basic facts about the particles and aerosols in question for the delimited environments. It also discusses the phenomenon behind particle adhesion and detachment, i.e. how particles stick to each other and to surfaces and how they can be removed.

2.1 Aerosols

An aerosol is defined as a suspension of solid or liquid particles in a gas, usually air [6, p.2]. Basically all air surrounding us contains microscopic particles of different size and concentration. The origin of these particles varies from natural sources (e.g. volcanic eruptions, pollen or sand storms) to anthropogenic sources (e.g. vehicle emissions, power plant emissions or dust from mining industry).

The shape of liquid particles is always spherical, whereas shapes of solid particles are vastly different and cover three general classes, depending on their dimensions in a three dimensional space.

- *Isometric particles* have roughly the same dimensions in all three directions, e.g. spherical, square or similarly shaped.
- *Platelets* have two larger dimensions and a third, smaller one. Leaves, flakes, disks and other shapes fall into this section.
- *Fibers* have two smaller dimensions and a third, larger one. Particles in this section have shapes like needles, prisms or threads [6, p.4].

Particulate matter (PM) in aerosols is commonly measured by its *aerodynamic equivalent diameter* (d_a) since the shape and density of different particulates varies vastly. A particle with an aerodynamic diameter of 10 µm is going to have the same aerodynamic characteristics as a sphere with a diameter of 10 µm and a density of 1 g/cm^3, which is defined as a standard density. There are of course many other ways to determine the equivalent diameter of an aspheric particle. *Stoke's diameter* (d_s), for instance, uses the same parameters as the aerodynamic diameter; however the original density is used instead of normalizing it to standard density. Using this measurement of course requires a lot more knowledge about the composition of the particles observed [7, pp.51-55].

Particulates suspended in gas generally have an aerodynamic diameter of 0.01-100 µm. The lower limit is determined by the transition from molecule to particle. Particles with diameters larger than 100 µm tend to have problems staying airborne, will eventually fall to the ground within a relatively small amount of time and are usually not considered when talking about aerosols. Even particles larger than 10 µm have limited time in the air and will eventually settle, but may be of significance when observing particle dispersion close to the source of emission [7, p.8].

The U.S. Environmental Protection Agency (EPA) has defined four standard terms for categorizing particulates according to size of PM as follows:

Table 2-1 Grouping of particulates by size according to the U.S. EPA

US-EPA term	Aerodynamic diameter	Abbreviation
Supercoarse	$d_a \geq 10$ µm	TSP[1] (< 100 µm)
Coarse	$10 > d_a \geq 2.5$ µm	PM_{10}
Fine	$2.5 > d_a \geq 0.1$ µm	$PM_{2.5}$
Ultrafine	$d_a < 0.1$ µm	$PM_{0.1}$

An illustrative size comparison is displayed in figure 2-1.

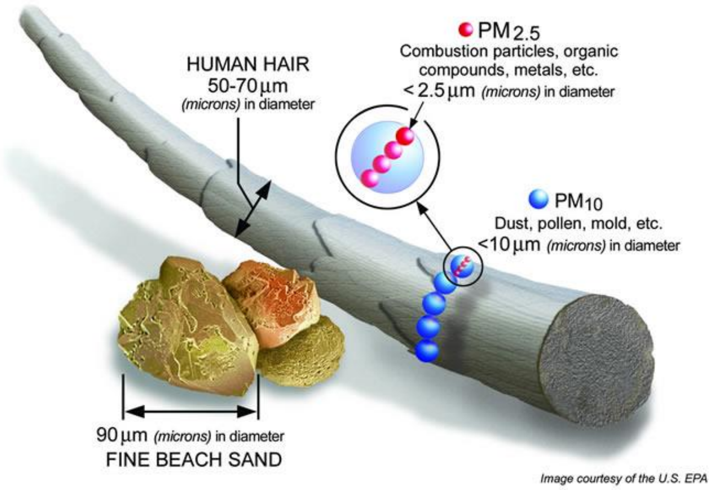

Image courtesy of the U.S. EPA

Figure 2-1 PM size comparison from U.S. EPA

An aerosol containing particulates is always in motion, as all molecules with temperatures exceeding absolute zero have some kinetic energy. The movement caused by kinetic energy causes constant collisions between molecules, particles and obstacles. Some common mechanisms are briefly described below.

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[1] TSP = Total Suspended Particulates; All particulates smaller than 100 µm

- *Impaction* occurs when there is a sudden change in the direction of the aerosol flow. Because of the inertia of larger particles, these tend to continue on the same trajectory as before, causing an impact. The inertia of particles is used in both cyclones and impactors, to separate larger particulates from the aerosol [8, pp.100-101].
- *Diffusion* occurs when constant collisions between molecules in an aerosol gas cause irregular movement of the particles, called Brownian motion. The random motion pattern of the particles may lead to collisions with obstacles or surfaces, where adhesion is possible. Because of the Brownian motion, an aerosol with an uneven concentration of particles in a gas will eventually form a uniform concentration [7, pp.154-163].
- *Thermophoresis* occurs when the particle reacts to a temperature gradient. As the particles heat up near a hot object, the thermal energy acquired translates to kinetic energy causing greater movement. The slower moving particles are then reflected away from the hot area when colliding with the fast moving particles. Thermophoresis is the reason dust marks are formed on walls containing water piping [7, pp.171-173].
- *Sedimentation* describes the settling of particulates as a response primarily to gravitational force, but may also occur through centrifugal or electromechanical forces. Larger particles with greater mass settle more rapidly than finer particles. When a surface or an object prevents particles from settling, adhesive forces between the macroscopic object and the particle take over. Adhesive forces between particulates combined with the force of sedimentation will eventually cause several layers of particles on the object [8, p.93].

2.2 Adhesion of Particles

As particles stick to a surface, it seems virtually impossible to get the surface clean. This is because the forces in action form a combined adhesive force, which on a microscopic level is dominant compared to e.g. gravity. Therefore, it is possible for dust to stick to surfaces facing downwards. Large surfaces aren’t the only areas where particle adhesion is occurring. Particles also stick to each other and form agglomerates, i.e. clusters of particles through the adhesive forces. The agglomerates are sometimes regarded as particles with larger aerodynamic diameters.

In the process of particle adhesion, several forces interact to generate a joint adhering force. Van der Waals forces, electrostatic forces and, when in a humid environment, capillary forces work together to make the adhesion possible. Hence, the total adhesive force may be described as a sum of the previously mentioned forces.

$$F_{ad} = F_{vdW} + F_{ES} + F_{cap} \tag{2-1}$$

2.2.1 Van der Waals forces (F_{vdW})

The van der Waals forces are generated through the random movement of electrons in any material. Due to the randomness, there is always a momentary polarity present in the substrate i.e. one side is positive, while the other is negative. The same phenomenon occurs within the particulate which causes attraction. Van der Waals forces between a flat surface and a spherical particle are estimated using

$$F_{vdW} = \frac{A * d}{12 * x^2} \tag{2-2}$$

where A represents the Hamaker constant which varies depending on the material, d is the average diameter of the particle and x is the average distance between particle and surface. These forces quickly decrease with increasing separation distance and are negligible at a distance of a few molecular diameters [7, p.142].

2.2.2 Electrostatic forces (F_{ES})

Most particles larger than 0.1 µm carry an electric charge due to either diffusion between different particles or as a result of the creation of the particulate itself. Particles with only positive or negative charges repel each other, while particles of different type charges attract each other. Since most non-conductive surfaces carry charges of some form, particulates carrying opposite charges are attracted to the surface. The electrostatic forces are estimated using

$$F_{ES} = \frac{K_E * q^2}{x_q^2} \tag{2-3}$$

where K_E is a constant of proportionality, q represents the net charge and x_q is the separation distance of opposite charges. Empirical approximations show that the average number of Boltzmann equilibrium charges is proportional to the square root of the particle diameter, $\sqrt{d}$ [9].

2.2.3 Capillary forces (F_{cap})

Capillary forces occur as liquid is enclosed between the particle and the surface (figure 2-2). In a humid environment, liquid (e.g. water) molecules are clustered with air particulate. As the particle is pushed against the surface, the liquid forms a meniscus between the particle and the surface, increasing the total adhesive force. The equation estimating capillary forces between a sphere and a flat surface with a relative humidity greater than 90% is given by

$$F_{cap} = 2 * \pi * \gamma * d \tag{2-4}$$

where Υ denotes the surface tension of the liquid and d the diameter of the particle or in case of particles with rough, aspherical surfaces, the diameter of the liquid curvature [7, p.143].

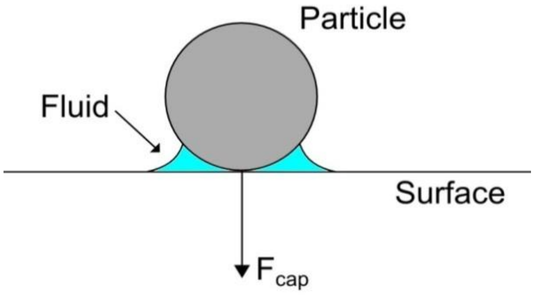

Figure 2-2 Illustration of capillary force

The formulas described in section 2.2.1 through 2.2.3 are, however, greatly simplified and only apply in vacuum environments, with spherical particles on completely flat surfaces etc. They are used to estimate the forces in play and are then verified by empirical tests described in section 2.3. In reality, particles and surfaces have asperities and have irregular shapes, causing only a few contact points. However, over time the adhesive forces may cause flattening of the surfaces, which increases the number of contact points and thus the total adhesive force. Normally van der Waals forces and capillary forces are greater than the electrostatic forces, with the exception of particles containing high charges.

Corn (1961) suggested an empirical experiment based formula specific to hard materials, clean surfaces and particles of glass and quartz at 25ºC and particle diameters larger than 20 µm, describing the total adhesive force on a single particle [7, p.144]:

$$F_{adh} = 0.063 * d_p * [1 + 0.009 * (\%RH)] \tag{2-5}$$

where the total adhesive force F_{adh} is in Newtons, the particle diameter d_p in meters, and the relative humidity $\%RH$ in percent.

2.3 Other adhesion mechanisms

The mechanisms described in the previous section are the main components of particle adhesion. Adhesion in general is possible using many other mechanisms, which are briefly presented below [10]:

- Mechanical adhesion, where voids of the surfaces are filled with adhesive material, interlocking the two. Velcro and textile glue are examples of mechanical adhesion.
- Chemical adhesion, which occurs when surface atoms of two substrates form a chemical bond of ionic, covalent or hydrogen type. This mechanism requires small distances between the surfaces, as chemical bonds are effective over nanoscale distances. Examples of chemical adhesion are certain types of glue.

- Diffusive adhesion, which often occurs when both materials are soluble in each other and heat or pressure is involved in the adhesive process. Sintering of ceramic or metal powder is an example of diffusive adhesion.

2.4 Detachment and resuspension of particles

Depending on the impact velocity and impact angle of the particles approaching an object, they may not always stick to the surface. A higher velocity or an impact angle approaching the tangent of the surface will make the particle bounce off the substrate [11].

However, if particles do stick to the substrate, there are several ways to force separation. The acting adhesive forces are, as mentioned earlier, quite large and hard to overcome. Particles can be removed by contact, such as brushing or wiping, or using non-contact cleaning such as vibration, air/ water jet or rotation. A contaminated surface requires extremely high removal forces to once again become completely free from contamination.

To estimate the removal force empirically, the most common removal methods are:

- *Rotation* – Contaminated disks are placed facing away from the rotation center on a centrifuge. The disks are then rotated at different angular velocities for a fixed amount of time. After each cycle, the disk is examined for removed particles [7, p.144].
- *Air* – An air jet is used to blow air at a contaminated surface for a fixed amount of time. The air velocity is gradually increased to detach all contaminants [7, p.145].
- *Vibration* – A vibration inducing device is used to shake a contaminated surface, either horizontally or vertically. To get any significant results, this method requires extreme accelerations, preferably above 1000 times the gravitational acceleration [12].

While the adhesive forces are proportional to the first order of the particle diameter, removal forces are proportional to the second and third order. Accordingly finer particulates are harder to separate than coarser. A comparison between removal forces on spherical particles made by Hinds [7, p.144] is shown in Table 2.

Table 2-2 Comparison of adhesive, gravitational and air current forces on spherical particles of standard density

		Force (N)	
Diameter (µm)	**Adhesion[2]**	**Gravity**	**Air Current (10 m/s)**
0.1	10^{-8}	$5*10^{-18}$	$2*10^{-10}$
1.0	10^{-7}	$5*10^{-15}$	$2*10^{-9}$
10	10^{-6}	$5*10^{-12}$	$3*10^{-8}$
100	10^{-5}	$5*10^{-9}$	$6*10^{-7}$

To get a complete separation, particles also have to be transported away from the surface. This is called *resuspension* and is accomplished using one of three models for separation [13]:

- *Lift-off*, when the normal component of the applied force exceeds the pull-off force, the particle is lifted off the surface.
- *Sliding*, when the tangential component of the applied force exceeds total normal force multiplied by a friction coefficient, the particle begins to slide.
- *Rolling*, when the total torque about a pint on the edge of the contact circle is equal to zero, the particle will begin to roll around that point and thus off the surface.

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[2] Calculated using equation (2-5) with 50% RH

3 Market analysis

This chapter intends to introduce the reader to the major actors in the digital video surveillance industry and above all, what solutions they have come up with to the current date, along with their pros and cons. It also discusses some of the less conventional solutions from minor, niched companies.

3.1 Major actors in digital video surveillance

There are no other Scandinavian companies that have specialized in digital video surveillance. Most actors are based in Germany, USA and East Asia.

Some of the major global actors can be viewed in Table 3-1 [14].

Table 3-1 Major actors in digital video surveillance

Continent	Country	Company
Asia	Japan	Canon
		Sony
		Panasonic
	South Korea	Samsung
North America	USA	Pelco
		Cisco Systems
Europe	Germany	Bosch
		Mobotix
	Italy	Videotec

3.2 Common solutions

When searching for surveillance camera cleaning solutions, the most common methods to come across are a) manual cleaning and b) wiper cleaning:

a) As a great majority of surveillance cameras are mounted in areas where they are easily accessible and/or not exposed to heavy, continuous contamination, manual cleaning is still very common as it is economically viable, especially in countries where labor costs are low [15]. There are products developed to facilitate manual cleaning, e.g. the DomeWizard^{TM} (figure 3-1) from the company Dotworkz [16], which is a microfiber cloth, attached to elastic arms and mounted onto a telescopic shaft to enable cleaning of elevated dome cameras from the ground. It is not, however, a realistic option for this report to provide a cleaning solution of manual nature, with reference to the problem formulation.

Figure 3-1 DomeWizard from Dotworkz

b) The most common automated solution is wiper cleaning. Several major actors, e.g. Pelco and Bosch, offer solutions for fixed cameras that can be compared with car windshield wipers (figure 3-2), which is based on a mechanism of removing dirt with an elastomer material, mostly in combination with water to “soften” the particles and reduce the risk of scratching the surface. The approach has significant advantages, being that the cleaning mechanism can be activated remotely, but it also includes drawbacks and is so far limited to fixed cameras as there are few or no wiper solutions available for dome cameras that have reached a market breakthrough. Axis does not offer wiper accessories for fixed cameras in their current product catalog.

Figure 3-2 Pelco camera with windshield wiper

3.3 Original solutions

Among Axis' competitors, there are few other cleaning solutions besides the two mentioned in the previous section. The exception is a fixed camera housing produced by Videotec from Italy (figure 3-3). In front of the lens window are two windings connected with a roll of plastic film (Mylar, a type of PET). The film is the medium in contact with the surrounding environment and thus the surface that is exposed to contamination. As the film is dirty, the windings rotate to replace the dirty film with a new stripe of clean film. The housings are designed to hold 350 steps of film, after which the plastic film roll needs to be replaced [17].

Figure 3-3 Film roll camera housing from Videotec

Another solution that stands out is produced by Pelco and Wizebox CCTV Equipment from Russia. While Pelco have been mentioned before as a major actor in digital video surveillance, Wizebox is not an actual competitor to Axis as they have specialized in external housings and additional equipment accessories and not in the camera technology.

Along with some selected housings, intended for dirty environments, Pelco and Wizebox offer a pneumatic blend (figure 3-4) in the shape of a ring with multiple nozzles aimed inwards, worked out in order to prevent adhesion of contaminants by creating an air barrier in front of the lens with the supply of compressed air [18]. The backside again, however, is that the solution is only compatible with fixed cameras, not dome cameras.

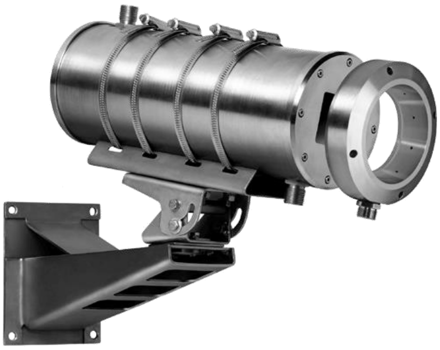

Figure 3-4 Pneumatic blend from Wizebox

4 Primary concept generation

In this chapter, a wide variety of conceptual solutions are generated through various methods. The generated concepts are categorized based on their nature and characteristics. A brief theoretical review is given for each category to explain the underlying principles of each concept. Descriptions, pros, cons, limitations and requirements are listed for each concept to provide the reader with all aspects of significance. Concept sketches are designed using the software Inkscape.

4.1 Generating methods

When generating primary concepts at an initial stage, it helps to keep an open mind and to let imagination run wild and not to limit creativity to concepts that feel completely realistic. An unconventional solution could very well be the most effective choice.

To achieve a broad spectrum of conceptual solutions, several generative methods of different characters were used. The aim was to cover every imaginable category of cleaning, i.e. cleaning methods based on a certain supply or mechanism. The main methods used were:

- Brainstorming through internal discussions. Mindmapping was used to get a good overview of the nature of generated concepts.
- A workshop was held with representatives from different departments at Axis to get inputs and ideas from different views of perspective.
- Benchmarking, not only towards competitors and how their solutions function, but also to cleaning solutions in general, regardless of business.
- The *XYZ*-method which consists of letting *X* persons generate *Y* concepts and describe them on a piece of paper through text and illustrations. After *Z* minutes the papers are passed forward to the next person, and the cycle repeats [19].

These generative approaches led to a number of conceptual solutions of varying characters, all explained in sections 4.2-4.6.

4.2 Coating concepts

4.2.1 Theory

Coatings are generally passive methods of cleaning, i.e. their function is to repel contaminants, rather than to remove them and/or to facilitate for other cleaning methods. Repellent behavior is obtained by eliminating the impact from the different adhesive forces (see chapter 2 Theory, pp. 7-9). For this application, the coating needs to be "invisible", to not interfere with the optical performance. This enables combinations with other cleaning methods.

A couple of common phenomena to come across when searching for dirt repellent coatings are those of hydrophobia and hydrophilia, which both explain the different characteristics of how water behaves when coming in contact with another material. As the words imply, hydrophobic materials repel water (greek hydros=water and phobia=fear) [20] while hydrophilic materials attracts water (philia=love) [21].

A simple way of establishing the hydro characteristics of a material is by measuring the angle θ that a water droplet forms with the surface plane (figure 4-1). A high θ implies hydrophobic characteristics and oppositely, a low θ implies hydrophilic characteristics [20, 21].

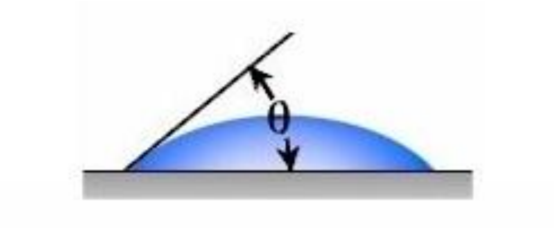

Figure 4-1 Water droplet contact angle θ

Superhydrophobic ($\theta > 150°$) or superhydrophilic ($\theta < 10°$) [20, 21] surfaces are often referred to as self-cleaning. They clean automatically when coming in contact with water, either by forming close to spherical droplets that rolls off the surface, picking up and carrying away contaminants (superhydrophobic) or by "sinking" into the surface, forming a droplet free water layer of uniform thickness that rinses away contaminants (superhydrophilic).

Superhydrophobia in nature is known as the "lotus effect", as lotus leaves display extremely hydrophobic characteristics (figure 4-2). Attempts to create superhydrophobic surfaces have mainly consisted of trying to imitate the lotus leaf's surface structure, usually by adhering Silica (Silicon dioxide, SiO_2) nanoparticles to a low friction surface (e.g. PTFE, commonly known as Teflon) [22].

Figure 4-2 A superhydrophobic lotus leaf

Superhydrophilia is usually obtained by coating a surface with Titania (Titanium dioxide, TiO_2) and subjecting it to light irradiation. TiO_2 can also act as a photocatalyst, which allows decomposition of organic compounds when exposed to UV radiation [23].

Another similar phenomenon is that of the Namib Desert beetle. The beetle dwells in extremely arid areas and is able to survive because of a uniquely developed attribute. Its back surface consists of both hydrophobic and hydrophilic areas. By facing its back towards early morning fog breezes, micro droplets are “pushed” by the hydrophobic surfaces towards the hydrophilic and are then rinsed down towards the mouth. By transferring this structure to a surface, water could theoretically be controlled to keep away from unwanted areas, e.g. where a camera lens is faced [24].

If water supply is not an option, however, there are other means to facilitate cleaning and lower the adhesive force components. Van der Waals forces are inevitable and capillary forces only exists where there is humidity, but electro-static forces are controllable as they only appear where there are static tensions. Tension build-ups can be prevented by making the exposed surface electrically conductive. If there is no electro-static component active on the adhesive force, then logically particles are less likely to adhere and/or are easier to detach.

4.2.2 Concepts

Superhydrophobic coating

Description – By applying a water repellent coating, water that hits the dome surface form droplets (figure 4-3) that gather contaminants and roll of.

Commentary – So far, attempts to create superhydrophobic surfaces have not been perfected enough to generate a commercial breakthrough. Commercial products may function for a short period of time, but get worn out, losing the superhydrophobic abilities [25]. In theory however, the method is appealing as it would only require small amounts of water to keep the dome clean, meaning the dome would be maintenance free if mounted outside with occasional precipitation.

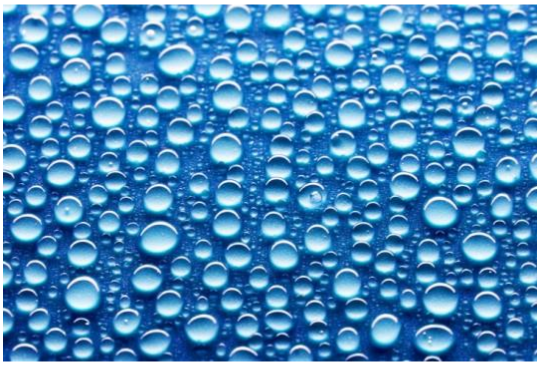

Figure 4-3 Superhydrophobic surface

Superhydrophilic coating

Description – By applying a water absorbing coating, water that hits the surface "sinks into" the surface to form an even layer (figure 4-4) that rinses away contaminants.

Commentary – Even though the technique has come further than its hydrophobic equivalent, the commercially available products get worn, as with the hydrophobic products [25]. Other than that, the same principles apply here; the method only requires small amounts of water to keep the dome clean, with the exception that TiO_2 also has the ability to decompose organic contaminants under UV radiation.

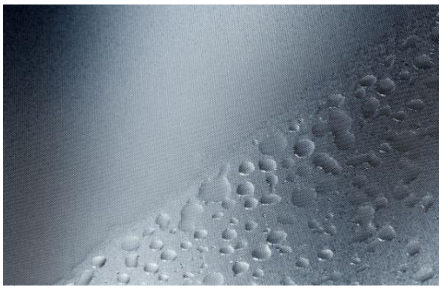

Figure 4-4 Superhydrophilic surface (upper left) and an uncoated reference (lower right)

Namib Desert beetle coating

Description – By applying both superhydrophobic and syperhydrophilic coated areas, similar to the back surface structure of the Namib Desert beetle (figure 4-5), water can be controlled to stay away from the areas where the lens will be faced.

Commentary – The idea of this concept is to compensate for the flaws of synthetically generated hydrophobic and hydrophilic surfaces. The opposing (attracting/repelling) forces add up to generate sufficient effects for a longer time when the coatings start to wear out. This coating would, again, only require water but would be even more complex to achieve than with an entirely hydrophobic or hydrophilic dome.

Figure 4-5 Namib Desert beetle

Etched insect wing pattern

Description – The reason insects are able to fly during heavy precipitation is that they have developed superhydrophobic wings (figure 4-6) which keep them from becoming heavier through soaking. By modifying the dome surface to imitate the pattern of an insect wing by laser etching, similar characteristics are obtained [26].

Commentary – The advantages compared to previous mentioned chemically induced coatings is that this is a more permanent solution. It is, however, a rather unexplored territory and the technique is not yet perfected, meaning there could be flaws and negative effects on optical performance.

Figure 4-6 Superhydrophobic insect wing

Antistatic coating

Description – PC and PMMA (the currently used dome materials) are isolating plastics that build up high static tensions [25]. By applying an electrically conductive, anti-static coating, static tensions are led away from the dome surface (figure 4-7), which eliminates the electro-static component of the adhesion force.

Commentary – As an antistatic coating would only eliminate the electro-static component of the adhesion force, it will only facilitate for other concepts and needs to be combined to keep contaminants away entirely. The most probable obstacle to overcome for this concept is to find a coating with sufficient transparency and other optical properties.

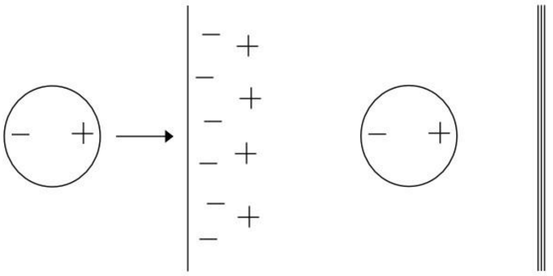

Figure 4-7 Surface with (left) and without (right) static tension build-up

4.3 Air concepts

4.3.1 Theory

Cleaning with air could act as both active and passive cleaning, by either blowing contaminants off the surface or by preventing them from even reaching the surface. The latter scenario requires a continuous airflow and consequently access to industrial compressed air supply, whereas active air cleaning may only require gusts, in which case it could theoretically be sufficient with the type of compressed air one can get from disposable pressurized container cans, if necessary.

As reviewed in the particle detachment theory section (p. 10), blowing air is a flexible method of cleaning as the probability for particle detachment increases with air velocity and particle size (figure 4-8) [7, p.146]. It is therefore possible to optimize the airflow needed for detaching different sized particles by dimensioning nozzle diameters, using throttles etc.

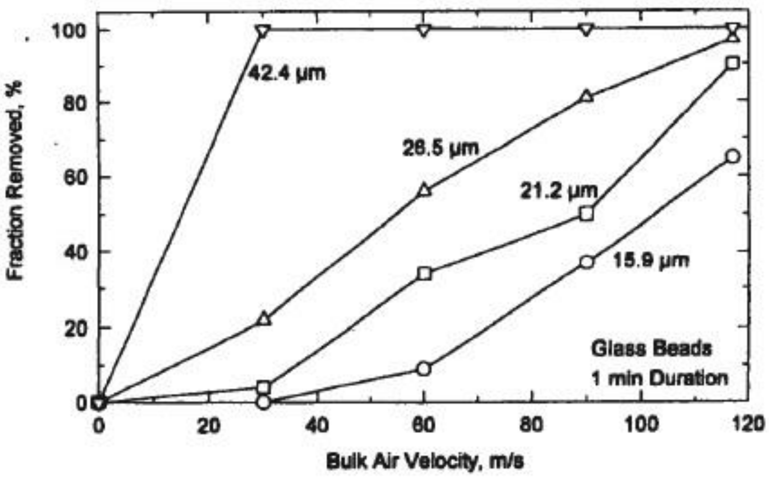

Figure 4-8 Particle removal due to different wind speeds and particle sizes

An aspect to take into account when considering solutions based on compressed air is that the air must be clean. Trying to clean a surface with contaminated air could be counterproductive. If the particles in the airflow are small enough, they may adhere to the surface, and if they are bigger, they may instead scratch the surface, leaving permanent marks. It could also be a problem to promote the concept of cleaning with dirty air [27].

4.3.2 Concepts

Turbulent air cushion

Description – By blowing air through a gap (or directly on the dome surface), turbulent whirls are obtained (figure 4-9), building an air cushion that prevents contaminants from reaching the surface.

Commentary – Depending on what air source is used, this concept will hardly suffice to detach already adhered particles. The main purpose is instead to keep contaminants from adhering. The air cushion therefore needs to reach to the top to enable coverage of the entire dome, which is the main challenge for this concept.

Figure 4-9 Turbulent air cushion concept sketch

Air shield cone

Description – By blowing compressed air through a ring with a pattern of nozzles designed to create a cone formed air shield surrounding the dome (figure 4-10), contaminants are prevented from breaching through to the dome surface.

Commentary – As this concept is meant to form a cone surrounding the dome, meaning no air will hit the actual dome, it will not be possible to remove contaminants that breach through the cone to the dome surface. It also requires supply from compressed air, which is not always available and which pulls high electrical effects (in the kW range) [28].

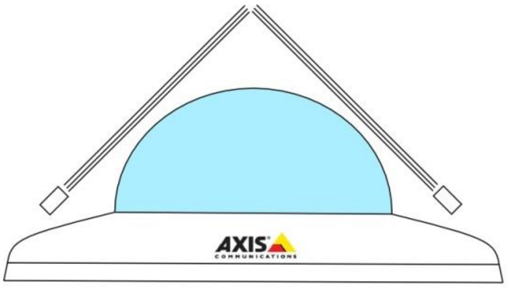

Figure 4-10 Air shield cone concept sketch

Channel jet

Description – By creating an airflow through a cylindrical pipe matching the geometry of the camera housing, wind speeds are increased along the periphery, as $A_{out}<A_{in}$, and the air flow follow a stream line pattern (figure 4-11). By using this

mechanism, contaminants are blown off and therefore prevented to adhere to the dome.

Commentary – As the outlet area is smaller than the area of the air intake, there will be a pressure build-up within the air channel. It is essential that the mechanism generating the airflow can withstand this pressure, preferably with a wide safety margin, to function optimally. The mechanism also needs to be powerful enough to deliver a high volume rate, regardless of what kind of filtering method is used to provide clean air.

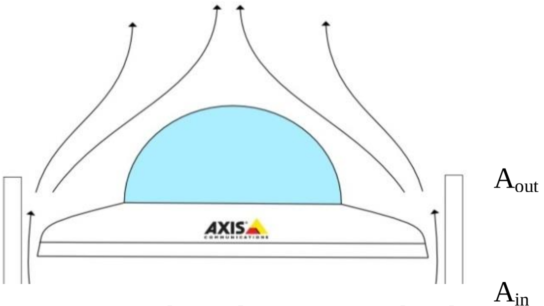

Figure 4-11 Channel jet concept sketch

Cyclonic filter

Description – Regular particle filters needs to be replaced when the absorbed layer of dust prevents it from functioning desirably. By using a cyclonic filter (figure 4-12), clean air is obtained and can be used either to blow air directly onto the dome or coupled with another air based solution to get a clean air supply, without needing to replace or maintain it.

Commentary – The main advantage with using a cyclonic filter is that it, in theory, does not require any maintenance or replacing of contaminated parts. The backside is that the filter's efficiency decreases with particle sizes (figure 4-13) [6, pp. 98-99] and the method is consequently best suited for environments with rather large, mechanically generated particles, rather than combustion particles.

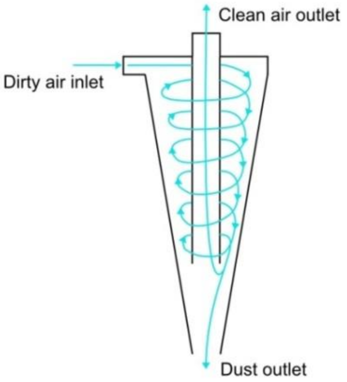

Figure 4-12 Cyclonic filter concept sketch

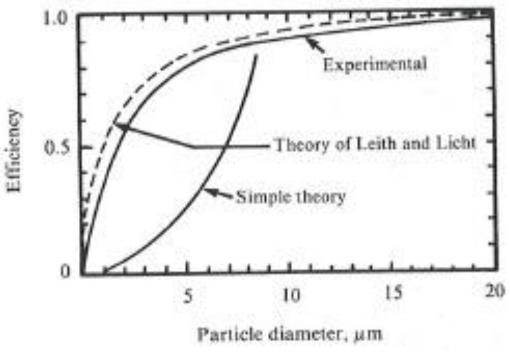

Figure 4-13 Theoretical and experimental values on the efficiency of cyclonic filters

4.4 Disposable materials concepts

4.4.1 Theory

By protecting the dome (or at least the parts where the lens is faced) with an external, removable film, contaminants never reach the actual dome cover at all and consequently do not adhere to it. Instead, they adhere to the external film, which can be disposed when the image quality is considered to be substandard. Such a method does not require modification of the camera, but is an external feature or accessory that would be easy to implement right away.

An obvious problem with usage of disposable materials is that it is not an environmentally friendly solution, unless the solution includes an effective way of collecting the used material for recycling purposes. Taking into account a way to take care of the used materials could thus be essential out of an environmental point of view.

Other essential preconditions to consider include e.g. insulation between the film and the surface and film material properties:

- If there already are dust and particles between the film and the surface, the method loses its purpose as the film, when applied, prevents cleaning of the dome. It is therefore essential to ensure that the dome is clean before installing a device based on disposable film, either by eliminating the distance between the film and the surface or by ensuring that the space between the film and the surface is inaccessible to foreign particles.
- The film’s material properties need to meet Axis’ requirements for optical performance, including e.g. light transmittance, risk of glares and other attributes that could affect visibility. By choosing a material with low friction, good possibilities to combine with a coating and/or other means to prevent adhesion, it is possible to prolong the lifetime of the film, given that it does not affect the optical performance.

4.4.2 Concepts

Film layers

Description – By using several layers of removable film on the dome (figure 4-14), the surface is protected against particle adhesion. When a film layer is contaminated, it is removed and a new, clean layer takes its place as outer layer.

Commentary – The more layers that sits on the dome, the longer time there will be until a new set of layers needs to be attached. The balance act is to appreciate how many layers can sit on top of the dome, without compromising the optical performance. The concept also requires a mechanism which removes the contaminated domes and preferably a method to gather the used layers to minimize littering.

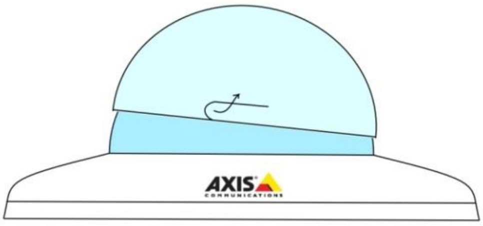

Figure 4-14 Film layers concept sketch

Film roll

Description – This concept is inspired by goggles, used by motocross dirt bike drivers (figure 4-16) [29]. The principle is obtained by applying two connected rolls with transparent film (one feeder and one collector) to the dome cover (figure 4-15). When the active film is contaminated, clean film is rolled out from the feeder, while the collector gathers up the contaminated stripe.

Commentary – This concept has potential to last longer than the film layer solution, being that it, in theory, could hold an infinite number of clean stripes to protect the dome. However, the straight roll can only keep parts of the dome clean, which is not optimal for PTZ cameras. If the roll is visible, it could also eliminate the illusion of an "all-seeing eye", which is one of the soul purposes for a dome camera. Another challenge is to make sure to seal the space between the roll and the dome surface.

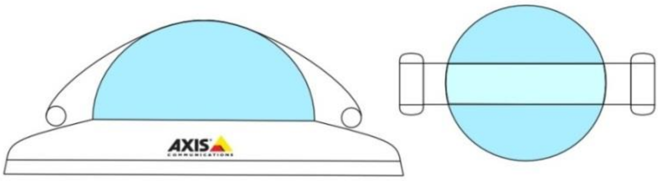

Figure 4-15 Film roll concept sketch

Figure 4-16 Dirt bike goggles with film roll

4.5 Sonic waves/vibration concepts

4.5.1 Theory

Using sonic waves or other means to generate vibrations could act as both active and passive cleaning, depending on concept and usage. The principle is based on finding a suitable combination of frequency and waveform which generates forces that exceed the adhesive forces and thus shake off or keep contaminants away from the vibrating surface. As reviewed in the particle adhesion theory section (p. 10), vibrations alone are seldom enough to generate sufficient forces for particle detachment. However, in combination with other methods, it can provide unique properties.

An important aspect to consider for vibration solutions is how the mechanism affects sealing and insulation. Axis' outdoor cameras follow the IEC (International Electrotechnical Commission) 60529 standard on Ingress Protection codes (IP). IP codes classify and rate the degree of protection provided against the intrusion of solids (e.g. dust) and liquids (e.g. water) in housings and casings surrounding electrical components.

IP codes consist of two numerical digits, one for solid particle protection (0-6) and one for liquid ingress protection (0-8), where each value define testing method specifications and acceptable outcomes. Axis cameras mounted in harsh outdoor environments are generally classed as IP66, which define protections as follow [30]:

- Solid particle protection value 6, being the highest possible value, implies an impenetrable, dust tight protection, regardless of particle size.
- Liquid ingress protection value 6 implies protection against powerful water jets from a three meter range, with Ø12.5 mm nozzles at a volume flow rate of 100 liters/minute and a pressure of 100 kPa. The casing should withstand these stresses from any direction, under a minimum duration of three minutes.

Due to the environments specified in the delimitation section (p. 3), it is very likely that the cameras mounted in the chosen areas need to pass IP66 classification. Since it is a rather tough classification, it is essential to consider this when developing vibration solutions. It is possible to get around the insulation problem by vibrating the entire camera, so that nothing moves relative to its neighboring part, but such a solution could affect the internal electronics and thus only redirects the problem.

Another important aspect to consider is that of resonance. If the applied vibration hits a frequency, consistent with the eigenfrequency of the exposed part of the camera housing or interior, it could originate undesirably large forces and amplitudes. Exposure to large amplitudes could cause problems with insulation and even mechanical damage such as rupture or fatigue, depending on what part is vibrating and for how long. It is therefore of great importance to be clear with the exposed object’s eigenfrequencies and to have a wide margin of safety for these.

It is also a possibility to take advantage of the phenomenon of resonance in a positive way. If the contaminant particles themselves vibrate at a frequency consistent with their eigenfrequencies, they will be exposed to resonance, which theoretically could generate sufficiently strong forces to overcome the adhesive forces. The problem is that there are an infinite number of particle sizes and consequently an infinite number of eigenfrequencies to hit to expose all possible sizes to resonance.

4.5.2 Concepts

Pneumatic pistons

Description – Pneumatic pistons are connected to the housing (figure 4-17). The pistons are activated remotely to perform a rapid, linear movement, which ejects contaminants. The pistons can be run continuously.

Commentary – The major challenges with having pistons shake the camera chassis is to make sure that the camera retains IP66 classification and that the rapid movements and acceleration does not damage internal electronics. The solution will require compressed air supply.

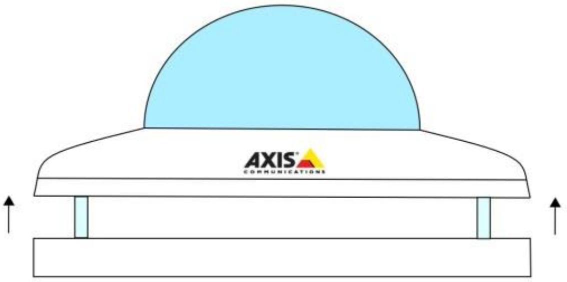

Figure 4-17 Pneumatic pistons concept sketch

Vibration plate

Description – By connecting the dome to a vibrating mechanism (figure 4-18), contaminants are less likely to stick or are simply ejected off the surface. The frequency is set to optimize detachment for particle sizes and characteristics in the usage environment.

Commentary – The upside to this concept is that it will not require high electrical effects, but is a rather economical solution. To retain IP66 classification, the sealing between the dome and the chassis needs to be modified for this concept to be successful. It would also be preferable to keep the vibrating mechanism separate from the PCB and other electronics, to minimize the risk of damage due to the generated amplitudes.

Figure 4-18 Vibration plate concept sketch

Ultra-/Megasonic cannons

Description – By aiming sonic cannons (figure 4-19), which send out ultra-frequent sound waves towards the dome surface, the dome is set into a vibrating motion, ejecting adhered particles.

Commentary – Ultrasonic cleaning is an up-and-coming technique that has grown popular due to its gentle characteristics. It is usually used in liquids as the ultra-frequent vibrations create microscopic bubbles which implode, releasing great amounts of energy. Applying the technique in a non-liquid environment is yet a rather unexplored territory, meaning it would need an extensive amount of research, but it would be a gentle way of removing contaminants, without jeopardizing insulation and internal components.

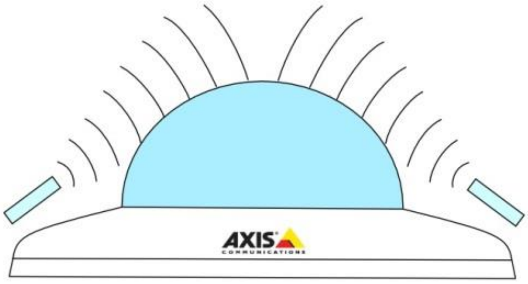

Figure 4-19 Ultra-/Megasonic cannons concept sketch

Piezo electric element(s)

Description – Piezo elements have the ability of transforming electrical energy to mechanical work, in this case vibrations with extremely high frequencies. By attaching an element to the dome (figure 4-20) and running it, through a voltage source, ultra frequent vibrations spread through the dome. By sweeping through a frequency interval, consistent with the adhered particles eigenfrequencies, they achieve resonance and are consequently exposed to forces larger than that of the adhesion and are therefore detached, as higher accelerations are obtained [31].

Commentary – As mentioned earlier, an infinite number of particle sizes implicates an infinite number of eigenfrequencies, meaning it is desirable to map the interval of common particle sizes in the environment in question, to narrow down the frequencies that need to be hit to gain desirable results. Another aspect to consider is where the element(s) are best placed, to not block the field of view [31].

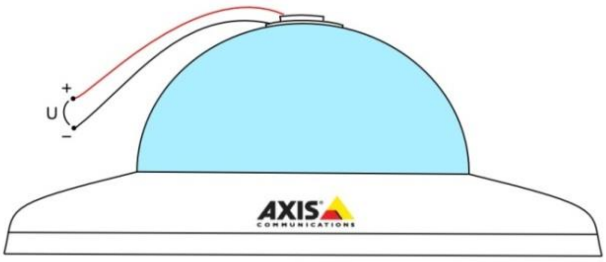

Figure 4-20 Piezo electric element concept sketch

Rotating dome

Description – By applying a circular motion to the dome (figure 4-21), contaminants are less likely to stick to the surface or are simply hurled away. The rotational velocity is set to generate sufficiently large centripetal forces required to detach contaminants.

Commentary – Since the dome needs to be separate from the chassis, to be free to rotate, the insulation between the dome and the chassis needs to be modified to retain IP66 classification. Implementing a ball bearing would reduce the electrical effect needed to run the rotator continuously.

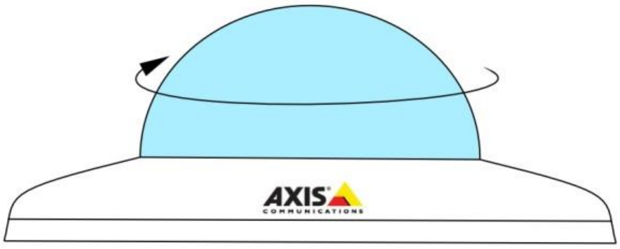

Figure 4-21 Rotating dome concept sketch

4.6 Active concepts

4.6.1 Theory

As mentioned before, the purpose of active cleaning solutions are to remove particles that have already adhered to the surface. While earlier concepts have had passive abilities or sometimes both passive and active, this chapter will focus purely on active methods.

Generally, active cleaning solutions require larger forces than solutions designed to repel contaminants, as the adhesive forces on small particles (micrometer-sized) exceed other common forces by order of magnitude [7, p. 141]. On a practicable level, it is easier to generate sufficient forces with contact cleaning such as wiping, as corresponding detaching forces generated by e.g. blowing air requires very high pressures. There are, however, major backsides to cleaning surfaces with direct contact, especially when handling scratch sensitive materials such as PMMA [32, p. 17], which is the case for many of Axis' dome covers. It could also subject possible coatings to abrasion which would counteract the whole purpose of cleaning the dome. It is therefore desirable to design any contact solution or to pretreat the exposed surface to minimize damages such as scratches and similar defects.

When cleaning with a mechanism, which will move across the field of view (e.g. wipers) when activated, it is important that the device is robust and reliable. If e.g. a fan mounted behind the camera stops working, nothing will happen except that it will not clean the dome or repel contaminants from it. If a wiper mechanism fails when activated, it could have dire consequences if the wiper blade stops in the field of view, especially if the camera is mounted in a difficultly accessible area. Making sure the solution is robust, or by designing a backup mechanism that will prevent an active solution from blocking the view while malfunctioning is desirable.

4.6.2 Concepts

Contact wiper

Description – By moving a semicircle contact wiper radially around the dome center (figure 4-22), contaminants are removed by the material in contact with the dome. Contact materials such as e.g. elastomers or microfiber cloths may be varied or combined after desire.

Commentary – Important aspects to consider before implementing a contact wiper is to design it to minimize the risk of scratching the dome surface, either by applying a medium to soften the adhered contaminants or by using a gentle contact material that applies a tangential force, rather than a force towards the dome surface. It is also important that the rotational device is robust or has a backup mechanism in case of failure, so that the failing wiper does not stop in the field of view.

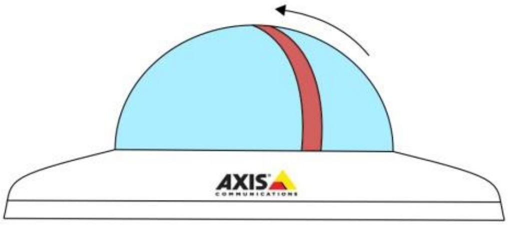

Figure 4-22 Contact wiper concept sketch

Non-contact wiper

Description – By moving a semicircle pipe radially around the center of the dome (figure 4-23) and supplying a liquid or gas medium through a pattern of nozzles, the dome is cleaned without any contact. Cleaning media or methods such as e.g. water, isopropanol, compressed air, magnets, vacuum or heat may be varied or combined after desire. It is also possible to combine the solution with a contact wiper.

Commentary – As with the contact wiper, this concept will also block the field of view if the mechanism fails while in motion. It is, however, a gentler alternative as the risk of scratching the dome is significantly lower than with the contact wiper.

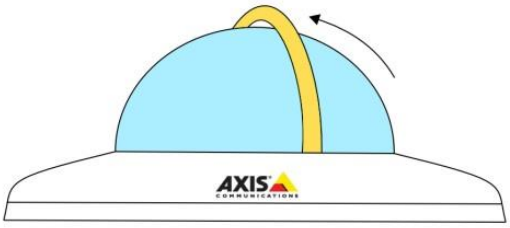

Figure 4-23 Non-contact wiper concept sketch

Eyelid mechanism

Description – By imitating the mechanism of a human eye, a lid with a moist inside (through a grid of nozzles) is moved radially (figure 4-24), actively cleaning the surface.

Commentary – This solution will always block half the dome, which is not a problem if implemented to a fixed dome camera. If the mechanism fails, however, the eye-lid will not just block parts of the view, like the wipers, but rather the entire view. Other than that it is also desirable to try and minimize the risk of scratching the dome as the eye-lid is set in motion.

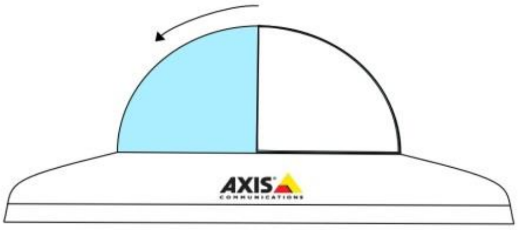

Figure 4-24 Eyelid mechanism concept sketch

Pyrolytic cleaning

Description – By facing a heat source towards the dome (figure 4-25), organic contaminants are turned into ashes, which are easily removed if combined with e.g. a wiper [33].

Commentary – The upside to pyrolytic cleaning is that it would facilitate for and reduce the risk of scratching if combined with a wiper. On the other hand, it would require heating at very high temperatures (≈500°C), which in turn requires a new, or coated dome material to resist the heat, as the current materials (PMMA and PC) reach their glass transition points already at about 90-150°C [34].

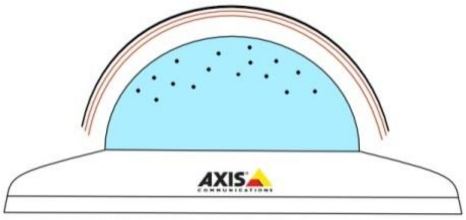

Figure 4-25 Pyrolytic cleaning concept sketch

Jet ring

Description – Same principle as with the non-contact wiper, but instead of using a radial motion, the jet ring would move axially (figure 4-26), spraying water, compressed air and/or other desired materials inwards through a pattern of nozzles.

Commentary – This concept is similar to the non-contact wiper. The advantage of the jet ring compared to the non-contact wiper is that it does not necessarily block the field of view if the mechanism fails. The downside is that the distance between the nozzles and the top of the dome would be greater, meaning cleaning would not be as efficient on the upper parts.

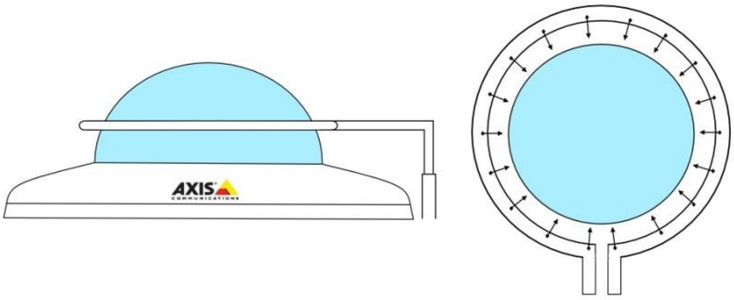

Figure 4-26 Jet ring concept sketch

5 Concept screening

This chapter intends to systematically weed out generated concepts so that further development, evaluation and testing can be focused on a manageable number of concepts. In order to take into account every important aspect, key criteria will be defined to estimate each concept's potential, according to the methods used in Ulrich and Eppinger's Product Design and Development [5, pp.150-154].

5.1 Purpose and approach

As the first step in concept selection, the purpose of concept screening is to narrow down the number of primary concepts in a quick and simple manner. This is achieved by establishing a number of significant criteria on a high level of abstraction and picking a reference concept, against which all other concepts are rated. More detailed ratings at this stage are largely meaningless, as the primary concepts are only general notions of the ultimate product.

First off, all thinkable evaluation parameters that could affect the concept's potential were taken into account. To limit down these to only relevant key criteria, it was deemed important to consult with Axis representatives with a longer experience and deeper insight in the company's values [35], to pull out only essential parameters at this early stage.

As criteria relevance partially depends on mounting environment, the screening focuses on cameras mounted in open-pit mining sites, as it is defined as the primary environment in the objective section (p. 3).

5.2 Establishment of evaluation criteria

There are numerous attributes that define the market potential of a product of this nature. The following list will cover and explain all parameters with more or less significance:

1. Product cost – What will the finished product cost to the customer (fixed cost)?
2. Operating costs – How much will the product cost while in operation (variable costs)?
3. Development costs – Will the product demand extensive research and resources to develop and optimize?
4. Environmental impact – Will the product cause particular adverse effects on the environment over the course of its entire lifecycle?

5. Ease of implementation to Axis' current products – Will the solution require structural changes of the camera to function optimally?
6. User-friendly – Are the product's features easy to understand and operate?
7. Insulation and sealing – Does the solution affect the IPxx-classification?
8. Space efficiency – Is the product bulky and unwieldy?
9. Passive cleaning – How well does the solution repel contaminants?
10. Active cleaning – How well does the solution detach adhered particles?
11. Visibility – How will the solution affect optical performance?
12. Maintenance – Will the solution need regular maintenance in order to function desirably?
13. Ease of promotion – Will the solution and the used mechanism be easy to promote to the buying market?
14. Supplies – Will the solution require other supplies than electricity, such as compressed air and water?
15. Weight – Is the product heavy?
16. Complexity – Is the product made up by many different components?
17. Noise – Will the product, while activated, generate high noise levels?
18. Robustness – Is the solution durable and rugged?
19. Versatility – Is the solution suitable different environments, particle sizes and climates?
20. Impact on internal electronics – Will the product expose the internal electronics, e.g. the printed circuit board (PCB), to potential damaging stresses?
21. Aesthetic design – Will the product be aesthetically appealing?
22. Mounting – Will mounting of the product be quick and straightforward?
23. Malfunction effects – Will a mechanical failure affect the camera, other than that the product will not clean anymore?
24. Abrasion – Will the product risk exposing the camera dome and/or chassis to scratching or wear?
25. Technology maturity – Is the used technology fully developed, thus functional and sufficiently robust for the task?

These are all considered to be parameters which to different degrees, depending on e.g. mounting environment and intended production volume, will affect the solution's overall impression.

Through reviewing and discussing all 25 parameters, listed in previous section, and their significance, the following conclusions were made:

- The product's physical appearance, out of an aesthetical point of view, is of secondary nature as the cameras in question will be mounted in industrial sites where functionality and reliability is assumed to be of much greater importance than appearance. Aesthetic design, Space efficiency and Weight should therefore not be considered to be key criteria at this point. This rules out parameters 8, 15 and 21.
- Minimizing costs is not of high priority either. Development costs are generally close to negligible if the product reaches market breakthrough. The purchasing and operating costs of the product are considered to be less

important for the buyer if the product meets its functional purpose. This rules out parameters 1, 2, 3 and 5.

- User related attributes such as ease of handling and ease of mounting are also of less importance as a product intended for mining sites falls under the category of niche products. It is assumed that such industrial environments have employees responsible for security that have some technical competence and, above all, time to learn the products and to customize its performance based on their needs. This rules out parameters 6 and 22.

Generally, functionality, reliability and robustness should be in focus. Note, however, that parameters that are deemed to have less significance at this point are not necessarily insignificant for the final solution.

After revising some parameters and bundling similar items to reach a higher level of abstraction, the following (table 5-1) were established to be the most essential key criteria:

Table 5-1 Evaluation criteria

Criteria	Parameters covered	Comment
Low maintenance	12	The main purpose of the project is to lower the maintenance frequency of the camera. It would be counterproductive if the solution mechanism needed frequent maintenance.
Cleaning abilities	9, 10	Whether the cleaning mechanism is active or passive have little or no matter as long as the camera dome is kept free from contamination.
Market possibilities	4, 13, 17	Technical perfection does not automatically lead to commercial success. Unconventional, earlier unproven mechanisms might find it harder to reach acceptance than more classical cleaning methods. Noise and environment aspects are also considered here.
Low complexity	16	As complexity and number of acting components more often than not are related to robustness and reliability, it is desirable to keep the solution as simple as possible.
Robustness	18, 25	Due to the specified environment and the rough outer conditions that follow with it, the solution might be exposed to disturbances such as strong gusts and stone chips. A successful mechanism needs to deliver desirable results, regardless of external conditions.

Supply requirements	14	The only supply that can always be assumed to be available is electricity, as it is needed to run the camera. Availability of other supplies such as water and compressed air are not as commonplace. A solution that only requires electricity would reach a bigger market.
Risk of Damage	7, 20, 23, 24	Keeping the camera dome clean must not be at the expense of IPxx-classification, a scratch-free dome, functionality of internal electronics or other vital functions.
Environment versatility	19	Even though focus is on the defined primary environment, if the solution proves to be suitable for other types of environments, it would mean a significant advantage.
Effects on optical performance	11	Minor deviations in picture quality may be approved if the upside is that the camera dome is kept clean, but there is a threshold and optimally, the picture quality is not affected at all by the cleaning mechanism.

5.3 Concept screening matrix

A concept screening matrix (table 5-2) is often used to provide a schematic overview of the screening process. Before rating the concepts, a reference needs to be chosen, against which all other concepts are rated. Usually, the existing or untreated product is used as reference but such an approach would give over-simplistic results in the screening. An untreated dome is e.g. obviously less complex than all solutions, which would rule out the significance of that criterion. In this case, the contact wiper concept was instead chosen as reference as the mechanism is the most common automated solution on the market today and also considered to be a conventional and, compared to the other concepts, neutral solution.

Note that the characters should be interpreted as: + for “better than”, 0 for “same as” and – for “worse than”.

Note also that the concepts selected for further development are subjects for combination, which will be discussed in chapter 6.

Table 5-2 Concept screening matrix[3]

	Low maintenance	**Dirt removing/repellent**	**Market possibilities**	**Low complexity**	**Robustness**	**Supply requirements**	**Risk of damage**	**Environment versatility**	**Effects on optical performance**	**Sum -'s**	**Sum 0's**	**Sum +'s**	**Net score**	**Rank**	**Continue?**
Superhydrophobic coating	+	0	+	+	-	0	+	0	0	1	4	4	3	7	No
Superhydrophilic coating	+	0	+	+	-	0	+	0	0	1	4	4	3	7	No
Namib Desert Beetle	+	0	0	0	-	0	+	0	0	1	6	2	1	12	No
Etched insect wing pattern	+	0	-	-	0	0	+	0	-	3	4	2	-1	15	No
Antistatic coating	+	0	+	+	-	+	+	0	0	1	3	5	4	1	**Yes**
Turbulent air cushion	+	0	0	+	+	0	+	0	0	0	5	4	4	1	**Yes**
Air shield cone	+	+	+	0	+	-	+	0	0	1	3	5	4	1	**Yes**
Channel jet	+	0	0	+	+	0	+	0	0	0	5	4	4	1	**Yes**
Film layers	0	+	+	0	0	-	+	+	0	1	4	4	3	7	No
Film roll	0	+	+	0	0	-	0	+	0	1	5	3	2	10	No
Pneumatic piston	-	-	-	-	0	-	0	0	0	5	4	0	-5	19	No
Vibration plate	+	0	+	+	0	+	0	0	0	0	5	4	4	1	**Yes**
Ultra-/Megasonic cannons	+	0	+	-	0	0	+	0	0	1	5	3	2	10	No
Infrasonic	0	0	-	0	0	-	0	0	0	2	7	0	-2	17	No
Piezoelectric elements	0	0	+	-	0	+	0	0	0	1	6	2	1	12	No
Rotating dome	0	-	-	-	0	0	0	0	0	3	6	0	-3	18	No
Contact wiper (ref)	0	0	0	0	0	0	0	0	0	0	9	0	0	14	No
Non-contact wiper	0	0	+	-	0	-	0	0	0	2	6	1	-1	15	No
Eyelid mechanism	-	-	0	-	-	0	-	0	-	6	3	0	-6	20	No
Pyrolytic cleaning	-	-	-	0	0	0	-	-	-	6	3	0	-6	20	No
Jet ring	+	0	+	+	0	-	+	0	+	1	3	5	4	1	**Yes**

---

[3] Assessments made by Alfred Ekermo and Victor Norell

6 Preliminary testing

As primary concepts for further evaluation and development have now been selected, this chapter intends to test the efficiency of the chosen mechanisms in practice, through simplified prototypes. The prototypes will not consider how the product will be designed and integrated to the product, but merely what cleaning or repelling effects the mechanisms have on dusts.

6.1 Prototype design

Antistatic coating

Since a coating will not interfere with the other mechanisms, it will be combined with all other concepts to demonstrate if the effect, if any, is especially effective in combination with a specific concept. The exposed test dome will therefore be coated on half the area and remain untreated on the other half (figure 6-1).

Transparent, permanent conductive coatings need to be specially treated and ordered. While optical performance is not considered for this section, a simple graphite spray is used [36]. Graphite is highly electrically conductive, making it satisfactory for methodology evaluation.

Figure 6-1 Test dome halfway coated with graphite spray

Channel Jet

An electrically driven duct fan, delivering 280 m^3/h (≈77.8 l/min), with an inner diameter of 125 mm is used to supply the air flow (figure 6-2) [37]. The test dome's outer diameter is 100 mm, leaving a symmetric gap of 12.5 mm between the dome and the cylinder wall.

To facilitate a straighter airflow, a cylinder with a slight slope to account for the diameter difference between the dome and the fan motor is designed in the CAD software Creo Parametric 2.0 and printed in PLA (Polylactic Acid) with a 3D printer. This way, all air is forced to flow along the cylinder wall.

Figure 6-2 Channel jet prototype with dust chamber suspension

Turbulent air cushion

While the channel jet is partly built to investigate the air flow behavior and streamline effects around the dome, this concept intends to build a barrier that ensures air coverage of the entire dome. A simple way of doing this is to re-use the channel jet prototype but to redirect the air outlet. For this purpose, a simple modification of a funnel suffices (figure 6-3).

Figure 6-3 Modified channel jet prototype to achieve air cushion mechanism

Air shield cone

To withstand the high pressure generated, a compressed air hose is used. The hose is connected in both ends with a T-tube to permit compressed air supply from only one inlet. Furthermore, a dense pattern of 2 mm holes are drilled with an angle to form an air cone around the dome when compressed air is supplied (figure 6-4).

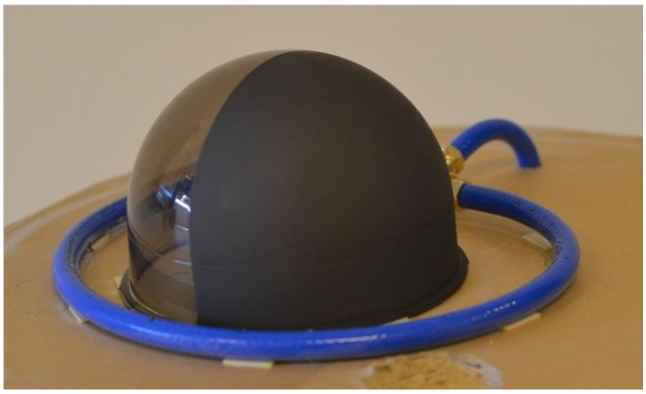

Figure 6-4 Air shield cone prototype

Air jet ring

As this prototype is more or less an active version of the previous air shield cone, a compressed air hose which can be moved manually is sufficient, with the exception that the holes are now drilled with an angle to face the dome instead of the dome’s surroundings (figure 6-5).

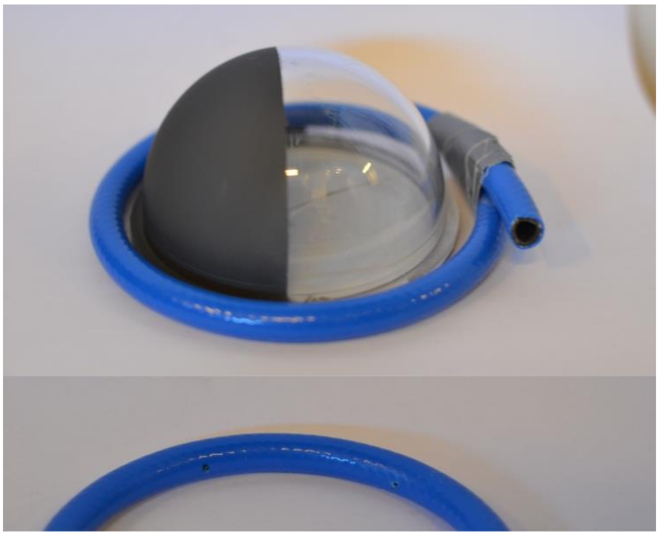

Figure 6-5 Air jet ring prototype

Vibration plate

To generate high frequent vibrations with low amplitudes, an electrodynamic vibrator is used, i.e. a speaker without a box or membrane [38]. The vibrator is connected to an amplifier [39], which in turn is connected to a tone generator that can supply frequencies in the interval 2-20,000 Hz with various waveforms. The speaker is attached to rigid plates on both sides to avoid absorption so that vibrations are translated through to the dome without losses (figure 6-6).

Figure 6-6 Vibration plate prototype

6.2 Test design

The target was to simulate an authentic environment, close to reality. To do this, an existing dust chamber at Axis was used (figure 6-7), containing a compressed air inlet, a filtered outlet and several different lids to consider the suspension needs for every conceptual design, as shown in the previous section (e.g. figure 6-2).

Figure 6-7 Dust test chamber with inlet, filtered outlet and suspension lid

The dust used was *ISO 12103-1, A2 Fine Test Dust* from Powder Technology Inc. The material is estimated to have similar attributes to that of mining mineral dusts, as it is taken from the dry Salt River Valley in Arizona, USA. Arizona dust has been proven to contain a high percentage of extremely fine particles, making it a tough test substance. The particle size distribution by volume percentage is displayed in Table 6-1 [40].

Table 6-1 ISO 12103-1, A2 Fine Test Dust particle size distribution by volume pct.

Size (µm)	Volume (% smaller than)
1	2.5-3.5
2	10.5-12.5
3	18.5-22.0
4	25.5-29.5
5	31.0-36.0
7	41.0-46.0
10	50.0-54.0
20	70.0-74.0
40	88.0-91.0
80	99.5-100
120	100

Note that the numbers should be interpreted as e.g. “2.5-3.5% of the volume contains of particles smaller than 1 µm”.

The initial test procedures are specified as follows:

- The duration of the tests is limited to three minutes, as the time amount is deemed sufficient at this stage for a fair evaluation.
- Three one-second gusts of compressed air under eight bar pressure are added to the bottom of the chamber at t = 0, 1 and 2 minutes, partly to create a fog but also to generate strong gusts that will simulate particles getting thrown against the dome sporadically.

The exception is for the vibration plate concept. Due to the risk of damaging the electronics because of the extreme contamination, the vibrating device will not be tested in the chamber but contaminated by brushing dust on the dome alone.

6.3 Results

To display how an untreated dome gets affected by the specified test procedure, a dome was suspended in the dust chamber to undergo the exact same contamination event and thus work as a reference (figure 6-8), against which all other test subjects can be compared. For the preliminary testing, the results were evaluated through visual comparison between the different solutions.

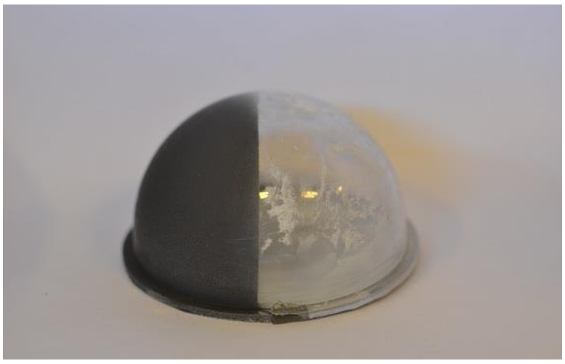

Figure 6-8 Contaminated reference dome

Although the results from the upcoming preliminary methodology tests should not be viewed upon as absolute truths, they do provide hints on the efficiency of each mechanism.

Antistatic coating

A recurring outcome was that the graphite coated part of the dome displayed significant advantages, compared to the uncoated half, regardless of what mechanism the coating was combined with (figures 6-9 – 6-13). A part of the dust repelling outcome can likely be attributed to the change in surface structure when applying the spray, which lowers the surface friction, but the coating shows promise, making it a subject for further development and evaluation. The test also highlighted the possible significance of modifying the surface structure.

Channel jet

As can be seen in the picture below (figure 6-9), the channel jet solution did not provide desired effects, but rather reversed effects as the dome seemed even more contaminated than the untreated reference. When examining the airflow, it was established that desired streamline effects were not fulfilled, as there was a large zone on top of the dome that the airflow did not reach and therefore could not protect. Notable, however, is that the coated half, as mentioned before, remained clean.

Figure 6-9 Channel jet before (left) and after (right) testing in dust chamber

Turbulent air cushion

By redirecting the outlet air from the channel jet concept, results changed dramatically (figure 6-10). Airflow examination showed that air now covered the entire dome, leaving no area unprotected. There were small deposits of dust on the uncoated half but overall the results were satisfactory, being that the prototype at this point is far from optimized.

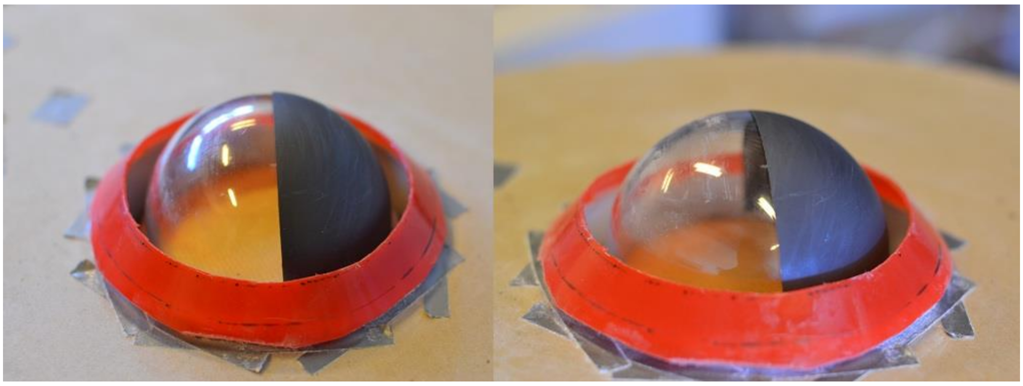

Figure 6-10 Air cushion before (left) and after (right) testing in dust chamber

Air shield cone

The outcome of the air shield cone (figure 6-11) was neither perfect, nor insignificant, but rather somewhere in between. As this solution does not have the ability to detach adhered particles (as the air holes are not directed towards the dome), it needs to exhibit superior repelling abilities. Constantly running a compressor that pulls effects in the kW range is not desirable if the cleaning effects are not completely satisfactory.

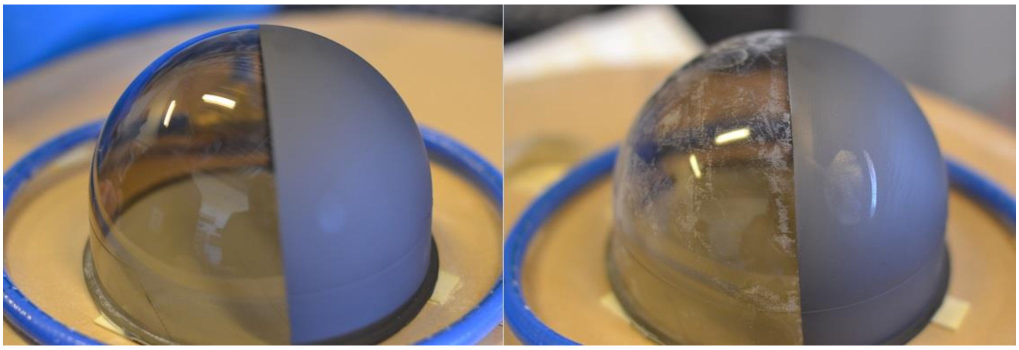

Figure 6-11 Air shield cone before (left) and after (right) testing in dust chamber

Air jet ring

As this is an active cleaning mechanism, the testing was carried through in reverse, compared to the previous methods, i.e. the dome was contaminated according to the test specifications without any protection, whereupon the ring was moved axially under a three second duration. As the air jet decrease in energy shortly after leaving the outlet holes, the mechanism was more efficient on the lower parts of the dome, where the holes are closer to the surface (figure 6-12).

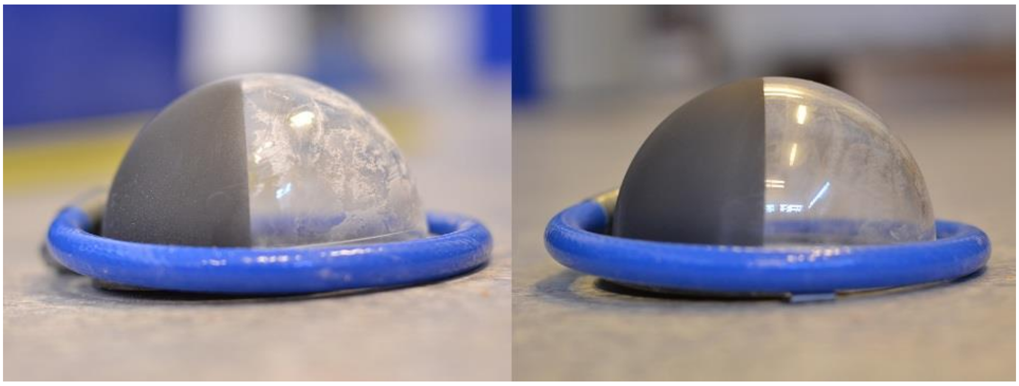

Figure 6-12 Air jet ring before (left) and after (right) testing

Vibration plate

The sinusoid frequency was swept from 20 to about 500 Hz to see how different frequencies affected the outcome. The initial impulse generated detachment of the outer dust layer (figure 6-13). Aside from that there was little or no further detachment, regardless of frequency or waveform. Some dust detached when hitting an eigenfrequency (f ≈ 35 Hz), but that also generated large amplitudes, which is not desirable out of an insulation (IPxx) point of view.

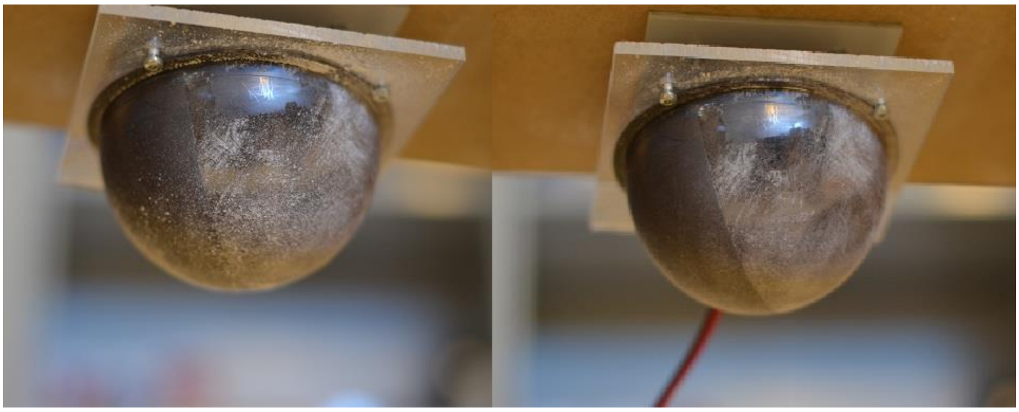

Figure 6-13 Vibration plate before (left) and after (right) testing

6.4 Concept selection

Concept scoring, in accordance with Ulrich and Eppinger [5, p.154], differs from the screening part mainly because the evaluation criteria are weighted to really emphasize the criteria that hold more significance to the objective. Due to the objective of this project, keeping the camera clean by either removing or repelling contaminants can more or less be seen as a requirement, rather than a desirable criterion. Being that only one preliminary test (the turbulent air cushion) stood out in keeping the dome clean, there is no need for an extensive scoring section. An evaluation meeting was also held with Axis representatives, which confirmed this perception [41]. This is why the purpose of the turbulent air cushion (building a protective air barrier around the dome) will henceforth be the concept for further developing.

7 Implementation and design

The most promising principle solution has now been selected. This chapter intends to implement the mechanism onto an existing Axis camera model and to optimize geometries and components to achieve the best results possible by considering relevant theory and common design rules. The aim for this chapter is to result in a preliminary prototype which will undergo a proof of concept field test.

7.1 Subject camera model

In order to be able to demonstrate a solution prototype, it would be preferable to choose a suitable camera model as primary subject, both to focus dimensioning and other specifications to a single model and to test a camera that is likely to be mounted in the delimited environment.

After reviewing different model options with Axis representatives [41], the Axis P55 PTZ series was chosen, model P5512 (figure 7-1).

Figure 7-1 Axis P5512 PTZ

7.2 Air flow theory

The purpose of this section is to introduce the reader to some basic theory about air flow, along with some guidelines on how to steer it to make use of all generated flow in an optimal manner. The design guidelines will then be applied on the upcoming concepts on what air flow generation source will be used.

7.2.1 Flow emergence and Reynolds number

Air flow occurs when there is a pressure difference over a distance. The gas will move from the higher pressure zone to the lower, creating a flow. There are two ways to describe the characteristics of a flow – laminar and turbulent. A laminar flow can be described as a flow of parallel layers and generally occurs at low speeds. Often currents display a more chaotic flow pattern, which is commonly known as turbulent flow [42]. To determine the predicted type of flow, Reynolds number can be calculated using

$$Re = \frac{wL}{v}$$

where w denotes the average velocity of the fluid, L denotes a characteristic distance for the body (for flows in pipes L equal the diameter of the pipe) and v is the kinematic viscosity of the fluid. Viscosity measures fluid or gas resistance to gradual deformation by shear stress or tensile stress [43]. It corresponds to the informal notion of "ease of flow". As an example, water flows easier than honey and thus water has lower viscosity than honey. In order to get the kinematic viscosity, one has to know the dynamic viscosity μ and the density ρ of the fluid [42].

$$v = \frac{\mu}{\rho}$$

A lower Reynolds number translates to a more laminar flow, while a higher number translates to a turbulent flow (figure 7-2). Normally the transition between laminar and turbulent flow in a pipe occurs with a Reynolds number around 2100-4000. This interval is called transition flow, where both laminar flow and turbulent flow may occur [42].

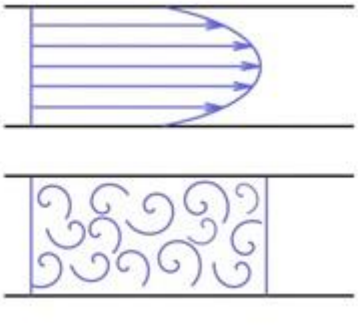

Figure 7-2 Laminar (upper) and turbulent (lower) flow

For example, air flowing at 2 m/s through a pipe with a diameter of 0.1 meters at 20ºC results in a Reynolds number value of [42]

$$Re = \frac{2 * 0.1}{\left(\frac{1.82 * 10^{-5}}{1.204}\right)} \approx 13{,}000$$

To get a laminar flow, either the velocity has to be significantly lower or the diameter of the pipe smaller. Since the dynamic viscosity of air is very low, laminar flow is difficult to achieve. For example, water has a dynamic viscosity of about 55 times higher than air, making it easier in most cases to achieve laminar flow for water than for air [42].

If the flow is directed using sharp bends or through sudden area variations, there will be pressure losses which cause the flow to lose energy, called *minor losses*. To avoid any losses, larger radii in bends and smooth area transitions is preferable when designing systems. There are also frictional losses or *major losses* due to the roughness of the inner walls or in case of laminar flow, depending on Reynolds number.

7.2.2 Design guidelines

As the design of the solution was initiated, fluid mechanics professor Johan Revstedt was consulted on how to model the cavity where the air travels from source to outlet or nozzles. Since a solution where the air flow suffers minimal pressure losses was desirable, Revstedt suggested small bends with large radii on the walls together with an outlet pointed at the tangent of the dome. The outlet should also be designed so that velocity vectors in all points of the outlet are perpendicular to the outlet plane to make use of all generated flow optimally [44].

The intention of creating a protective boundary layer of air flow is for the air current to cover the entire dome. The P5512 PTZ dome has got a spherical part and a short cylindrical part at the bottom. There is a visible joint at the boundary where the geometries meet. This joint is the lower limit for where the lens can face [45]. Any added feature may not rise above this joint, making the top of the dome difficult to reach. To accomplish this, either a low velocity laminar flow, creeping along the dome surface, or a flow aimed at the top of the dome from a wider perimeter has to be generated. Low velocity airflow, however, is not desirable as it is less likely to prevent particles from reaching the dome, hence adhering to the surface. A wider perimeter outlet would make the solution bulky and further increase the distance from nozzle to dome, causing the airflow to lose energy. Considering that the lens is seldom pointed towards the top of the dome [46], keeping the side of the dome clean is prioritized. This area is shaded in figure 7-3.

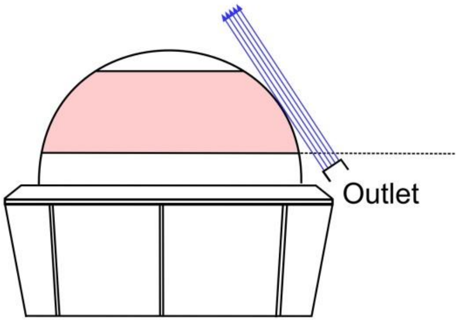

Figure 7-3 Prioritized area of the dome

7.3 Air supply

It has so far been established that the final product should consist of a protective air cushion surrounding the dome, but the source from where the air will be generated is still unspecified. This section intends to generate and evaluate a number of options of supplying the air flow out of relevant aspects, such as wind speeds on different parts of the dome, mounting possibilities and electrical effect consumption.

7.3.1 Big fan

As with the preliminary testing prototype “channel jet” (Chapter 6, p. 44), this alternative would consist of a single axial fan placed behind the camera (figure 7-4), which would send the airflow along the outer periphery of the camera housing. Directing the air to cover the entire dome is accomplished by designing optimized outlets which will both redirect the airflow and do it in such a way so that minimal pressure losses occur.

A downside with using a big axial fan is that the usual way of mounting the P5512 PTZ would not be possible since the rotator (the motor) would be blocking the bottom of the camera where the holding bracket is usually attached. An alternative way of mounting the camera needs to be developed to enable realization of this solution.

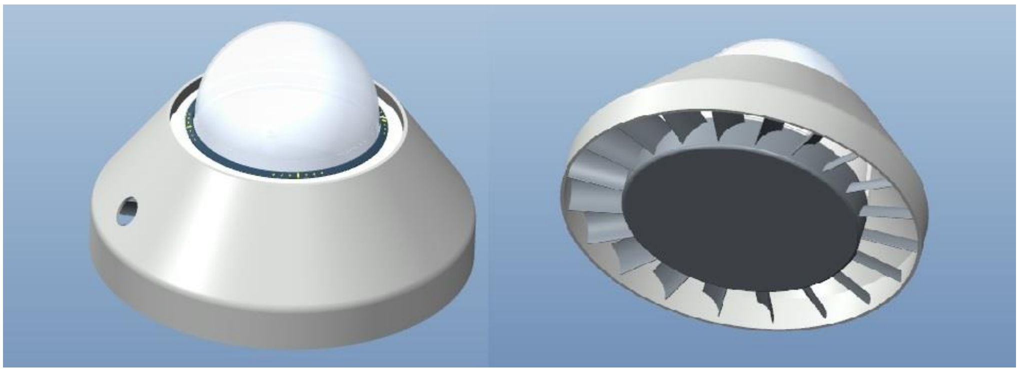

Figure 7-4 Big fan concept

7.3.2 Multiple small fans

Using multiple small fans instead of a single big fan is a way of getting around potential mounting problems. Unlike the big fan solution, by using multiple small fans the camera can be mounted as usual as the fans would sit on the outside of the camera, and not behind it (figure 7-5).

Problematic aspects for this solution mainly consists of questions regarding what airflows can be achieved, using smaller, less powerful fans. Airflow depends on the rotational speed of the motor and the circular area that the blades cover. Smaller fans would cover a smaller area and would have less room to house a powerful motor than one big axial fan, leading to either a smaller airflow, or to greater demands on electrical effects and other fan performance specifications.

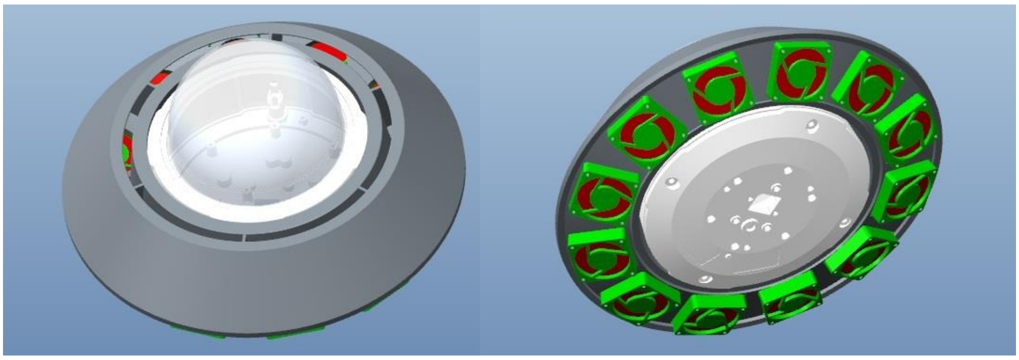

Figure 7-5 Multiple small fans concept containing twelve fans

7.3.3 Dyson fan

The Dyson Air Multiplier (figure 7-6) is a bladeless fan, based on the technology developed by entrepreneur Sir James Dyson. A powerful fan mounted in the pedestal holding the tube takes in air which is fed to the tube. The airflow propagates and builds up pressure within the tube. A small slit allows the air to leave the tube at high speed (figure 7-7). This initial flow produces an induced airflow through the entire tube by entraining surrounding air [47], resulting in a slim, esthetically appealing fan. It can be mounted completely externally which eliminates mounting problems for the camera, as with the option of using multiple small fans. Another advantage is that the Dyson fan runs at very low effects (about 30 W, i.e. less than a normal light bulb) [48].

Problems mainly consist of what wind speeds that can be generated. For the technique to function optimally, the area inside the tube needs to be open to take maximum advantage of the induced air. A camera mounted in the center would block a big part of the tube area, decreasing the efficiency of the fan.

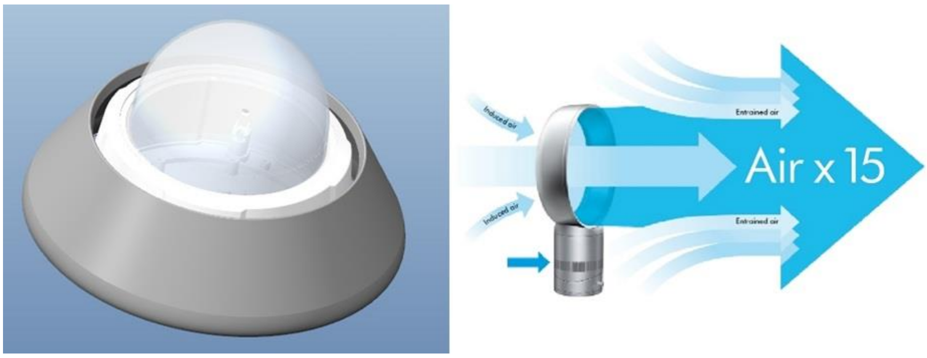

Figure 7-6 Dyson fan concept (left) and Dyson Air Multiplier (right)

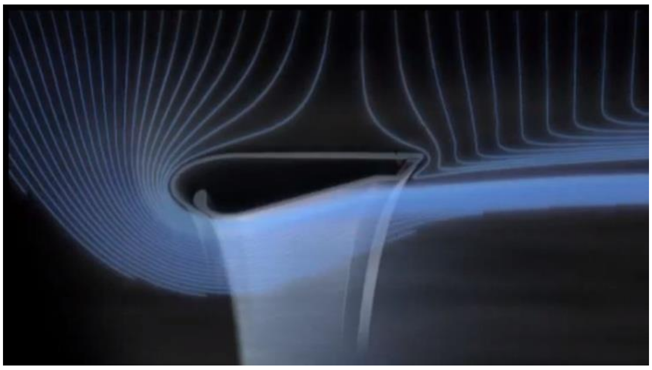

Figure 7-7 Dyson Air Multiplier upper cross section flow

7.3.4 Compressed air

The option of using compressed air is appealing out of several perspectives. The compressor can be placed at a remote location and supply the air through a slim compressed air hose, which of course means less bulkiness around the actual camera compared to e.g. an axial fan. Using compressed air is also a great way to generate very high wind speeds, which if placed and aimed at the surface at a close distance would have a greater chance of detaching and resuspending adhered particles (figure 4-8, p. 22).

The purpose of the solution, however, is to build a permanent air cushion around the dome, meaning the compressor would need to run continuously, generating a lot of noise and pulling electrical effects in the kW range (a standard workshop compressor pulls about 4,0 kW [28]). Out of an economic, environmental and partly ergonomic point of view (due to the loud noise generated), using compressed air continuously is not durable and such a solution would likely meet marketing difficulties. This is why a solution based on compressed air as the source of generating the airflow is ruled out for further consideration already at this stage. Note, however, that if compressed air supply is available through existing infrastructure, it could be a more viable option.

7.4 Air flow simulation

To evaluate the different air supply options, the proposed alternatives were combined with the guidelines from the theoretical section and roughly modeled digitally using the CAD software Pro/ENGINEER Wildfire 5.0. The models were then linked to Autodesk Simulation CFD 2012, a computational fluid dynamics software, which allows for flow simulations in different media. A simulation model was defined and run for all different options. This section reviews the simulated theoretical outcomes, which will be used as a base for selection.

7.4.1 Approach

Apart from the actual model, each simulation also contained a Ø5 meter sphere, to simulate air surroundings. Fan blades were substituted by a solid air part to allow for desired boundary conditions (e.g. wind speed in on one side and gage pressure on the other side). These preconditions do not suffice for a perfect model, as there are other aspects to consider, e.g. outer wind gusts and the fact that a fan consisting of blades will not produce a perfectly straight airflow. They are, however, sufficient to approximate initial wind speeds.

Wind speeds for each case were calculated using a subject fan that was selected for each individual case. Volume flow rates for fans are usually provided in m^3/h. To achieve the generated wind speed (in this case given in mm/s), the volume flow rate was recalculated to velocity using equation (7-1) and the area covered by the fan blades (figure 7-8).

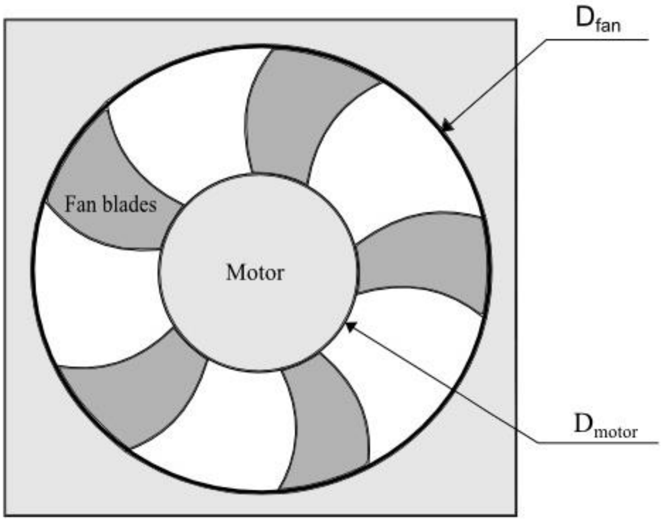

Figure 7-8 Fan dimensions

$$\frac{mm}{s} = \left(\frac{4}{\pi\left(D_{fan}^2 - D_{motor}^2\right) \cdot 3600 \cdot 10^{-9}}\right) \cdot \frac{m^3}{h} \qquad (7\text{-}1)$$

For example, a fan with a volume flow rate of 100 m^3/h and dimensions D_{fan}=100 mm and D_{motor}=50 mm would, according to the theoretical model, produce the initial wind speed:

$$\left(\frac{4}{\pi(100^2 - 50^2) \cdot 3600 \cdot 10^{-9}}\right) \cdot 100 = \mathbf{4,715.7}\ \frac{\boldsymbol{mm}}{\boldsymbol{s}}$$

Note that defining velocity as the acting boundary condition in the simulation model is merely for the purpose of a more convenient setup. Volume flow rate [Q] is still the decisive element to achieve high wind speeds near the dome. If static pressure is constant in an incompressible flow, Q is constant, meaning whatever flow generated by the fan (Q_1) must also leave the outlet/nozzle (Q_2) [42, p. 50].

$$Q_1 = Q_2 \rightarrow\ v_1 A_1 = v_2 A_2 \qquad (7\text{-}2)$$

Since Q_1 is always known, the outlet velocity, v_2, can ideally be controlled by modifying the outlet area, A_2. Pressure is not constant and air is a compressible medium, however, meaning exact practical values cannot be achieved using this model but the basic principle still applies; a smaller outlet area equals higher outlet velocities, which is why the volume flow rate of the fan is the decisive specification.

For the purpose of easier comparison between the simulation results, the numerical scale was held fix for every simulation, resulting in less nuanced differences within the less successful simulation results, but a better overview when comparing different methods with each other. Finding top wind speeds for the less successful results is obtained by either probing or by using both variable and fix scales.

7.4.2 Preliminary test prototype

As a first step, the preliminary test prototype from chapter 6 was modeled, using the dimensions and specifications of the duct fan [37], to provide the theoretical results of the preliminary test prototype. This way, it can be used as a reference when compared with the different air supply options, as the results from the preliminary tests are known.

The dimensions and volume flow rate (280 m^3/h) of the duct fan produced, according to equation (7-1), initial wind speeds of about 6,000 mm/s. The result from the simulation is displayed in figure 7-9.

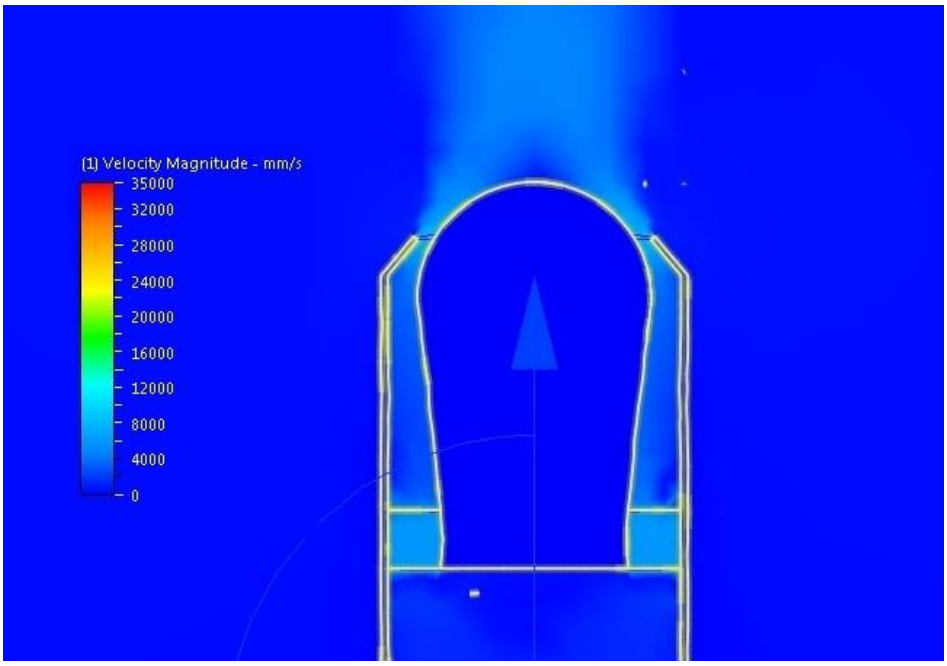

Figure 7-9 Simulated wind speeds for the preliminary test channel jet with funnel

As expected, the flow did not reach the top of the dome, as the wind speeds leaving the outlet, in this case the area between the dome and the tip of the funnel, reached values at about 8,000 mm/s.

7.4.3 Big fan

The big fan concept was tested for various designs, each with different tweaks such as different outlet area sizes, with and without the inner wall and different shapes on the outer wall radius. The simulation displayed in figure 7-10 reached the best results, which also confirmed the significance of the design guidelines from the theory section (p. 49), as the best big fan concept design was the one that followed all guidelines strictly.

The dimensions and volume flow rate (815 m^3/h) of the selected subject fan [49] produced, according to equation (7-1), initial wind speeds of about 9,000 mm/s.

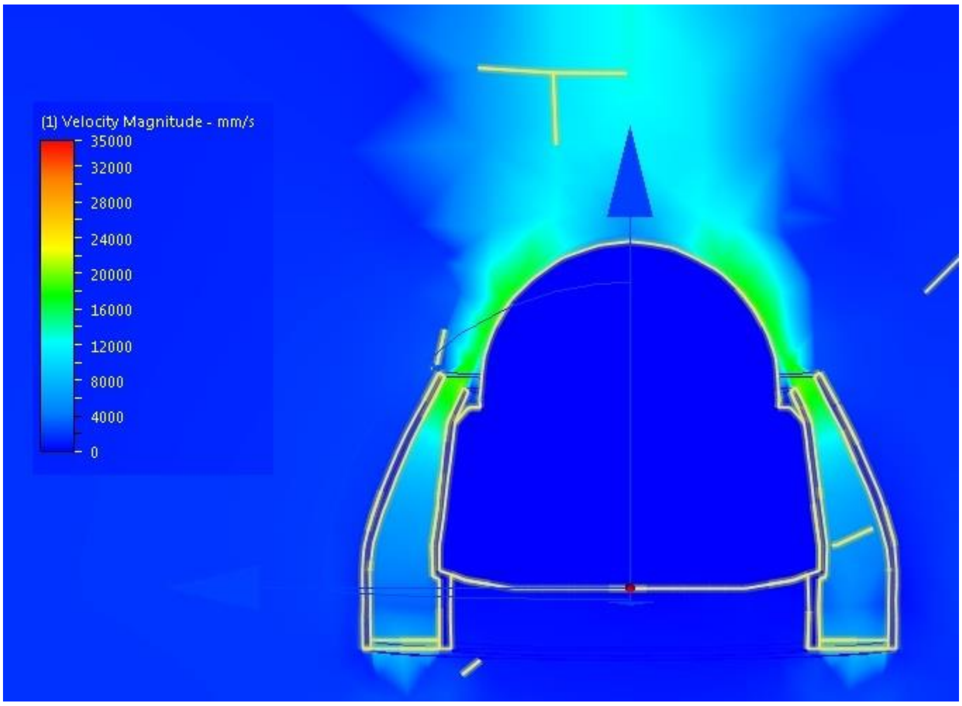

Figure 7-10 Simulated wind speeds for the big fan

Again, wind speeds are too high to creep along the dome surface to cover the top of the dome, but the prioritized area (displayed shaded in figure 7-3, p. 49) seems very well protected by this design as wind speeds here exceeds 15,000 mm/s at any given point.

7.4.4 Multiple smaller fans

The diameters of the subject fans (figure 7-11) were only 40 mm, making it possible to fit twelve fans around the dome. To compensate for their lesser power, walls were modeled to reduce the outlet area to increase the outlet wind speeds.

The dimensions and volume flow rate (6 m^3/h) of the twelve selected subject fans [50] produced, according to equation (7-1), initial wind speeds of about 1,800 mm/s.

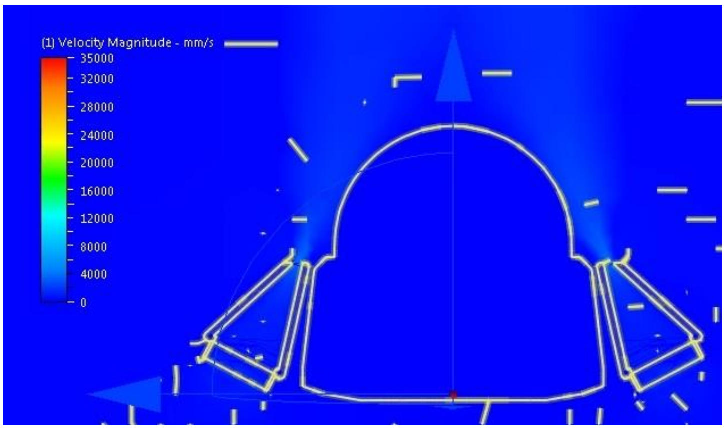

Figure 7-11 Simulated wind speeds for the multiple small fans

Because of the extremely low volume flow rate generated by each fan (6 m^3/h), the model did not have much effect at all. Although difficult to tell, probing showed that outlet speeds reached values at about 6,000 mm/s but the volume flow rate was simply not sufficient to build a satisfactory barrier. More powerful fans would have improved the results, but at the expense of higher demands on electrical effects.

7.4.5 Dyson fan

The Dyson technology took several years to develop, meaning an accurate simulation model is difficult to achieve. The model displayed in figure 7-12 was designed, inspired by the cross section dimensions of a Dyson Air Multiplier. It was simulated without the camera at first to confirm that the model had the desired effect.

The dimensions and volume flow rate (110 m^3/h) of the selected subject fan [51] produced, according to equation (7-1), initial wind speeds (at the slit) of about 10,000 mm/s.

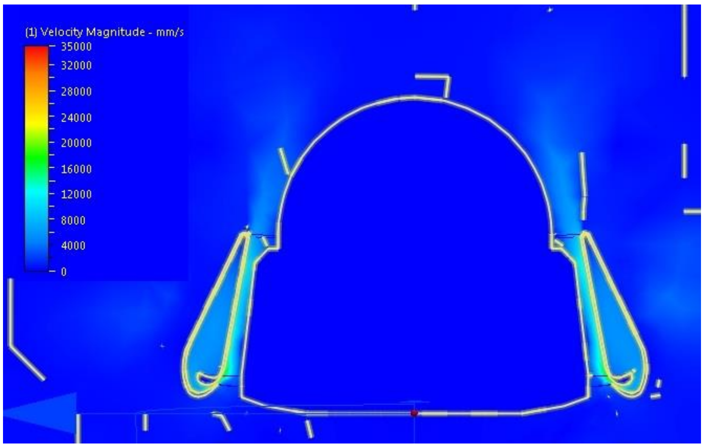

Figure 7-12 Simulated wind speeds for the Dyson fan

As predicted, having the camera blocking the area inside the pipe eliminated the possibility to generate air entrainment along the initial flow near the slit. Wind speeds at the slit reached values that exceeded 20,000 mm/s but at a very small area, which was not sufficient to cover the dome.

7.4.6 Selection of air supply method

The results are not completely accurate, due to e.g. coarse mesh settings and too few iterations run to reach convergence. This approach was deliberate, since there were numerous simulations to run and increased accuracy means a more time consuming analysis. Therefore, provided velocity values at this point are not absolute, but sufficient to distinguish the different methods from each other.

When comparing the different outcomes of each option, it is obvious that the big fan solution is the best way of generating high wind speeds around the dome, simply because its bigger area generates much higher volume flow rates than the alternatives. Therefore, using a big fan mounted behind the camera is deemed to be the best option to achieve satisfactory results, and will thus be implemented on the prototype.

7.5 Prototype design

The first step in putting together a prototype of this nature is finding a suitable fan, as adjacent components will depend on its dimensions. The dimensions of the fan are also important to ensure that generated air is possible to transport smoothly to the channels along the camera housings outer periphery, i.e. the diameter of the fan is preferably slightly larger than the camera housing diameter, to not force extra bends, causing energy losses.

With low energy consumption, high volume flow rate and desirable dimensions as decisive criteria, the *ebm-papst W1G200* (figure 7-13) [52] was an adequate choice. A CAD model of the fan was made using technical drawings to facilitate further modeling and for simulation purposes (figure 7-13). A CAD model of the Axis P5512 PTZ camera was provided by Axis.

Figure 7-13 ebm-papst W1G200 fan (left) and CAD model (right)

Table 7-1 Technical specifications for chosen prototype fan

ebm-papst W1G200	
Mass	2.13 kg
Fan blade diameter	200 mm
Volume flow rate (Max)	1090 m^3/h
Electrical effect (Max)	55 W
Rotational velocity (Max)	2950 rpm
Noise (Max)	60 dB
Maximum back pressure	120 Pa

Table 7-1 above displays some of the selected fan's technical specifications [52]. The camera supplies about three times as much flow as the duct fan from the preliminary channel jet test and it pulls 55 W, slightly more than a regular light bulb.

With gathered information from simulation and theory, the modeling of a possible solution was initiated. Since the outer diameter of the camera housing is larger than the motor of the fan, an adapter (figure 7-14) was desirable to guide the airflow towards the camera housings outer periphery. For assembling purposes, it was designed to take advantage of the existing holes of the fan and camera housing. This part would also act as an adapter between fan and camera housing to make room for a protruding Ethernet cable. To avoid a bulky design, the height of the adapter was set to 30 mm, just enough to route the Ethernet cable through the side of the adapter. To isolate the hole where the Ethernet cable is pulled through, a rubber gasket was used.

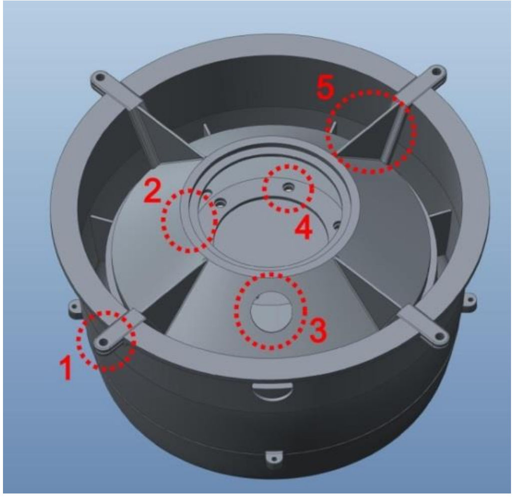

Figure 7-14 The adapter mounted between the fan and the camera housing

1. Ears with holes, aligned with the holes on the fan to facilitate assembling.
2. Cap to prevent air from reaching the inside of the adapter and provide easy access to mount the adapter to the camera housing.
3. Penetration for Ethernet cable. A rubber gasket will seal any gaps.
4. Screw holes aligned with holes of camera housing
5. Flanges to help strengthen the adapter design and to keep the airflow evenly distributed.

A main body (figure 7-15) was designed to help guide the generated airflow towards the nozzle. It consists of an inner and an outer wall, designed to avoid pressure losses. To help align the camera to a snug fit, the surface of the inner wall facing the camera was shaped as the outer surface of the camera housing. As the performed simulations are theoretical, a variable size of the nozzle outlet would make an optimal airstream easier to establish. A variable outlet could, for example, be achieved by using an elastic material or by using exchangeable nozzles with different dimensions.

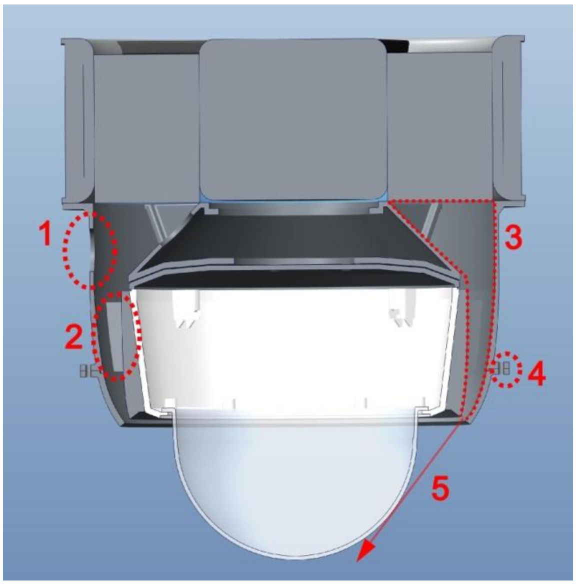

Figure 7-15 Main body with mounted nozzle

1. Penetration for Ethernet cable. A rubber gasket will seal any gaps.
2. Flanges to support the inner wall.
3. A cavity for the airflow including large radii and smooth area transitions at the lower part.
4. Holes aligned with holes of nozzle to provide easy assembly.
5. Outlet pointed at tangent of dome.

The proposed solution thus consists of four parts, camera excluded (figure 7-16):

1. An axial fan dimensioned slightly larger than the outer dimensions of the camera housing to ensure large flow along the outer periphery of the housing.
2. An adapter between the fan and the camera, which should distribute the airflow from the fan evenly and also act as a connection between fan and camera.
3. A body, wherein the airflow is directed towards the dome. The inner wall is designed to fit the shape of the camera housing to provide a natural lock-in, but also to facilitate all air to leave the outlet in the same direction (perpendicular to the outlet plane).
4. Exchangeable nozzles with different outlet areas, which is connected to the body via screw joints.

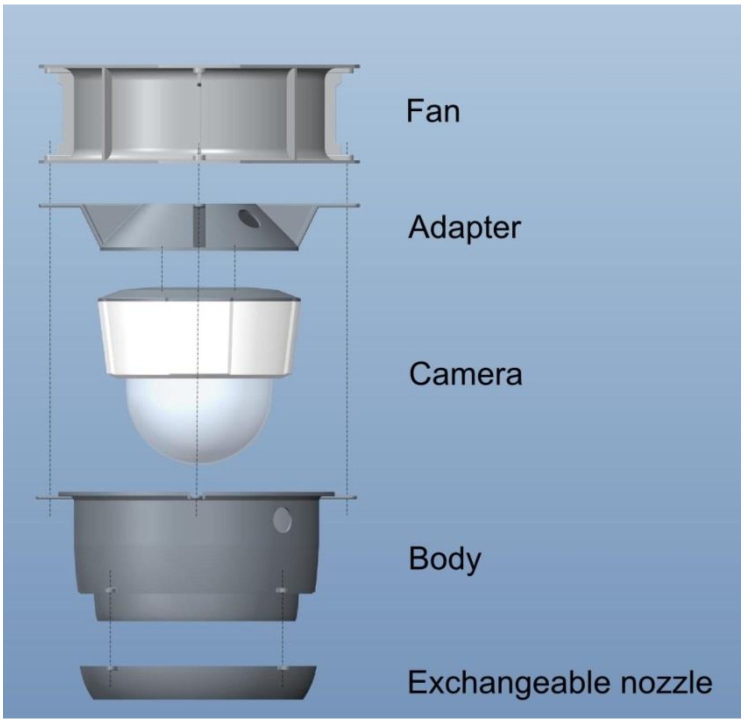

Figure 7-16 Exploded assembly view of the proposed prototype

The adapter is connected to the camera using standard screws on existing holes. As the camera is lowered into the body, it will auto align thanks to the shape of the inner wall of the body. An Ethernet cable, providing power and network accessibility is then connected to the camera and led through the gaskets in the adapter and the body. The assembly is then connected to the fan with screws through the ears of the adapter, the body and the mounting holes on the fan, secured by screws. Finally one of the exchangeable nozzles is connected to the main body using screws and nuts. The appearance of the assembled prototype is displayed in figure 7-17.

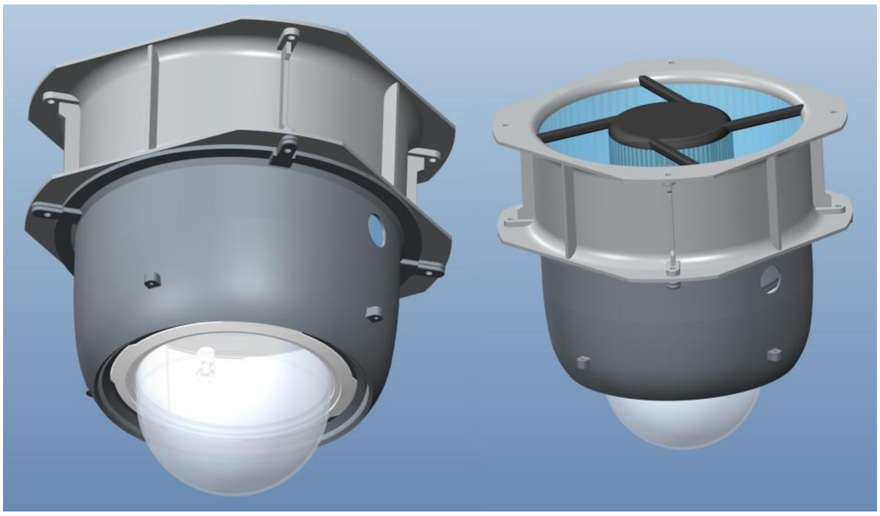

Figure 7-17 Digital model of the prototype proposal

An air flow simulation was conducted for the proposed prototype, using the same software and principals as the simulations from section 7.4. This time, however, a more accurate result was desirable, which is why mesh settings were modified to generate more elements (about 1,500,000 elements compared to about 300,000 elements in section 7.4). In addition to this, the simulation was run until it converged, which was after about 1,000 iterations, compared to 300 iterations in section 7.4. This simulation took about 7 hours, compared to about 1.5 hours in section 7.4. The results from the simulation are displayed in figures 7-18 and 7-19.

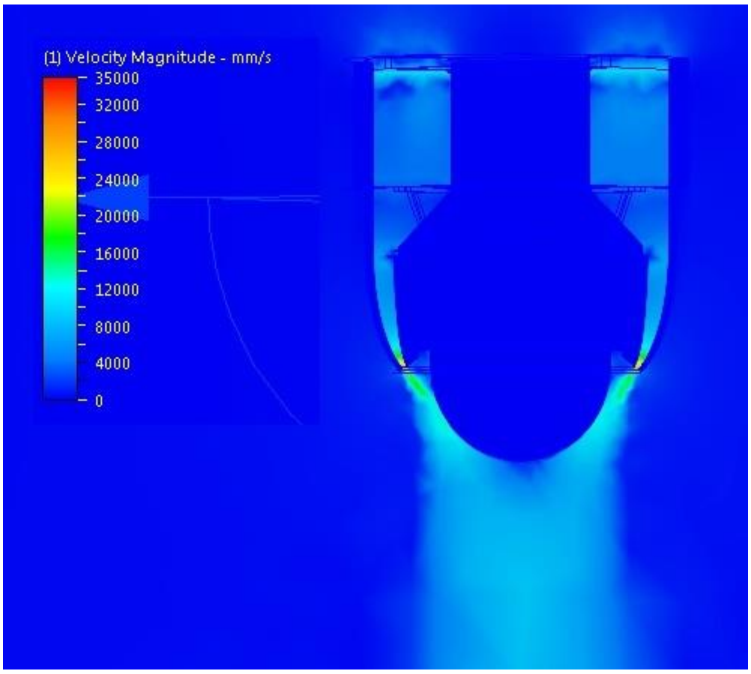

Figure 7-18 Simulated wind speeds for the proposed prototype

Probing showed that the air flow near the outlet reached velocities of about 30,000 mm/s. velocities at the prioritized area reached about 15,000 mm/s, which is significantly higher than that of the preliminary test.

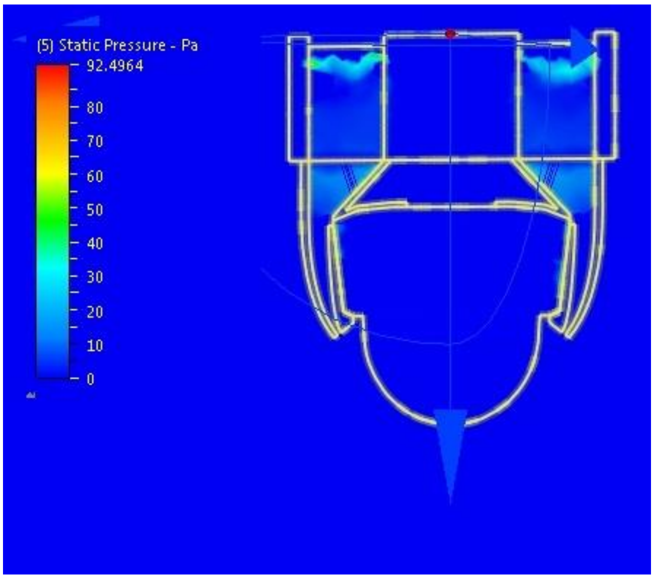

Figure 7-19 Simulated static pressures (>0 Pa) within the prototype

The maximum static pressure obtained using this outlet gap size (2mm) was 92.5 Pa. This value is important. The fan, according to table 7-1, can only withstand a back pressure of 120 Pa, which leaves a safety factor of

$$\frac{120\ Pa}{92.5\ Pa} \approx 1.3$$

when the fan is run at full effect. This does not leave a very wide margin, which is why the smallest gap on the manufactured nozzles will be at least 3 mm.

7.6 Prototyping

Since the prototype consists of rather complex shapes and demands tight tolerances, building it manually was deemed too difficult. Instead, contact was taken with a rapid prototyping company in Ystad called GT Prototyper (GTP). With usage environment and other specifications in consideration, GTP suggested manufacturing the prototype using Selective Laser Sintering (SLS) [53] which is based on using carbon dioxide laser to fuse small particles of plastic into a mass with desired shape [54].

The material used was polyamide (more specifically PA2200), as it is an easily processed material, exhibit sufficient properties in terms of stiffness and temperature resistance. Polyamide is used in e.g. electric power tool covers. Its main drawback for the purpose of the prototype is that polyamide absorbs excess moisture from surrounding air, which can alter the mechanical properties and dimensional stability. This problem can, however, be prevented by infiltrating a substance which reduces water absorption [32, pp. 19-20].

Before the prototype was ordered, a structural analysis was conducted to make sure that the product would endure the applied forces and that no plastic deformation would occur in the designed model. The analysis was set up using the assembled model from Pro/Engineer Wildfire 5.0 and connecting it to the simulation software Ansys Workbench 13. The material properties of PA2200 [55] were assigned, gravitational forces (9.81 m/s^2) were added to all parts and the weight of the camera (1.1 kg) [56] was transformed into Newton force and distributed over the three screws holding the camera from the adapter. The results are displayed in figures 7-20 and 7-21.

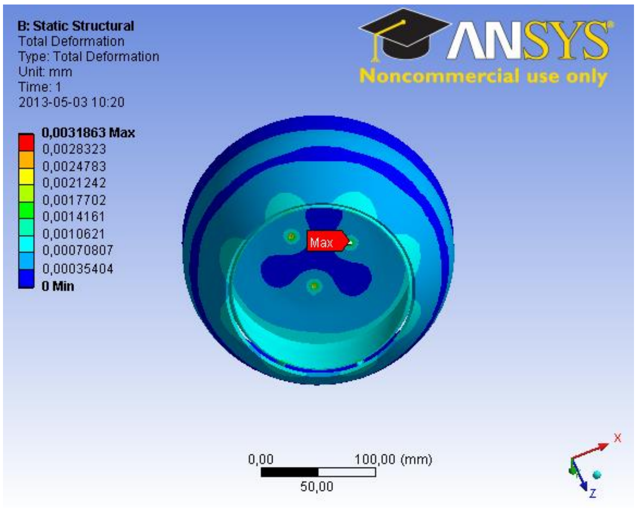

Figure 7-20 Total deformation

The maximum deformation when the camera is mounted will be about 3 µm, which is negligible in relation to the size of the different components of the structure.

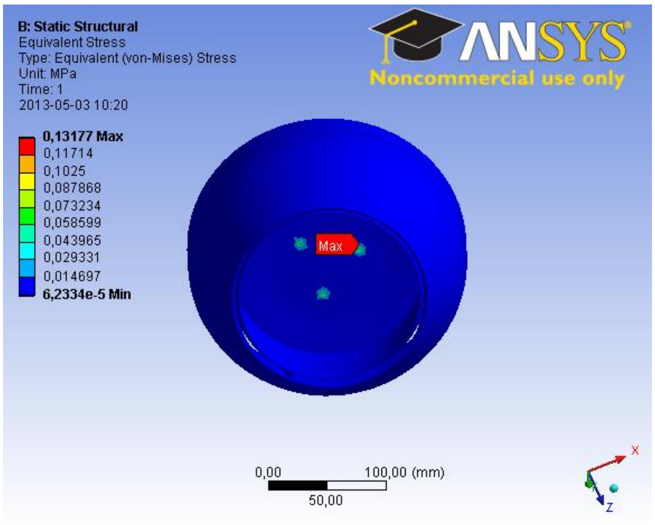

Figure 7-21 Equivalent von Mises stresses

The maximum equivalent von Mises stresses are obtained around the screws, but only reach a value of about 0.13 MPa. The safety factor displays the ratio between the material's yield strength (the limit where plastic deformation will occur) and the perceived von Mises stresses. PA2200 yield strength is 48 MPa [55]. The safety factor for this scenario would thus be

$$\frac{48\,MPa}{0.13177\,MPa} \approx 364$$

meaning the prototype will withstand applied forces with a wide margin.

With the sufficiency of the material properties and structural analysis confirmed, the prototype was ordered. Two different exchangeable nozzles were ordered with outlet width of 3mm and 8mm respectively for evaluation purposes. The real prototype is displayed in figure 7-22. More pictures of the printed parts can be viewed in Appendix A, pp. 97-101.

Figure 7-22 The prototype

7.7 Antistatic coating

Polycarbonate, the material used in the dome of the camera, is an excellent electrical insulator [57], which is useful for some aspects, but devastating when having a constant air flow hitting the dome surface, as with the case of the prototype. When the air molecules hit the surface, air friction causes a static build up in the material, a type of triboelectrification [58]. Since the material has high electrical resistivity, it will stay charged, increasing the adhesive ability of the dome due to larger electrostatic forces on particles.

To prevent unnecessary sticking of particles, a dome either of antistatic material or treated with antistatic coating would be desirable for this type of dirt repelling solution. The antistatic layer added is often conductive, meaning it will spread any excessive charges evenly on the surface [59]. To further eliminate any static electricity, the conductive surface can be grounded to operate in the same way as a lightning rod.

By using additives or coatings, deterioration of the optical properties of the dome is unavoidable. However, if the coating or additive reduces the risk of excessive contamination of the dome, the optical properties after a long period of time might still be significantly better than an untreated dome.

Coatings on substrates of this sort can be applied using one of the following options:

- Spraying
- Dip-coating
- Vacuum depositing

Spraying and dip-coating usually involve the coating being mixed with a volatile fluid such as ethanol, which quickly evaporates, leaving an even layer of coating [60]. These methods are often cheap to use, but leave a short-term effect on the substrate. By using a vacuum chamber to chemically bond the coating to the substrate, a longer lasting effect is possible but also makes the process more expensive and the lead time longer.

For field testing purposes, a short time effect is acceptable and re-application is also possible. Hence, the antistatic spray *PRF 8*-88 was chosen (figure 7-23) [61].

Figure 7-23 Transparent, antistatic spray

7.8 Filtering

As mentioned earlier, it is very likely that the air barrier needs to consist of clean air for the solution to fulfill its purpose. Several different types of filters were therefore tested on the fan alone, to evaluate the loss of flow they caused. HEPA filters, vacuum cleaner dust bags and kitchen fan filters were tested, with unsatisfactory results as the flow was significantly reduced.

One of the initial ideas was to couple the solution with a cyclonic filter, to eliminate the need for filter replacements. However, developing and optimizing a functional cyclonic filter is a complex task, requiring extensive theoretical research. The idea was therefore not further explored for this thesis, but still deemed to be an interesting and potential approach, if developed.

If cleaning with contaminated air should prove to be an issue, further investigations of filtering solutions need to be highly prioritized to make the proposed solution viable.

8 Field Testing

To evaluate the designed proof of concept prototype, field testing needs to be conducted. To achieve credibility, a thorough test protocol needs to be formed so the tests can be performed under fair and systematic manners. Further, a relevant way of measuring the test results needs to be established to enable easy interpretation and comparison of the different outcomes.

8.1 Approach

With the prototype assembled and fully functional, a field test was conducted in order to assess its ability to perform under difficult circumstances. The main purpose of the solution is to reduce the need for maintenance in terms of manual cleaning. In order to properly evaluate the developed prototype, it would have to be monitored over a longer period of time. To obtain quick results and initially confirm its functionality, an accelerated test was performed which would simulate a very dusty environment for a shorter amount of time.

8.2 Test environment

An accelerated test was designed for the specific requirements. A sealed tent (3x3 meters) was used as test environment to act as a large dust chamber. To create the dust necessary for the test, an angle grinder was used to grind a concrete slab which generated concrete dust. This dust mostly contains of quartz particles with sizes ranging from 1-100 µm [62], which is similar to the dust generated in open pit mining. It is considered to generate a very extreme environment as the small distances will “throw” particles towards the dome and circulate within the tent.

Two Axis P55 cameras was used throughout the testing, one modified with the proposed solution and one unmodified acting as a reference. These were mounted 1.5 meters away from each other on a T-pole to minimize the influence of the fan on the reference camera (figure 8-1). A Power over Ethernet switch handled the electricity and connectivity of the cameras. The fan was connected to an adjustable power supply unit (PSU) to enable different electrical inputs.

Figure 8-1 Proposed solution and reference camera, mounted in test environment

After connecting all equipment, the cables were led outside to monitor the test in a safe environment.

Initially, the intention was to form an evaluation protocol based on numbers to get a quantitative value on the improvement, by e.g. measuring number of particles that adhered to the dome surface, measuring changes in light transmittance etc. Consulting with Axis representatives, however, revealed that such tests are difficult to design and there are many different things to measure, meaning a single number describing the picture quality is difficult to achieve and could also be irrelevant because of the many aspects to consider [63]. Their proposal was instead to only use photo images and simply compare pictures to each other. Different objects and a test image (figure 8-2) were therefore placed in the tent to evaluate differences in picture qualities between different solutions and the reference camera. These images will be combined with camera pictures taken from outside the dome to display exterior differences.

Figure 8-2 Reference objects for picture quality evaluation

Since the main purpose of the testing was to evaluate if a constant airflow is enough to deflect contaminants from the dome, the fan was connected to a ventilation pipe through the roof of the tent, bringing clean air from the outside, to eliminate the need for air filtering. Filtering is of course an issue, but in order to determine if the airflow repel contaminants, this was set aside for the proof of concept evaluation.

8.3 Test structure

Two different settings were used on the PSU to achieve different volume flow rates from the fan. The numbers in Table 8-1 are taken from the fan's technical specification data sheet [52].

Table 8-1 Fan settings

Setting	Voltage	Rotational velocity	Current	Volume flow rate
High	24 V	2950 rpm	2.60 A	1095 m^3/h
Low	16 V	2145 rpm	2.18 A	565 m^3/h

To determine the efficiency of the solutions, the field test consists of six individual tests to evaluate different combinations, as seen in Table 8-2.

Table 8-2 Test structure matrix

Test No.	Antistatic treatment	Fan setting	Nozzle size	Air source
#1	No	High	8 mm	Outside
#2	No	Low	8 mm	Outside
#3	No	Low	3 mm	Outside
#4	No	High	3 mm	Outside
#5	Yes	-	-	Outside
#6	No	-	-	Inside

Note that fan velocity and nozzle size for test #6 will use the settings from the most successful result from test #1 – test #4, to evaluate what happens when using contaminated air as source. The settings for test #5 will also depend on the results from test #1 – test #4.

For the purpose of equal preconditions, the reference camera will be used and photographed after every test, as the test method is not perfected, meaning some factors might be coincidental, leaving different results on the reference camera.

For safety and repeatability, a test protocol was compiled:

1. Mount and connect the cameras (test subject and reference) and verify their functionality.
2. Point the cameras at the point where the reference object/picture is visible. The settings of the cameras should be identical.
3. Make sure the test environment is sealed tight, except for inlet and outlet of the prototype.
4. Start the fan, using the predetermined settings and make sure the inlet and outlet of the test environment is working satisfactory.
5. Take pictures of the reference object/picture with the cameras before the test. Also take photos of the cameras, their domes and housings before the test begins.
6. Wear safety goggles, protective overall and suitable respiratory equipment before entering the test environment.
7. Grind the concrete slab with the angle grinder for about one minute, enough to create a proper dust cloud.
8. Gently step out of the test environment and wait for about 5 minutes, to allow the dust to settle. This will be enough to achieve visible results.
9. Clear the test environment from all the dust. Take photos of the camera domes and housings and use the contaminated cameras to take pictures of the reference objects and the test image, through the dome.
10. Clean the camera domes and repeat step 5-10 for the following tests.

9 Results / Proof of concept

The results from the accelerated field test are displayed in this chapter, using pictures taken both from outside and inside the dome. The displayed results follow the same order as Table 8-1. The results from this test are then to be used in the upcoming, more extensive field test. The chapter ends with commentaries and conclusions on the different outcomes to discuss which factors hold more or less significance on the results.

9.1 Nozzle size: 8 mm, Fan setting: High

The exterior results from the first setting (using the nozzle with larger outlet and higher electrical effect) are displayed in figure 9-1.

Figure 9-1 Protected dome (left) and unprotected reference dome (right)

The protected dome was close to unaltered after grinding the concrete slab. The small areas that did get contaminated were thin and evenly distributed, which did not have a significant impact on visibility. The reference got severely contaminated. The concrete dust gathered in amassed clusters which resulted in picture quality deviations.

9.2 Nozzle size: 8 mm, Fan setting: Low

The exterior results from the second setting (using the nozzle with larger outlet and lower electrical effect) are displayed in figure 9-2.

Figure 9-2 Protected dome (left) and unprotected reference dome (right)

The results, using the same nozzle as test #1 but about half the electrical effect on the fan, were similar. The protected dome did, although hard to tell from the picture above, allow more concrete dust breakthrough. The dust that adhered was still evenly distributed, unlike the reference, where the dust formed agglomerates and clusters on the surface.

9.3 Nozzle size: 3 mm, Fan setting: Low

The exterior results from the third setting (using the nozzle with smaller outlet and lower electrical effect) are displayed in figure 9-3.

Figure 9-3 Protected dome (left) and unprotected reference dome (right)

Using a low electrical effect on the smaller nozzle had a counterproductive effect as the dome got even more contaminated than the reference. It is clearly visible where the airflow hits the dome (the line with higher dust concentration) and the contamination covered the entire dome below the line.

9.4 Nozzle size: 3 mm, Fan setting: High

The exterior results from the fourth setting (using the nozzle with smaller outlet and higher electrical effect) are displayed in figure 9-4.

Figure 9-4 Protected dome (left) and unprotected reference dome (right)

Although slightly better than the previous test, generating a higher flow through the smaller nozzle did not produce satisfactory results either. The contamination is more evenly distributed, but still severe, which affected visibility significantly.

9.5 Antistatic treated dome

The purpose of this test was to determine the effects of an antistatic coating. To be able to evaluate how an antistatic coating acts with different preconditions, both cameras were coated on half the dome. The settings chosen for the protected camera were those of the second test (8 mm nozzle, low electrical effect), as the intention was to use an efficient setting, but not too efficient, as the antistatic effects would not provide the same visible results on a completely clean dome. The exterior results from the fifth test are displayed in figure 9-5, where the right halves in both pictures are coated.

Figure 9-5 Protected dome with antistatic coating (left) and antistatic coated reference dome (right)

Coating the dome with the spray had the same effects on both domes. The coated half displayed a more even distribution, as predicted from section 7.7, which differs from the left halves (and earlier tests) where the dust still form agglomerates which produce stains on the picture, rather than altering the entire picture through an even distribution.

9.6 Contaminated air source

As this test was conducted to determine the significance of filtering the air source, the settings from the most successful test was used, in this case meaning the larger nozzle (8 mm) and the higher setting on the fan (24 V, 2.6 A) from the first test (figure 9-1). The exterior results from the sixth test are displayed in figure 9-6.

Figure 9-6 Protected dome (left) and unprotected reference dome (right)

Using unfiltered air caused even worse contamination than that of the reference camera. Even though more evenly distributed, the protected camera attracted large quantities of dust, which covered the entire dome.

9.7 Pictures through dome cover

To achieve the most significant differences in picture quality when taking still pictures through the dome, pictures from the first and most successful test were chosen, along with pictures from the reference camera. The results are displayed in figure 9-7 and figure 9-8.

Figure 9-7 Picture from protected camera before (left) and after (right) contamination

The picture taken after grinding the concrete slab, although displaying a grey shade as the surrounding air was not entirely cleared, did not contain any stains or deviations.

Figure 9-8 Picture from unprotected reference before (left) and after (right) contamination

As seen on the lower right of the picture taken after grinding the concrete slab, there were clusters of dust on the camera lens, in this case producing defined lines and deviations in the picture.

9.8 Conclusions[4]

Based the results of the field tests, a few conclusions were drawn:

- Building the air barrier with contaminated air is not a viable option, meaning an efficient way of filtering the air source without losing to much volume flow rate is essential.
- The nozzle outlet size seems to have more significance than the volume flow rate, as the larger nozzle provided much better results for both fan settings than the smaller nozzle. A too small nozzle seemed to create powerful whirls which “threw” the dust towards the dome surface, rather than to repel it.
- The antistatic spray caused the dust to spread evenly on the surface, rather than forming defined clusters.

An overall conclusion was that the method, with the right dimensions, fan settings and filtering, had a successful outcome and is worth considering developing to a final product.

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[4] Conclusions drawn by Alfred Ekermo, Victor Norell, Thomas Ekdahl and Magnus Jendbro

10 Final design proposal

As the accelerated test had a satisfactory outcome, thus confirming the principle solution of sending air from behind the camera to build a protective barrier, this chapter intends to provide Axis with a proposal on how to implement the solution on a final design if the more extensive field test should also display satisfactory results as well. Guidelines on a suitable manufacturing method will also be presented.

10.1 Aesthetic design

The current prototype was designed and tested for proof of concept purposes. The prototype, with the bulky fan mounted close to the actual camera, is not very appealing out of an aesthetic point of view. Consulting with different Axis representatives led to the conclusion that the less noticeable the solution, the better [64].

Further discussions revealed that the most common way of mounting the P5512 is by using a wall bracket (figure 10-1) where the Ethernet cable is led through a hollow pipe. If the air supply to the prototype air channel could come from the hollow pipe, it would mean smaller modifications around the camera itself, as it would also eliminate the need for the adapter and other features, added to compensate for the mounting issues obtained by placing the fan behind the camera.

Figure 10-10-1 Axis P5512 PTZ mounted on wall bracket

By placing standoff screws between the camera housing and the mounting plate on the bottom of the pipe to create a distance between the camera and pipe (figure 10-2), then it is possible to mount an air guiding body, using the same guidelines as for the prototype of the project. The only question that remains is how to generate sufficient air flows through the pipe.

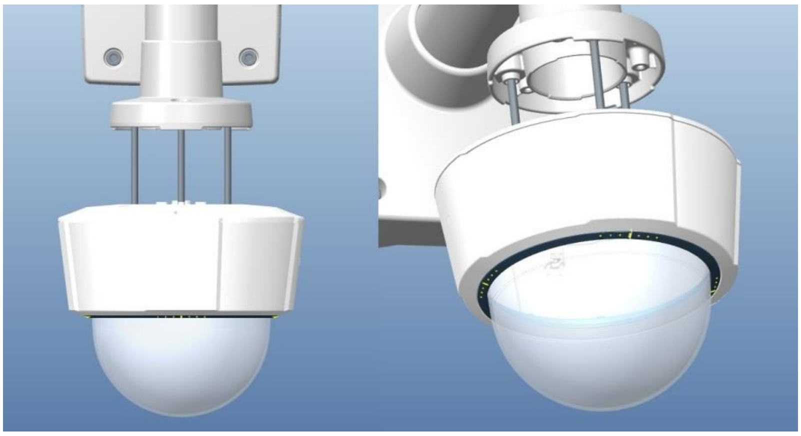

Figure 10-2 Standoff screws between camera housing and bracket

A body leading the air, similar to that of the prototype, was modeled and assembled to the camera mounted on the wall bracket with added standoff screws. A simulation, using the same software and principle settings as for the simulations in chapter 7, was conducted by placing a radial fan below the wall bracket box. The results are displayed in figure 10-3.

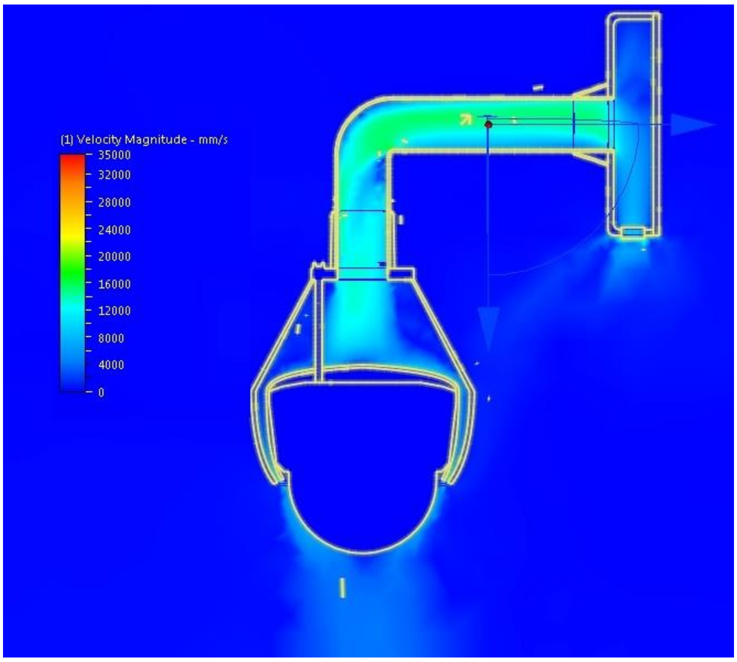

Figure 10-3 Simulated wind speeds of a proposed final design

The simulation showed that the sharp 90 degree bends cause pressure losses which reduce the wind speed significantly.

The model was rendered using the software Bunkspeed Shot. The result (figure 10-4) should be seen as a proposal of how a final design could look, if the question of air supply can be solved, e.g. by pressurizing the box.

Figure 10-4 Rendered proposal of a final design

10.2 Manufacturing

As mentioned earlier, the prototype in this project was designed and tested for proof of concept purposes, i.e. the crucial issue was to establish if building an air barrier around the dome is sufficient to keep contaminants away. Therefore, the design mainly focused on design for functionality. There were some design for manufacture and design for assembly, but merely to ensure that the prototype would function desirably, and was thus not optimized. If a final product were to be implemented, then other factors will need to be taken into consideration and further optimized to reach satisfactory results on all levels.

The current outdoor version of Axis P5512 PTZ comes with a protective sunshield (figure 10-5), designed to reduce temperature rise around the camera induced by UV radiation. The air guiding body would replace this shield and provide the same function, meaning producing the product in the same material as the sunshield (PC/ASA) would be sufficient. PC/ASA has got high impact strength, good dimension stability under high temperatures and is UV resistant, all essential properties for the application in question [65].

Figure 10-5 Sunshield for Axis P5512 PTZ

PC/ASA is also suitable for injection molding, which would be the recommended manufacturing method, as the method allows complex products to be made in one piece, without any demands on post processing. General rules apply for the molding process [32, pp. 123-136], including

- using radii around edges to distribute tension stresses evenly.
- placing ingot hole(s) strategically for an even material distribution.
- keeping even wall thickness to reduce the risk of warping etc.
- considering all of the materials specific properties, so that essential criteria are not neglected.
- integrating many functions in the same detail to minimize post processing and assembling.
- increasing rigidity using ribs, rather than solid flanges.
- avoiding tight tolerances to avoid high manufacturing costs.
- using suitable merging methods to avoid tension sensitive areas
- etc…

A common problem when injection molding complex details containing cavities is that confluence lines are inevitable. Areas with confluence lines are generally weaker than other areas and thus more vulnerable to strains [32, p. 135]. However, PC/ASA melt has got low viscosity [65], which reduces the negative effects of confluence lines as meeting flows blend easier, the lower the viscosity of the fluid. Further, the product will not be exposed to large external forces, meaning drawbacks by using injection molding, such as confluence lines, will not have a significant impact.

11 Discussion

Based on the objective of the project, the outcome of the accelerated field test was satisfactory, as it resulted in a successful concept on how to prolong the time between manual maintenance in the delimited environment. All aspects, such as dimension optimization and a functioning filtering solution were not fulfilled, due to the slim extent of the project, but a thorough theoretical base has been founded to use for further work on the problem. Further work will also be conducted by Axis Communications. The results, presented to the department Product Concepts and New Ideas, along with about 30 other Axis employees, were well received and deemed to be sufficiently promising to proceed with the project.

As mentioned already in the introduction, there is a countless number of environments, particle materials and sizes and consequently countless scenarios where adhesive forces and characteristics differ. Finding a single solution, using a supply that is available regardless of environment that can handle any thinkable scenario is more or less unrealistic. It was therefore deemed necessary to use strict delimitations to narrow down the objective to a single environment, so that generation and evaluation would not get straggly. The downside is that the proposed solution is niched, and a positive result in the delimited environment does not necessarily imply positive results in other environments.

Even though the concept of building a protective air barrier around the dome focused on repelling dust, the solution can or will have a few positive side effects:

- Dew- and frost formations might find it difficult to settle, while the fan is running around the clock. By installing some kind of radiator or other heat generating mechanism close to the air source, one could also eliminate heavy snow from gathering on the dome.
- The sunshield would no longer be necessary as the air guiding body would have the same effect. It might even be a better option as the airflow would help to cool the camera on sunny days.
- A similar problem to that of contamination (i.e. a problem that lowers picture quality) was that insects and in some cases birds move on the dome surface, either blocking the view themselves or by leaving trails blocking the view. It is also common that spiders crawl in to the space between the sunshield and the camera housing, spinning webs [64]. All of these problems are eliminated as running a fan, generating high wind speeds along the camera housings outer periphery produces an inhospitable environment for these kinds of creatures.

12 Recommendations

As results have been achieved and discussed, the only thing that remains is to provide recommendations on how to pursue, based on this project's outcome and theory. Due to the complex nature of the problem, recommendations will be divided into a short term and a long term version, to take technological development and future possibilities into account.

12.1 Short term recommendations

To pursue the solution of this report, the primary task would be to investigate all possibilities on how to generate a sufficient airflow to make e.g. the final design proposal (figure 10-4, p 77) functional, but also to further investigate optimization of volume flow rates, outlet sizes, filtering (e.g. by looking into custom designed cyclonic filtering) and other aspects depending on mounting environment. If a sufficient flow of clean air can be achieved, then the used design guidelines for the prototype can be copied onto a final design.

If the mounting environment is such that continuous airflow is not a necessity, then using compressed air could be a viable option to use, e.g. in pulses when dust concentrations in the surrounding air are high. In such a scenario, it could be of interest to develop some kind of device or function that can sense dust concentrations and control on and off settings via a predetermined threshold value. If the air source can adjust generated flow, then a sensor could set the volume flow rate to suffice for the actual conditions, to minimize energy consumption, which could be desirable if the solution should pull higher effects than the prototype of this thesis (55W).

12.2 Long term recommendations

Repelling contaminants with the use of piezo transducers, capable of inducing vibrating frequencies at an ultra-sonic level, is an area to further investigate. The technique is currently used e.g. in digital cameras to clean the image sensor from dust. If a similar solution at a larger scale is applicable on the camera dome and it is possible to expose all adhered particles to their eigenfrequencies under a reasonable amount of time without blurring the picture or damaging the internal electronics of the camera, this solution would be likely to generate enough acceleration to detach adhered particles and is therefore an interesting principle to investigate.

Other approaches to consider in the future are those of hydrophobia and hydrophilia. As nanotechnology coatings are rapidly improving their ability to perform, this area should be closely monitored. The superhydrophobic and superhydrophilic coatings available for testing were not technically perfected for the purpose of this project as they got worn out and lost their ability rather quickly. Nano-coatings with impressive performance have already been presented, but are not yet available on a wide market. A camera dome with superhydrophobic abilities would prevent water based products to stick to the surface. Dry contaminants would easily wash away with rain, which would be suitable for Axis' outdoor cameras.

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Figure 2-1 PM size comparison from U.S. EPA
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Figure 4-2 A superhydrophobic lotus leaf
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Figure 4-3 Superhydrophobic surface
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Figure 4-4 Superhydrophilic surface (upper left) and an uncoated reference (lower right)
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Figure 4-6 Superhydrophobic insect wing
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Figure 4-7 Surface with (left) and without (right) static tension build-up
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Figure 4-8 Particle removal due to different wind speeds and particle sizes
[7, p.146]

Figure 4-9 Turbulent air cushion concept sketch
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Figure 4-10 Air shield cone concept sketch
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Figure 4-11 Channel jet concept sketch
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Figure 4-12 Cyclonic filter concept sketch
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Figure 4-13 Theoretical and experimental values on the efficiency of cyclonic filters [6, p.99]

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Figure 4-15 Film roll concept sketch
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Figure 4-16 Dirt bike goggles with film roll
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Figure 4-17 Pneumatic pistons concept sketch
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Figure 4-18 Vibration plate concept sketch
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Figure 4-19 Ultra-/Megasonic cannons concept sketch
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Figure 4-20 Piezo electric element concept sketch
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Figure 4-21 Rotating dome concept sketch
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Figure 4-22 Contact wiper concept sketch
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Figure 4-23 Non-contact wiper concept sketch
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Figure 4-24 Eyelid concept sketch
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Figure 4-25 Pyrolytic cleaning concept sketch
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Figure 4-26 Jet ring concept sketch
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Figure 6-1 Test dome halfway coated with graphite spray
Photography taken by Victor Norell

Figure 6-2 Channel jet prototype with dust chamber suspension
Photography taken by Victor Norell

Figure 6-3 Modified channel jet prototype to achieve air cushion mechanism
Photography taken by Victor Norell

Figure 6-4 Air shield cone prototype
Photography taken by Victor Norell

Figure 6-5 Air jet ring prototype
Photography taken by Victor Norell

Figure 6-6 Vibration plate prototype
Photography taken by Victor Norell

Figure 6-7 Dust test chamber with inlet, filtered outlet and suspension lid
Photography taken by Victor Norell

Figure 6-8 Contaminated reference dome
Photography taken by Victor Norell

Figure 6-9 Channel jet before (left) and after (right) testing in dust chamber
Photography taken by Victor Norell

Figure 6-10 Air cushion before (left) and after (right) testing in dust chamber
Photography taken by Victor Norell

Figure 6-11 Air shield before (left) and after (right) testing in dust chamber
Photography taken by Victor Norell

Figure 6-12 Air jet ring before (left) and after (right) testing
Photography taken by Victor Norell

Figure 6-13 Vibration plate before (left) and after (right) testing
Photography taken by Victor Norell

Figure 7-1 Axis P5512 PTZ
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Figure 7-4 Big fan concept
Made in Creo parametric 2.0 by Alfred Ekermo

Figure 7-5 Multiple small fans concept containing twelve fans
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Made in Autodesk simulation CFD 2012 by Alfred Ekermo and Victor Norell

Figure 7-11 Simulated wind speeds for the multiple small fans
Made in Autodesk simulation CFD 2012 by Alfred Ekermo and Victor Norell

Figure 7-12 Simulated wind speeds for the Dyson fan
Made in Autodesk simulation CFD 2012 by Alfred Ekermo and Victor Norell

Figure 7-13 ebm-papst W1G200 fan (left) and CAD model (right)
http://www.ebmpapst.se/sv/dat/media_manager/pid/1729/product-image/image.jpg.meta/large.jpg (left) 29 April 2013, Made in Creo parametric 2.0 by Victor Norell (right)

Figure 7-14 The adapter mounted between the fan and the camera housing
Made in Creo parametric 2.0 by Alfred Ekermo and Victor Norell

Figure 7-15 Main body with mounted nozzle
Made in Creo parametric 2.0 by Alfred Ekermo and Victor Norell

Figure 7-16 Exploded assembly view of the proposed prototype
Made in Creo parametric 2.0 by Victor Norell

Figure 7-17 Digital model of the prototype proposal
Made in Creo parametric 2.0 by Alfred Ekermo and Victor Norell

Figure 7-18 Simulated wind speeds for the proposed prototype
Made in Autodesk simulation CFD 2012 by Alfred Ekermo and Victor Norell

Figure 7-19 Simulated static pressures (>0 Pa) within the prototype
Made in Autodesk simulation CFD 2012 by Alfred Ekermo and Victor Norell

Figure 7-20 Total Deformation
Made in ANSYS Workbench 13 by Victor Norell

Figure 7-21 Equivalent von-Mises stresses
Made in ANSYS Workbench 13 by Victor Norell

Figure 7-22 The prototype
Photography taken by Alfred Ekermo

Figure 7-23 Transparent, antistatic spray
https://www1.elfa.se/data1/wwwroot/assets/large/8081648-01.jpg, 20 May 2013

Figure 8-1 Proposed solution and reference camera, mounted in test environment
Photography taken by Victor Norell

Figure 8-2 Reference objects for picture quality evaluation
Photography taken by Victor Norell

Figure 9-1 Protected dome (left) and unprotected reference dome (right)
Photographies taken by Alfred Ekermo

Figure 9-2 Protected dome (left) and unprotected reference dome (right)
Photographies taken by Alfred Ekermo

Figure 9-3 Protected dome (left) and unprotected reference dome (right)
Photographies taken by Alfred Ekermo

Figure 9-4 Protected dome (left) and unprotected reference dome (right)
Photographies taken by Alfred Ekermo

Figure 9-5 Protected dome with antistatic coating (left) and antistatic coated reference dome (right)
Photographies taken by Alfred Ekermo

Figure 9-6 Protected dome (left) and unprotected reference dome (right)
Photographies taken by Alfred Ekermo

Figure 9-7 Picture from protected camera before (left) and after (right) contamination
Photographies taken by Magnus Jendbro through Axis web interface

Figure 9-8 Picture from protected camera before (left) and after (right) contamination
Photographies taken by Magnus Jendbro through Axis web interface

Figure 10-1 Axis P5512 PTZ mounted on wall bracket
http://www.theinstallershop.co.uk/content/images/thumbs/0001006_axis_p5512_compact_indoor_ptz_12x_zoom_dome_ip_camera.jpeg, 8 May 2013

Figure 10-2 Standoff screws between camera housing and bracket
Made in Creo parametric 2.0 by Alfred Ekermo

Figure 10-3 Simulated wind speeds of a proposed final design
Made in Autodesk simulation CFD 2012 by Alfred Ekermo and Victor Norell

Figure 10-4 Rendered proposal of a final design
Made in Bunkspeed Shot by Alfred Ekermo

Figure 10-5 Sunshield for Axis P5512 PTZ
http://www.axis.com/products/video/accessories/images/product_list/sunshield_5800-151_large.jpg, 22 May 2013

Figure A-1 Nozzles
Photography taken by Victor Norell

Figure A-2 Nozzle outlet angles
Photography taken by Victor Norell

Figure A-3 Mounting ears
Photography taken by Victor Norell

Figure A-4 Adapter
Photography taken by Victor Norell

Figure A-5 Adapter
Photography taken by Victor Norell

Figure A-6 Adapter aligned with camera bottom
Photography taken by Victor Norell

Figure A-7 Body
Photography taken by Victor Norell

Figure A-8 Mounting ears and flanges supporting inner walls
Photography taken by Victor Norell

Figure A-9 Nozzle outlet
Photography taken by Victor Norell

Figure A-10 Ethernet cable penetration
Photography taken by Victor Norell

Figure B-1 Project time plan prediction
Made in Microsoft Excel 2010 by Alfred Ekermo and Victor Norell

Figure B-2 Project time plan outcome
Made in Microsoft Excel 2010 by Alfred Ekermo and Victor Norell

Appendix A: Prototype parts

Figure A- 1 Nozzles

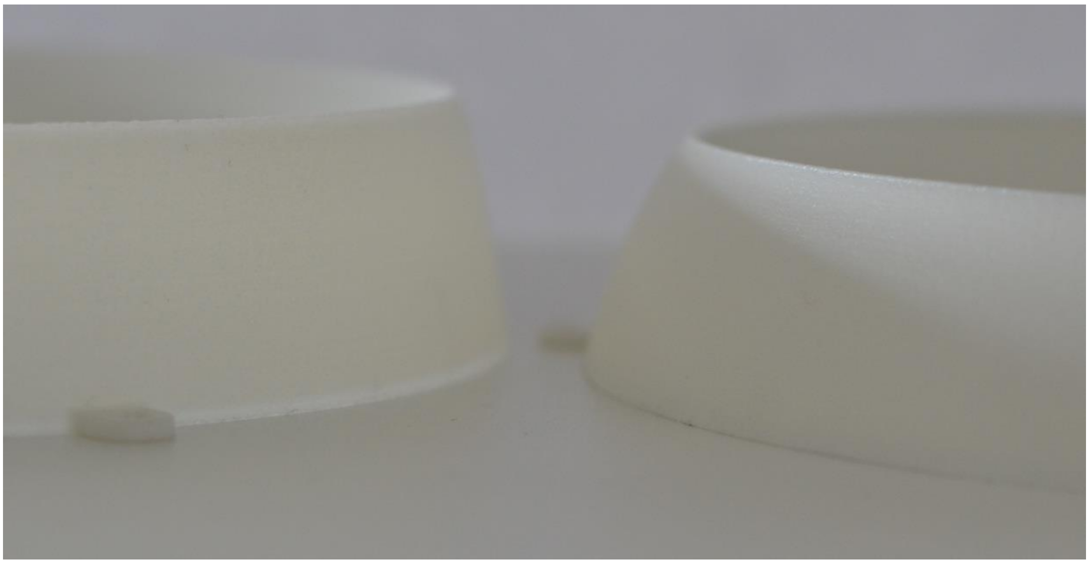

Figure A- 2 Nozzle outlet angles

Figure A- 3 Mounting ears

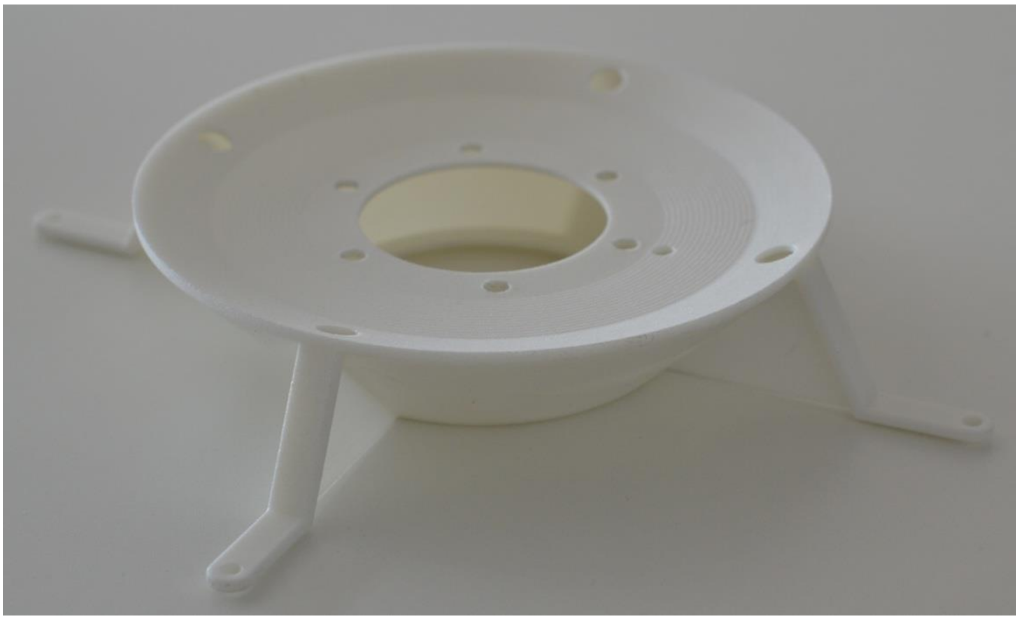

Figure A- 4 Adapter

Figure A- 5 Adapter

Figure A- 6 Adapter aligned with camera bottom

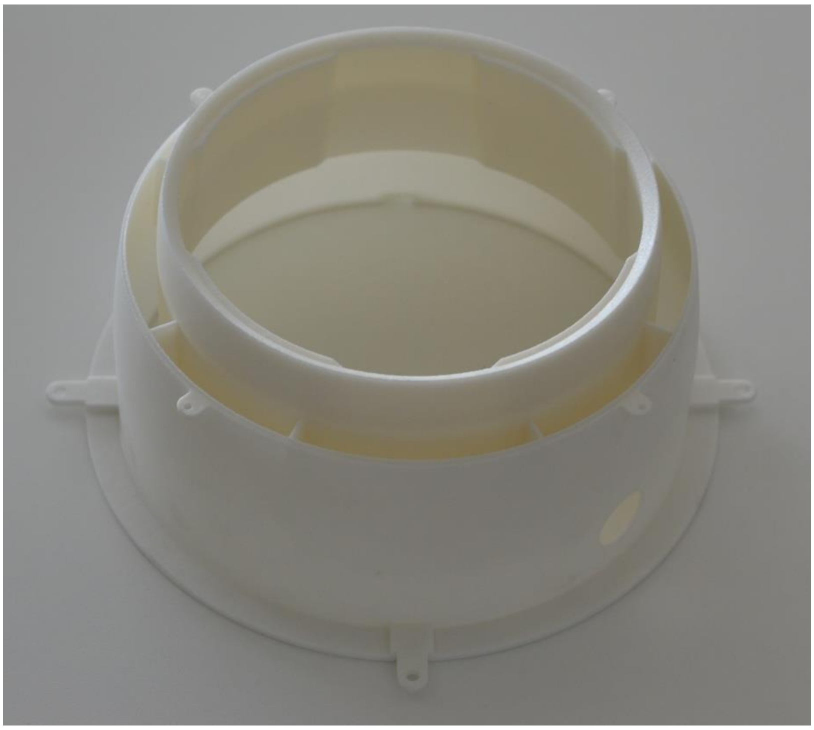

Figure A- 7 Body

Figure A- 8 Mounting ears and flanges supporting inner walls

Figure A- 9 Nozzle outlet

Figure A- 10 Ethernet cable penetration

Appendix B: Workload distribution and project time plans

B.1 Workload distribution

We feel that the workload has been evenly distributed between the both of us. Work structure and other decisive elements have been thoroughly discussed and agreed upon by us both.

For the purpose of a uniform linguistic style, the writing of the report was rather unevenly distributed, i.e. one of us wrote while the other did research, but we always kept each other updated and coordinated.

B.2 Project time plan prediction

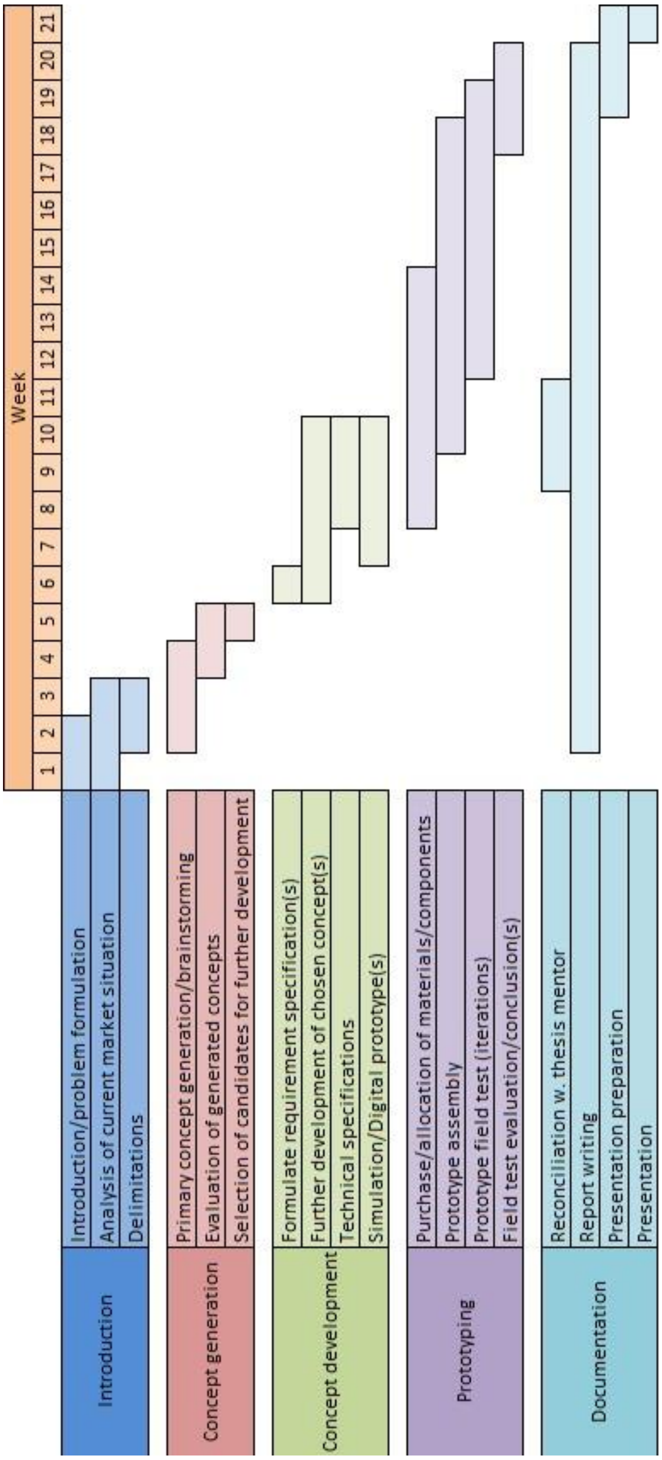

Figure B- 1 Project time plan prediction

B.3 Project time plan outcome

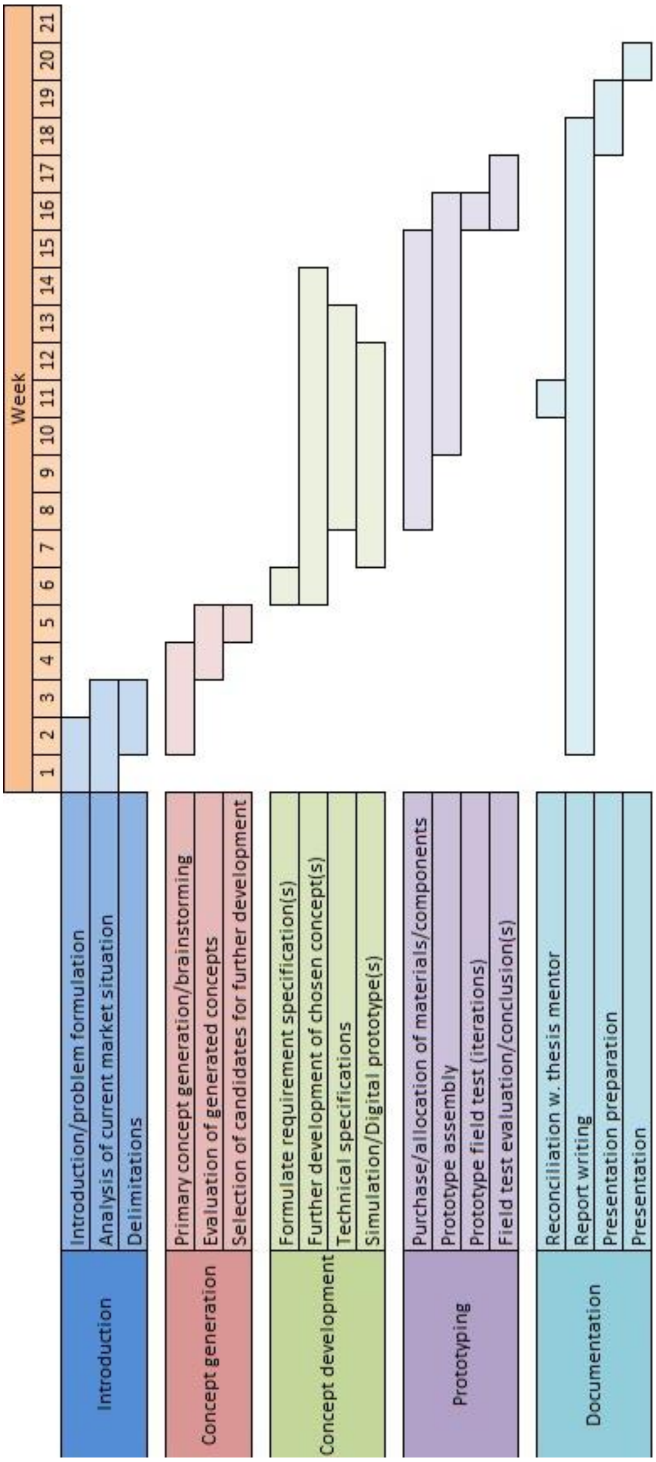

Figure B- 2 Project time plan outcome

Appendix C: Self evaluation

We are both pleased with our performance, as we have been committed and really tried hard to accomplish something of value, which we both feel that we have. Axis are going to proceed with further testing of the prototype, which shows that they too are pleased with the outcome of the project.

If we were to go back and do it all over again, we would have spent less time researching and brainstorming concepts that proved to be unsuccessful, time that could have been spent optimizing the chosen solution. However, such things are difficult to evaluate at early stages and by spending time on “bad concepts”, we did provide a valuable theoretical basis on which principles that have potential and which do not.

We have learned the importance of establishing clear delimitations, to not wander off, but to focus on the main objective. We have also gotten the opportunity to make use of our theoretical knowledge from the university in a real project, and thereby gotten confirmation that five years of studies have yielded results.