Development of a Multirotor Drone Airbag

Udvikling af en multirotor drone airbag

Thesis for the flexible master in product design and innovation

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Title Page

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Abstract

The aim for this thesis was to create social benefit through product development - by creating a safety device that will reduce human injury from impact by a multirotor drone.

Two primary methodologies were utilized: to evaluate social benefit, a sustainability analysis, which assessed the economic, environmental, and social impact of a product; for product development, a lean product development process.

The sustainability analysis was applied to three categories of safety devices: active systems (parachutes, airbags), propeller protection, and crumple zones. Active safety systems provided the highest social benefit. Parachute systems already exist on the market, so airbags were chosen for development.

Drone airbags show promise in applications where drones must operate at low altitude or in close proximity to people or obstacles. An airbag system will increase the cost, weight, and aerodynamic drag of the drone, so it is less applicable in low-risk operations. The airbag has some unique features when compared to parachutes. The main advantages are rapid inflation and the padding effect. The major disadvantage is less aerodynamic drag is generated upon activation.

A prototype airbag system was developed and installed on a 200mm, 200 gram Leora quadcopter drone and field-tested. The system weighed 208 grams, and reduced kinetic impact energy after free-fall from an altitude of 33.5 meter from 130 joules to 20 joules, and impact velocity from 25 m/s to 10 m/s. The airbag inflated in two seconds, stayed inflated for 10 seconds, provided 10 cm of cushioning to the bottom and edges of the drone, and, by use of four drag flaps, gave a drag coefficient of 1.1. The prototype was not aerodynamically self-righting.

A fully-developed drone airbag could represent the first ‘big red button’ (emergency safety stop) for a flying robot. It could detect and react to faults automatically, deploy, and fall safely to the ground. It could also prevent fly-aways.

In the future, the prototype system could be improved: the weight and inflation time could be reduced, and the airbag could be made aerodynamically self-righting or completely cover the drone. The cushioning effect upon impact with a person could be analyzed. An automatic activation method could be developed.

Reading guide

This thesis consists of two main parts: a social benefit analysis, and a product development portion. I use the social benefit analysis to decide which safety device will be most beneficial to develop. In the product development portion, I seek to solve some of the technological challenges, and move the product closer to adoption where it can provide social benefit. Each section of the report is divided into two parts: a social benefit part and a product development part. These two topics are highly interrelated, but are presented in a simplified, linear arrangement for ease of reading.

Abbreviations

1S	One, Series
3D	Three Dimensional
3P	People, Planet, Profit
ABS	Acrylonitrile butadiene styrene
BVLOS	Beyond Visual Line Of Sight
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
CO2	Carbon Dioxide
CSR	Corporate Social Responsibility
DIY	Do-It-Yourself
EPI	Environmental Performance Indicator
KE	Kinetic Energy
LCA	Life Cycle Assessment
LiPo/LIPO	Lithium Polymer
mAh	Milliampere Hour
NaN3	Sodium Azide
ROI	Return On Investment
SDU	Syddansk Universitet (University of Southern Denmark)
SPB	Social Purpose Business
SROI	Social Return On Investment
SW	South-West
Tx	Transmitter
UAV	Unmanned Aerial Vehicle
VR	Virtual Reality
WP	Work Package

Acknowledgement

I would like to thank my advisors Kjeld Jensen and Marianne Harbo Frederiksen for their guidance, feedback, and support during this thesis. Thanks to Davide Giacalone for providing the course ‘scientific reading and writing’, which was highly relevant and perfectly timed, and to Ulrik Schultz for his input regarding academic writing. Thanks to Anders la Cour-Harbo at Aalborg University for sharing his knowledge within drone safety and on the DroneImpact project. Thanks to Reynir Atlason for input on the sustainability analysis, and Brad Beach for his feedback regarding the thesis topic and development. Thanks to Martin Skriver for his insight into the software aspects of drone safety. Thanks to Erik Rudbeck at Para Service, the local parachute repair company, who took the time to share tips and advice on airbag fabrication. Thanks to Søren Jensen for the discussion about airbag inflation chemistry and patents/intellectual property, and Ivar Lund for information about the wind tunnel and aerodynamic testing. Thank you to Christian Wiggers of DroneFyn for letting me observe his multirotor operations and answering my interview questions.

Contents

Introduction

It is estimated that drone technology could create between 12,000 and 15,000 jobs in Denmark by 2050 (Research, 2015) and up to 150,000 jobs throughout the EU (Commission, 2014). With this many people employed to develop drones, it is likely the number of drones will only increase and, along with it, the probability of a drone crashing into a person. Safety concerns could lead to a reduced use of drones close to people, in densely populated urban environments, or in beyond visual line of sight (BVLOS) applications (SDU, 2015), lessening their social and commercial contributions.

Multirotor drones have the potential to be dangerous or even deadly. It has been estimated that the impact energy at a 50% threshold for human fatality is between 25 joules (Cour-Harbo, 2016b) and 200 joules (Radi, 2013a), and that a drone weighing as little as 250 grams could potentially be deadly (Cour-Harbo, 2016b). Injury statistics and medical records document many incidents of human injury, but this data has not been isolated to identify only drone-related injuries. Anecdotal evidence does exist; a drone lacerated singer Enrique Iglesias' hand requiring surgery (News, 2015), and videos on YouTube show drones crashing into people (YouTube, 2013). Some incidents are close-calls that do not result in injury, but are reminders of the possible danger (CNN, 2015; ESPN, 2015).

Figure 1 A drone almost struck World Cup skiing champion Marcel Hirscher. The drone was of sufficient size to cause serious injury. Drones were later banned by the international ski federation (CNN, 2015)

Drone safety devices are implemented in certain contexts and at various levels of effectivity. Some drones incorporate propeller protecting "bumpers" around the propellers, and some less-powerful multirotors utilize soft plastic propellers. Professionals and hobbyists can add a parachute system to increase safety and protect their investment (SkyCat, 2016).

Figure 2 The Aibot X6 incorporates safety bumpers around the propellers as it is used for inspection and is frequently operated in close proximity to structures (X6, 2016).

Airbags have proven to be effective safety devices, used in applications such as automobiles (Wikipedia, 2016), bicycle helmets (Hovding, 2016), and even the mars pathfinder landing system (NASA, 2016). Drone airbags do not currently exist on the market, and therefore represent a development opportunity.

Social benefit is the act of generating social value for society as a whole. A traditional viewpoint regards the pursuit of economic gain as separate from social benefit. In *The Blended Value Proposition: Integrating Social and Financial Returns*, Emerson discusses the examples of a traditional markets and charitable donations (Emerson, 2003). Charitable gifts seek to maximize social returns with no financial return on investment (100% social return), while traditional markets seeks to maximize profits with no defined social return component (100% financial return). Emerson claims this is a false dichotomy - the two are not mutually exclusive and we should seek to maximize both.

Elon Musk is a notable example of a social entrepreneur who has utilized product innovation to rapidly spread social benefit (Schrang, 2015). One of Musk’s missions is to increase usage of renewable energy sources. To do so, instead of making a sizable charitable donation, he has created electric cars (Tesla, 2016), energy storage systems (Powerwall, 2016), and the world’s largest lithium polymer battery factory (Gigafactory, 2016). He has used for-profit methods to grow the business faster early, thereby reaching more people - facilitating the use of renewables, all while providing jobs and making a profit for himself and shareholders. This is the approach taken in this thesis - to maximize social, financial, and environmental impacts.

Project aim

My aim for this thesis is to benefit society by developing a drone safety device, utilizing competencies developed during my masters in product design and innovation studies (the curriculum of the study is listed in the appendix, and the competencies are listed in the competencies map in the appendix). I will utilize a holistic approach, incorporating methods from social science and engineering. The first part of the project will look at social benefit; the second part will focus on technological development.

I will investigate the scenario of a multirotor drone impacting a person. The safety device should maximize social benefit, and the technology should be developed as much as possible to facilitate eventual widespread adoption of the product.

Research questions

I have identified two main research questions, each with a corresponding sub-question:

Social benefit

1. *Which social benefit model should be used for this project?*
    1.1. *Which multirotor drone safety device will benefit society the most?*

Product development

2. *Which product development model should be used for this project?*
    2.1. *What performance characteristics will the multirotor drone safety device have?*

Related work

My previous secondary research *Exploring Knowledge within Unmanned Aerial Systems Mechanical Design and its Influence on Human Injury* (Cawthorne, 2016) gives a detailed account of the mechanics of human injury by drone impact, and includes design recommendations from various sources predicted to reduce human injury. These include: *Human Injury Model for Small Unmanned Aircraft Impacts* (Radi, 2013a), *The Small Unmanned Aircraft Blunt Criterion Based Injury Potential Estimation (Magister, 2010)*, and *Mass Threshold for 'Harmless' Drones* (Cour-Harbo, 2016b).

The DroneImpact project at Aalborg University, led by Anders La Cour-Harbo, is also highly relevant (Cour-Harbo, 2016a). Anders and his team are utilizing an electromechanical rail to accelerate multirotor drones into simulated people or objects. Pieces of pork are used to recreate a crash into a human, and future tests will investigate drones crashing into objects such as vehicle windshields and aircraft wings. The project is ongoing and results have not yet been published, though videos of some of the experiments have been posted (A. University, 2016a).

Drone failure probability (Wu, 2012), safety of drones operated over inhabited areas (Clothier, 2006), failure rate criteria for equivalent level of safety (the same number of fatalities per million flight hours as commercial aviation) (King, 2005), and damage assessment of an aircraft with a drone (Radi, 2013b) have also been written about. Risk perception of the public and its acceptance of drones has also been investigated (R. A. Clothier, Greer, Greer, & Mehta, 2015).

Various methods of determining social value exist; Twan outlines eight of them (Twan, 2008). Other authors include Rothereo et al. (Rothereo, 2007), Olsen (Olsen, 2004), and Emerson (Emerson, 2003).

The idea of sustainable product design has been around for some time, and has been discussed by several authors including Hadfield (Hadfield, 2006) and Hemdi (Hemdi, 2009).

Additional related works will be discussed as they are introduced into the project.

Methods

Overview

Two primary methodologies were used: a sustainability analysis (Hadfield, 2006; B. University, 2016) also called the ‘triple bottom line’, which assesses the economic, environmental, and social impact of a product, and a lean product development process (Dryer, 2014). The sustainability analysis provided context to the topic of social innovation and answered the first research question. The lean product development process was used to develop the device itself and answered the second research question.

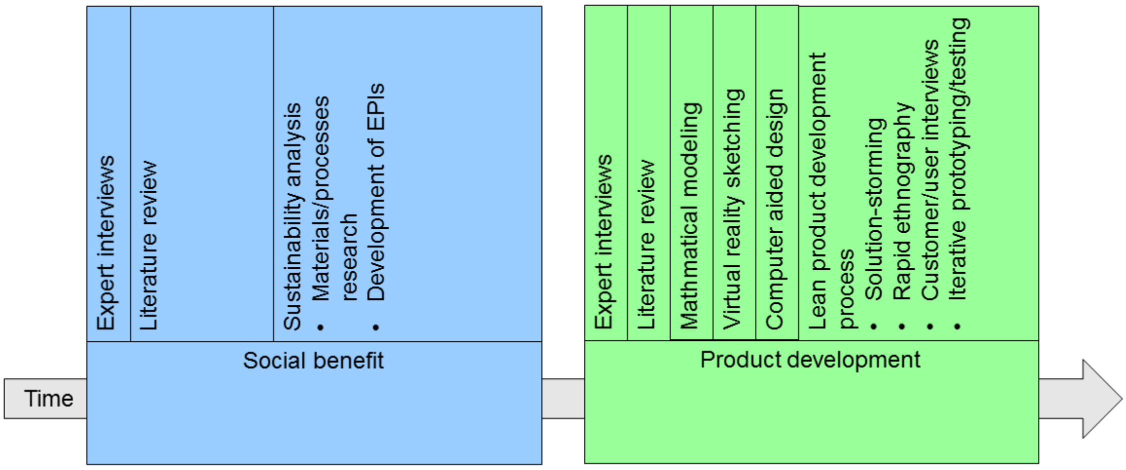
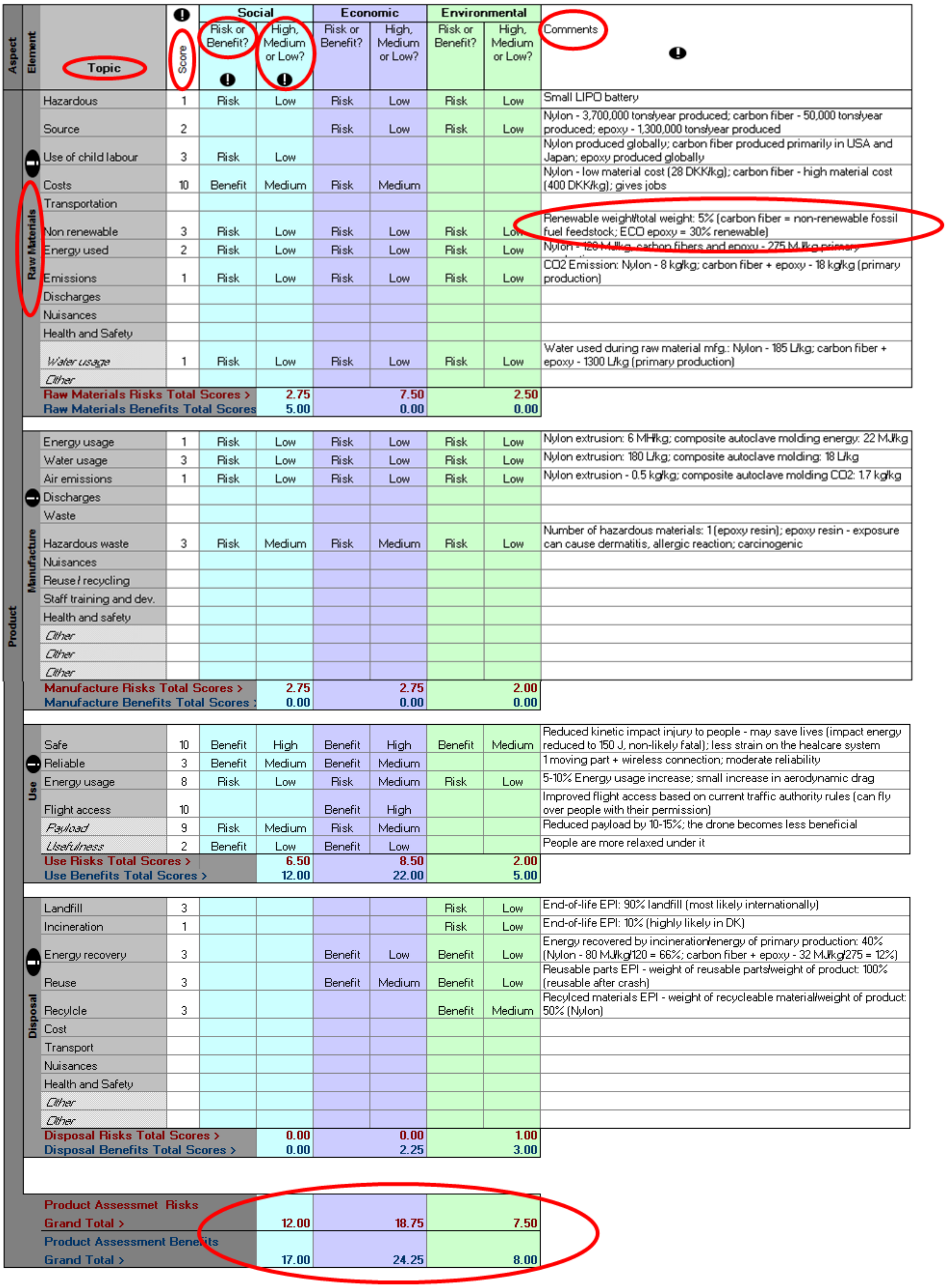


Figure 3 Schematic representation of the most important models used in this thesis, showing the approximate amount of time devoted to each. About half the time was used to investigate social benefit, the other half to product development. The process is depicted as linear, and without interrelations between the two parts for ease of reading. The detailed schedule is in the appendix.

Social benefit

Expert interviews (Atlason, 2016) and the literature review process (L. University, 2016) were used to investigating social benefit and identify a model to apply in the project. The SDU library (SDU, 2016) and Google Scholar (Google, 2016) were used as sources for the literature review. Keywords included: social innovation, social entrepreneurship, social value, social innovation product, social value creation, social return on investment, social value creation product, and triple bottom line.

The Bournemouth University sustainability analysis Excel spreadsheet (B. University, 2016) was used to perform the sustainability analysis - to calculate the most significant economic, environmental, and social benefits and risks of the safety devices, as shown in the figure. The tool is divided into three assessments: 1. Product assessment 2. Company assessment, and 3. Manufacturing site assessment. This thesis only utilized the product assessment portion of the tool.



Aspect	Element	Topic	Score	Social		Economic		Environmental		Comments
				Risk or Benefit?	High, Medium or Low?	Risk or Benefit?	High, Medium or Low?	Risk or Benefit?	High, Medium or Low?	
Product	Raw Materials	Hazardous	1	Risk	Low	Risk	Low	Risk	Low	Small LIPO battery
		Source	2			Risk	Low	Risk	Low	Nylon - 3,700,000 tons/year produced; carbon fiber - 50,000 tons/year produced; epoxy - 1,300,000 tons/year produced
		Use of child labour	3	Risk	Low					Nylon produced globally; carbon fiber produced primarily in USA and Japan; epoxy produced globally
		Costs	10	Benefit	Medium	Risk	Medium			Nylon - low material cost (28 DKK/kg); carbon fiber - high material cost (400 DKK/kg); gives jobs
		Transportation								
		Non renewable	3	Risk	Low	Risk	Low	Risk	Low	Renewable weight/total weight: 5% (carbon fiber = non-renewable fossil fuel feedstock; ECO epoxy = 30% renewable)
		Energy used	2	Risk	Low	Risk	Low	Risk	Low	Nylon - 120 MJ/kg, carbon fibers and epoxy - 275 MJ/kg primary
		Emissions	1	Risk	Low	Risk	Low	Risk	Low	CO2 Emission: Nylon - 8 kg/kg; carbon fiber + epoxy - 18 kg/kg (primary production)
		Discharges								
		Nuisances								
		Health and Safety								
		Water usage	1	Risk	Low	Risk	Low	Risk	Low	Water used during raw material mfg.: Nylon - 185 L/kg; carbon fiber + epoxy - 1300 L/kg (primary production)
		Other								
		Raw Materials Risks Total Scores >			**2.75**		**7.50**		**2.50**	
		Raw Materials Benefits Total Scores			**5.00**		**0.00**		**0.00**	
	Manufacture	Energy usage	1	Risk	Low	Risk	Low	Risk	Low	Nylon extrusion: 6 MH/kg; composite autoclave molding energy: 22 MJ/kg
		Water usage	3	Risk	Low	Risk	Low	Risk	Low	Nylon extrusion: 180 L/kg; composite autoclave molding: 18 L/kg
		Air emissions	1	Risk	Low	Risk	Low	Risk	Low	Nylon extrusion - 0.5 kg/kg; composite autoclave molding CO2: 1.7 kg/kg
		Discharges								
		Waste								
		Hazardous waste	3	Risk	Medium	Risk	Medium	Risk	Low	Number of hazardous materials: 1 (epoxy resin); epoxy resin - exposure can cause dermatitis, allergic reaction; carcinogenic
		Nuisances								
		Reuse / recycling								
		Staff training and dev.								
		Health and safety								
		Other								
		Other								
		Other								
		Manufacture Risks Total Scores >			**2.75**		**2.75**		**2.00**	
		Manufacture Benefits Total Scores >			**0.00**		**0.00**		**0.00**	
	Use	Safe	10	Benefit	High	Benefit	High	Benefit	Medium	Reduced kinetic impact injury to people - may save lives (impact energy reduced to 150 J, non-likely fatal); less strain on the healcare system
		Reliable	3	Benefit	Medium	Benefit	Medium			1 moving part + wireless connection; moderate reliability
		Energy usage	8	Risk	Low	Risk	Medium	Risk	Low	5-10% Energy usage increase; small increase in aerodynamic drag
		Flight access	10			Benefit	High			Improved flight access based on current traffic authority rules (can fly over people with their permission)
		Payload	9	Risk	Medium	Risk	Medium			Reduced payload by 10-15%; the drone becomes less beneficial
		Usefulness	2	Benefit	Low	Benefit	Low			People are more relaxed under it
		Use Risks Total Scores >			**6.50**		**8.50**		**2.00**	
		Use Benefits Total Scores >			**12.00**		**22.00**		**5.00**	
	Disposal	Landfill	3					Risk	Low	End-of-life EPI: 90% landfill (most likely internationally)
		Incineration	1					Risk	Low	End-of-life EPI: 10% (highly likely in DK)
		Energy recovery	3			Benefit	Low	Benefit	Low	Energy recovered by incineration/energy of primary production: 40% (Nylon - 80 MJ/kg/120 = 66%; carbon fiber + epoxy - 32 MJ/kg/275 = 12%)
		Reuse	3			Benefit	Medium	Benefit	Low	Reusable parts EPI - weight of reusable parts/weight of product: 100% (reusable after crash)
		Recylcle	3					Benefit	Medium	Recylced materials EPI - weight of recycleable material/weight of product: 50% (Nylon)
		Cost								
		Transport								
		Nuisances								
		Health and Safety								
		Other								
		Other								
		Disposal Risks Total Scores >			**0.00**		**0.00**		**1.00**	
		Disposal Benefits Total Scores >			**0.00**		**2.25**		**3.00**	
		Product Assessmet Risks Grand Total >			**12.00**		**18.75**		**7.50**	
		Product Assessment Benefits Grand Total >			**17.00**		**24.25**		**8.00**	

Figure 4 Product assessment portion of the sustainability analysis tool (B. University, 2016), with important elements circled in red. Subcategories for the product assessment are based on the product life cycle (raw material through disposal). Under each subcategory are several topics. Each topic is given an importance score and evaluated to be either a benefit or risk. Most subcategories contain environmental performance indicators (EPIs) in the comments column. Developed from: (B. University, 2016) EPI Data source: (CES, 2016)

Each of these assessments is divided into subcategories; for example, the product assessment is divided based on the product life cycle: raw materials, design, manufacture, distribution, use, disposal (though the design and distribution phases were not included in the analysis). Under each subcategory are several topics which should be assessed. For example, under the ‘raw materials’ category, topics include: hazardous materials, non-renewable materials, and energy used to produce the materials. In general, the template provided by Bournemouth was followed, but occasionally it was modified or additional criteria were included - for example, under the raw materials category the topic ‘water usage’ was added so the amount of water used during the manufacturing of the raw materials was considered.

Each topic is given a subjective importance score between one and ten, one being almost no importance, ten being very important. The importance scores are based on subjective customer input gathered during the ethnographic study, my own subjective assessment based on experience working within the drone industry, and objective materials and manufacturing data from the CES EduPack material database software developed by Cambridge University (CES, 2016) (data listed in the ‘comments’ column) which was then used to calculate environmental performance indicators (EPIs).

EPIs are often dimensionless quantities that are utilized early in the design process to quickly quantify environmental aspects of a product. Several are used in the analysis; for example, the recyclable material EPI, calculated by dividing the weight of recyclable material in the product by the the total weight of the product to give a dimensionless quantity (the percentage of recyclable material). The extensive catalogue of 250 EPIs that has been created at the Danish Technical University (Issa, 2015) was utilized. It is not possible to directly map the results of each EPI to the Bournemouth model, so a subjective rating must be developed.

Each topic is assessed for economic, environmental, and social impact: is it a benefit or a risk? and how significant is the impact? (low, medium, or high) The software then multiplies the importance score (one through ten) by the impact level (low = 0.25, medium = 0.5, high = 1.0) giving a result between zero and ten. Sub-totals are calculated for each subcategory (for example, within the ‘raw materials’ subcategory, the total environmental risk score is given.) The total risks and benefits for economic, environmental, and social impacts are shown at the bottom of the sheet.

The software ranks the impact score of each individual topic to identify the specific top five risks and benefits, which are displayed in a radar chart as shown in the figure. The radar charts are divided into three sections - one each for economic, environmental, and social impact. The total area of each radar chart indicates the cumulative top five benefits or risks, though the top benefit might not be the same topic as the top risk. New radar charts were created that eliminate topics which were not considered in this analysis.

Three relevant categories of safety devices were assessed against the sustainability model, with highest priority given to social benefit over economic or environmental benefit.

Product development

Product development models were identified and assessed with respect to compatibility with my competences (listed in the competence map in the appendix) and the project aim. The most appropriate method was then selected.

Expert interviews were used to get an overview of the current state of research within drone safety research. I visited Aalborg University and met with Anders la Cour-Harbo to find out more about their DroneImpact project (Cour-Harbo, 2016a). The details of the interview are attached as a digital appendix.

Multirotor drone safety devices were identified using the literature review process (L. University, 2016), my own previous research (Cawthorne, 2016), and the solution-storming process contained in the third phase of the lean product development process (Dryer, 2014). The solutions were grouped into themes, another technique described by Dryer.

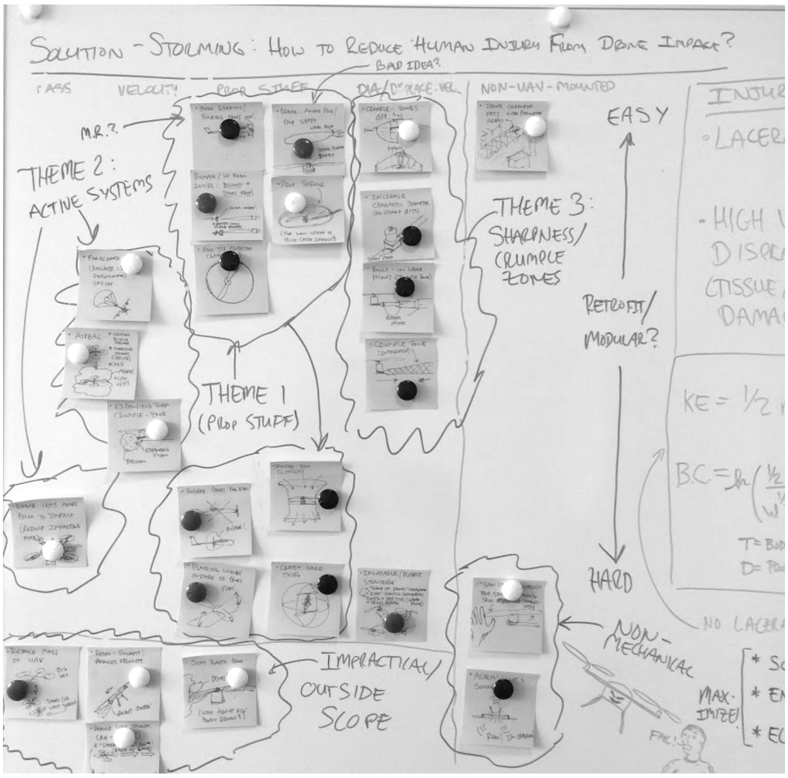
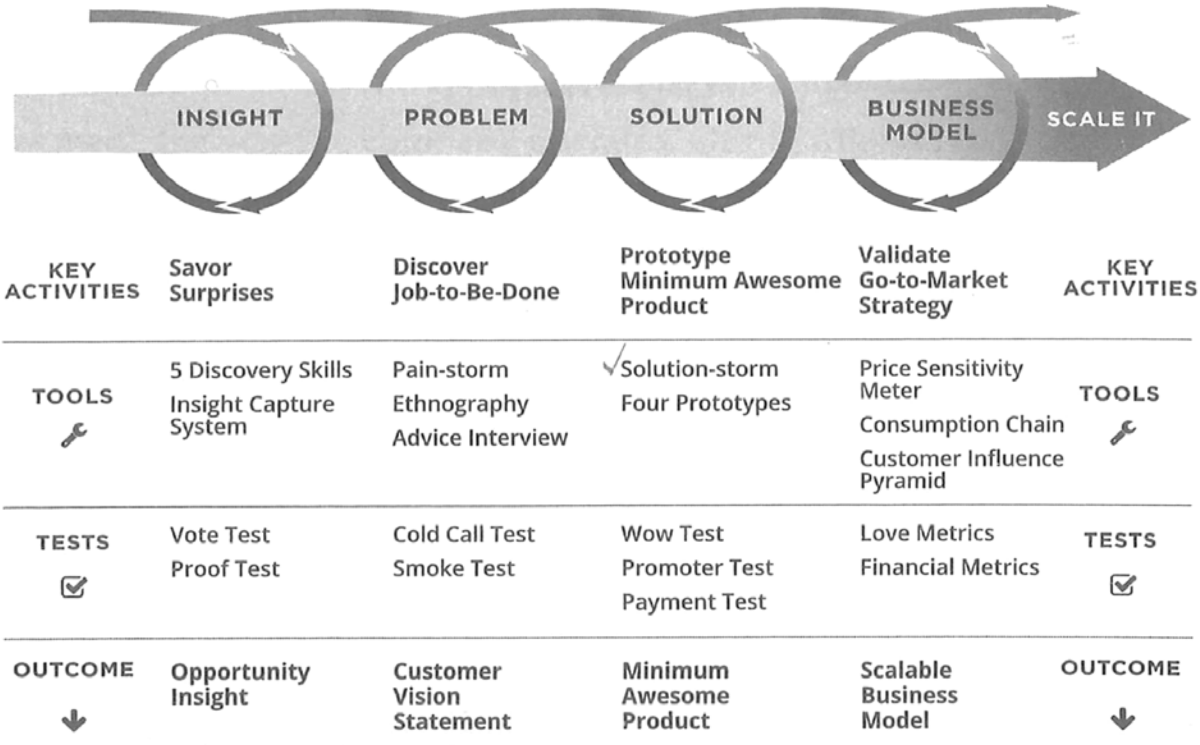


Figure 5 Solution-storming (Dryer, 2014) was used to identify multirotor drone safety devices, and then categorize them based on themes. Solutions were also rated on a spectrum from easy to retrofit/modular to difficult to retrofit. Non-mechanical solutions and those considered impractical or outside of the project scope were identified.

Rapid ethnography was performed (Millen, 2000), and a qualitative interview, as described in the lean product development process (Dryer, 2014) was used to gather feedback on various safety devices.

Figure 6 Rapid ethnography (Millen, 2000) was utilized to gain insight into how customer/users utilize drones and/or drone safety devices. During the ethnographic study, the customer/user was not informed of the specific aim of the research so as not to influence their behavior. The session was videotaped to document the interactions - links to the videos can be found in the appendix.

The lean product development process was used as a guide to develop the safety device; it consists of four iterative loops: 1. ‘Insight’ 2. ‘Problem’ 3. ‘Solution’ and 4. ‘Business model’.



KEY ACTIVITIES	Savor Surprises	Discover Job-to-Be-Done	Prototype Minimum Awesome Product	Validate Go-to-Market Strategy	KEY ACTIVITIES
TOOLS	5 Discovery Skills Insight Capture System	Pain-storm Ethnography Advice Interview	✓Solution-storm Four Prototypes	Price Sensitivity Meter Consumption Chain Customer Influence Pyramid	TOOLS
TESTS	Vote Test Proof Test	Cold Call Test Smoke Test	Wow Test Promoter Test Payment Test	Love Metrics Financial Metrics	TESTS
OUTCOME	Opportunity Insight	Customer Vision Statement	Minimum Awesome Product	Scalable Business Model	OUTCOME

Figure 7 The lean product development process (Dryer, 2014) was used as a guideline for the development of the drone safety device; the second and third phases (problem and solution) were utilized the most - specifically, tools such as ethnography, solution-storming, and iterative prototyping.

A patent search via Espacenet (Espacenet, 2016) and a general Google web search were performed to see if active safety systems such as parachutes and airbags for multirotor drones already existed in the market or had been patented.

A mathematical model was created to determine the kinetic energy of impact depending on airbag diameter.

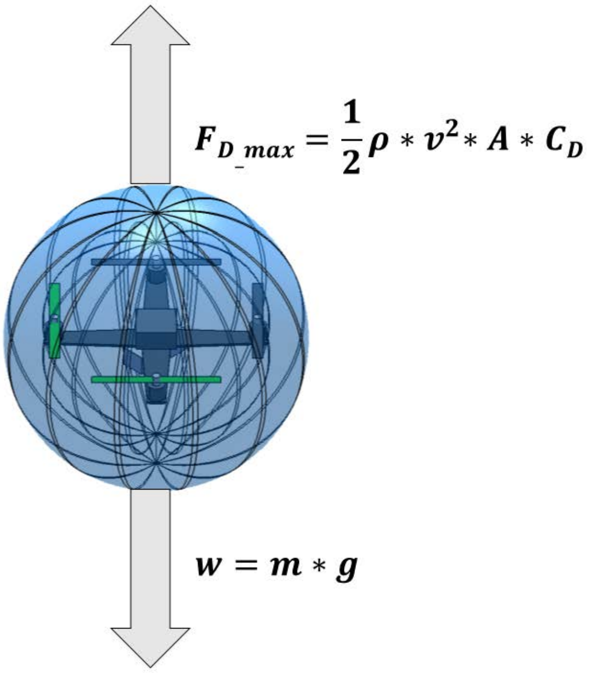


Figure 8 Free body diagram of a drone airbag (assumed to be a rough sphere) falling at terminal velocity. At this velocity the drag force (F_{D_max}) upward is equal and opposite to the weight of the drone (w). From this relationship, the impact velocity can be determined, and therefore the kinetic energy at impact. Drag force depends on the fluid density, in this case, air (ρ), the velocity of the system (v), the cross-sectional area of the sphere (A), and the coefficient of drag (C_D). This scenario represents a worst-case, where the drone has fallen from a significant height; if the drone was moving at moderate velocity and the airbag deployed just prior to impact with a person, the kinetic energy would be much less.

Kinetic energy at impact is then found from:

$$KE = 1/2 * m * v^2$$

where *m* is the mass of the drone/airbag system, and *v* is the impact/terminal velocity. Three-hundred and fifty gram, 1.5 kg, and 7 kg drones were analyzed. In addition, parameters such as the volume of the sphere (and therefore volume of gas required for inflation), as well as airbag surface area (leading to the weight of the airbag material) was determined. The detailed calculations are in the airbag mathematical model in the appendix.

The airbag's shape was developed using virtual reality sketching. An HTC Vive VR system running Google Tilt Brush software (Brush, 2016) was used.

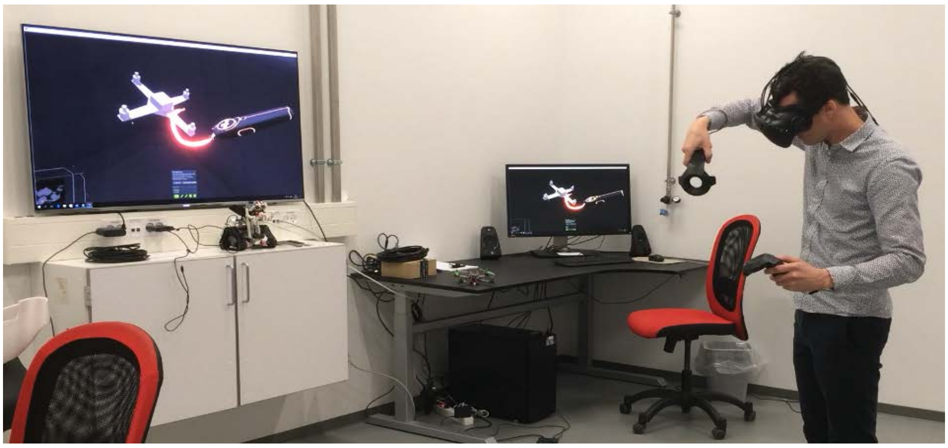


Figure 9 A CAD model of the drone was imported into a VR environment to allow airbags to be 'sketched' around it in three dimensions.

Stoichiometric calculations were performed to determine which compressed gas, a possible method of inflation, was the lightest per unit volume. The ideal gas law was applied to determine the volume at atmospheric pressure of a compressed gas generated from a given mass gas canister. These calculations are shown in the appendix.

An iterative prototyping process was used to develop the airbag, as outlined in the lean product development process. Following the model developed by Nielsen (Nielsen, 1993), several 'vertical prototypes' (prototypes built to isolate and analyze a single function) were built, along with a full-scale, scenario prototype, which was field-tested. The prototypes are detailed in the results section, as is the test plan for the full-scale testing of the proof-of-concept airbag.

Computer aided design software (Systemes, 2014) was used to model the drone and various mechanisms. Parts were 3D printed in ABS plastic using a Stratasys Fortus 380mc (Stratasys, 2016). The CAD files are included in the digital appendix, and images are in the appendix.

A journal was kept throughout the project to document resources and findings. Photos were taken and catalogued, and videos of the ethnographic analysis and each experiment were kept. All of these documents are listed in the appendix or attached as digital files with this thesis.

Results

Social benefit

The sustainability analysis, considering the economic, environmental, and social impact of a product - specifically, the Bournemouth University tool (B. University, 2016) was deemed the most appropriate method for determining social value for this project.

Research question:

1. *Which social benefit model should be used for this project?*

Answer:

1. *The sustainability analysis model or 'triple bottom line'* - *considering economic, environmental, and social impacts of the product; specifically, the Bournemouth University model, utilizing the Excel spreadsheet tool.*

The sustainability analysis showed that active systems gave the largest social and economic benefit with moderate economic risk - good for society, and possibly a good business.

Figure 10 Radar chart output of the product assessment for drone parachutes, showing the top five benefits and risks. The charts is divided into three parts: economic, environmental, and social impacts (benefits and risks). The total area of the radar chart indicates the cumulative benefit/risk. Results are on a scale from zero to ten, zero being no impact and ten being high impact. Developed from: (B. University, 2016)

Propeller protection also gave a large social benefit, but with large economic risk - good for society, but bad business.

Figure 11 Radar chart output of the product assessment for propeller protection. Results are on a scale from zero to ten, zero being no impact and ten being high impact. Developed from: (B. University, 2016)

Crumple zones gave only small social benefits, as well as some economic risk - ok for society, but bad business. All three themes had approximately equivalent environmental benefits and risks, all of which were quite small.

Figure 12 Radar chart output of the product assessment for crumple zones and foam padding. Results are on a scale from zero to ten, zero being no impact and ten being high impact. Developed from: (B. University, 2016)

These results allowed another research question to be answered.

Research question:

1.1. Which multirotor drone safety device will benefit society the most?

Answer:

1.1. Active systems, such as parachutes and airbags.

Product development

The lean product development model (Dryer, 2014) fit very well with my competencies and the goals of the project. It utilizes fast prototyping, a customer/user-focused approach, and an iterative, flexible approach.

Research question:

2. *Which product development model should be used for this project?*

Answer:

2. *The lean product development model, as presented by Furr and Dryer in the book* The Innovator's Method (Dryer, 2014)

The expert interview (Cour-Harbo, 2016a) revealed that there is still a lot of work to be done within the realm of drone safety and drone impact with people. The DroneImpact project is still in the exploratory phase, and an injury prediction model has not yet been developed.

My previous secondary research (Cawthorne, 2016) identified several design recommendations to improve drone safety.

Drone design recommendations for reducing human injury
1. Reduce drone kinetic energy by reducing mass, velocity, or slowing the drone down prior to impact using, for example, airbags or parachutes
2. Increase characteristic diameters for the exterior of the drone, and eliminate sharp protrusions
3. Shroud multirotor propellers; fixed wing aircraft should use pusher propellers, and motor braking and propeller folding should be applied; soft plastic rather than stiff carbon fiber propeller should be used
4. Incorporate deformable impact parts made of materials such as foam, and employ 'crumple zones', for example, creating built-in weak points in the arms of multirotors to help absorb impact energy

Table 1 Design recommendations for reducing human injury from drone impact. Most of the recommendations are valid for multirotor drones. From (Cawthorne, 2016), based on (Radi, 2013a) (Magister, 2010)(Cour-Harbo, 2016b).

These recommendations, along with literature review and the solution-storming process, identified many drone safety devices. See the figure for details.

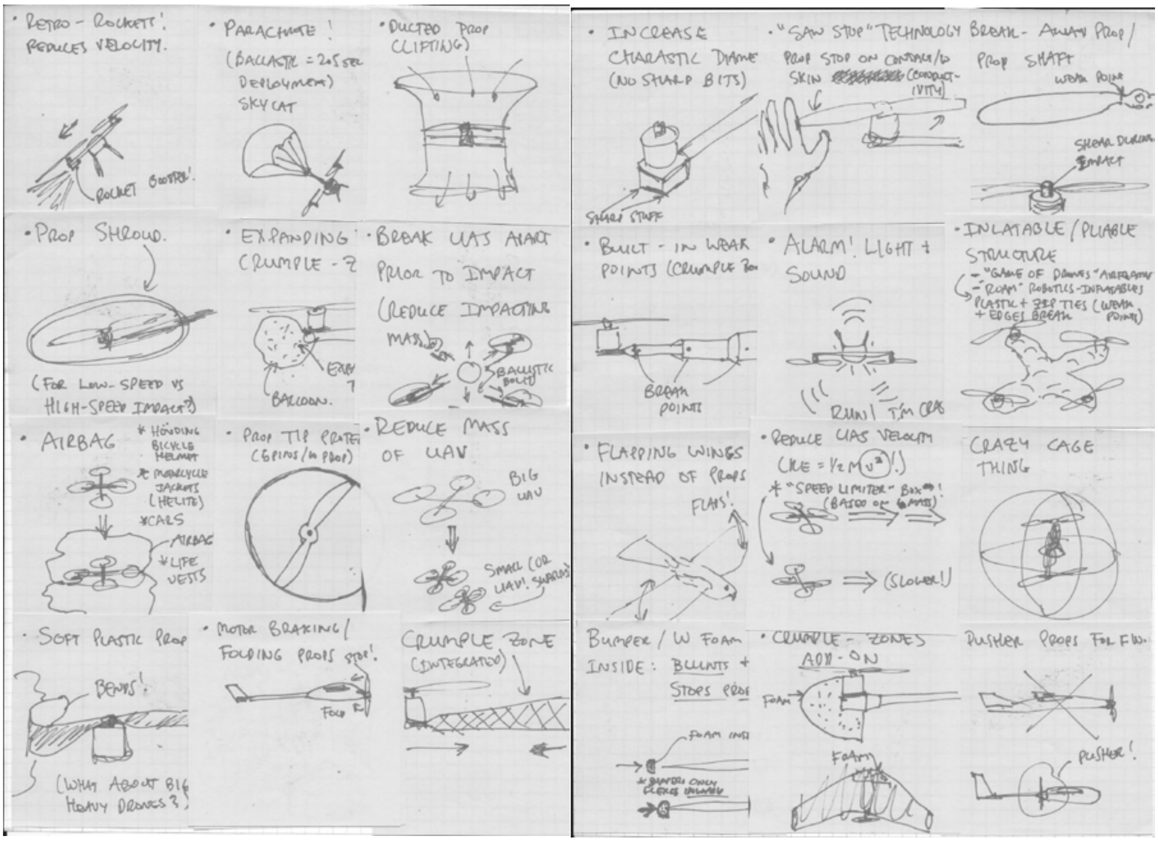


Figure 13 Sketches of some of the drone safety devices that were identified, including break-away propellers, inflatable/pliable structures, velocity-limiting software, propeller bumpers, complete drone-surrounding cages, parachutes, and airbags.

From these devices, three themes or categories were identified that fit within the scope of the project: active systems (parachutes, airbags), propeller protection (i.e. propeller protection ‘bumpers’ or shrouds), and crumple zones combined with foam padding.

The active systems theme performed the best of the three, so it was investigated further. The general web search and patent search showed that several drone parachutes exist on the market (Parachutes, 2016; Paramodels, 2016; SkyCat, 2016), but no drone airbags were found. The patent search returned results only for fixed-wing drones landing or crashing into the ground (明亮, 2015) or into water (Jacobs, 2015).

The mathematical model was used to calculate the diameter of the airbag required to prevent possible fatality (under 25-200 joules) at terminal velocity.

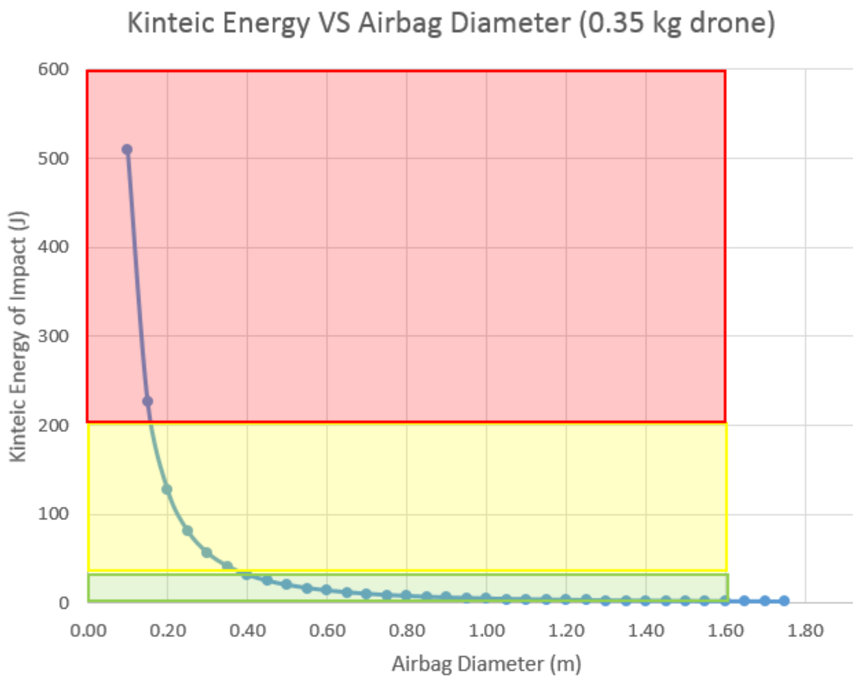


Figure 14 Graph of the maximum kinetic energy of a spherical airbag falling at terminal velocity versus airbag diameter for a 0.35 kg drone. A diameter of around 15 cm gives an impact energy of 200 joules, while a diameter of 40 cm gives an impact energy of 25 joules. Fatal impact energy is estimated to be between 25 and 200 joules.

Similar calculations were made for drones of 1.5 and 7 kg. The detailed calculations are in the appendix, and the Excel file is included as a digital attachment so other combinations of weight and drag can be analyzed. A summary of some of the findings is listed in the table.

Drone weight (kg)	**Diameter for 200 joules KE (cm)**	**Diameter for 25 joules KE (cm)**
0.35	15	40
1.5	55	160
7.0	240	680

Table 2 Drone flying weight (drone plus airbag) versus the diameter of a spherical airbag required to slow the drone's terminal impact energy to 200 joules or 25 joules. A 0.35 kg drone required a realistically-sized airbag of between 15 and 40 cm diameter.

Virtual reality sketching lead to the idea of creating drag flaps (similar to mini-parachutes) between each arm of the drone to increase the drag over that of a sphere.

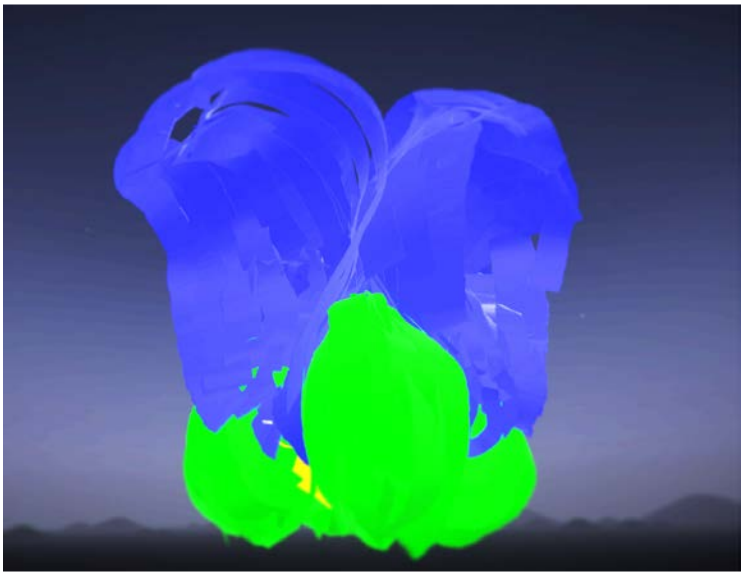


Figure 15 Virtual reality sketch of a drone airbag (in green) with drag flaps between the rotor arms (blue) created in Google Tiltbrush. This concept was used in the final airbag prototype. Image from: (Brush, 2016)

Three airbag prototypes were iteratively developed. Each one was designed to isolate and test certain functions and to develop fabrication techniques that could be used to build a proof-of-concept prototype for field testing. They also informed the estimation of performance specifications for a fully developed system. The highlights of these tests are listed below, and videos of each experiment are listed in the appendix.

Figure 16 Airbag prototype number one; this prototype was made with standard parachute material. Experiments showed the airbag material did not hold air, and deflated quickly. It could be folded under the drone such that the drone could still fly.

Figure 17 Airbag prototype number two; this prototype was constructed of zero-porosity parachute material. It showed it was possible to fabricate a robust airbag by sewing, but this induced leaks in the seams. The shape did not fully wrap around the drone as intended (only marginally). The shape did fold down tightly enough that the drone could still fly. This airbag was also used to check aerodynamic stability. It was filled with small styrofoam spheres (as it was not airtight), and dropped from two heights - 4 meters and 7 meters, at different orientations (bottom down, sideways, upside down, and thrown with spin). The airbag always landed bottom down, except when dropped upside down; then, it remained upside down.

An experiment was performed to determine how long it takes for a commercially available 16 gram CO2 cartridge to completely empty using a bicycle tire inflation valve, and to verify the volume of CO2 at atmospheric pressure. The CO2 cartridge emptied in 3.5 seconds, and produced eight liters of CO2 at normal pressure (a video of the experiment is listed in the appendix). Stoichiometric calculations predicted 8.7 liters of CO2 (calculations are the in appendix).

A test was performed to see if multiple airbags could be inflated at once. It used a lower plastic bag of four liters volume and an upper bag of two liters volume, connected together via tubes to the CO2 canister. Both airbags inflated fully, though the upper bag, with a longer tube run and less direct connection to the canister inflated slightly slower. The lower bag burst at 1.3 bar pressure.

Two more experiments were performed to investigating if the airbag would inflate while folded down and held in place with rubber bands or with tape. The sewn airbag made from zero-porosity parachute material, with a volume of 11.4 liters, did not unfold fully, while the fully-sealed plastic bag with a volume of four liters unfolded effectively.

Finally, the x-shaped prototype was constructed. Inflation tests were first carried out in the lab; once successful, a full-scale test was performed. Details are in the figures, and videos of all the tests are listed in the appendix.

Figure 18 Airbag prototype number three; this prototype was X-shaped to follow the arms of the drone. It had a smaller volume to facilitate inflation and an inner bladder plastic welded at the seams (in practice the seams leaked when pressurized). The triangular-shaped drag flaps can be seen standing upright between the drone's arms. An inflation test we carried out in the lab, then the system was field-tested.

The prototype airbag was mounted to a 200 mm Leora quadcopter drone that weighs 200 grams (rOsewhite, 2016). The airbag system weighs 208 grams (see the weight breakdown in the appendix for details) and is inflated by a 16 gram cartridge of compressed CO2. The airbag is 2.5 liters in volume, fills in 2 seconds, and stays inflated for 10 seconds. The airbag provides 10 cm of impact cushioning to the bottom and edges of the drone, and incorporates four drag flaps to slow the drone prior to impact.

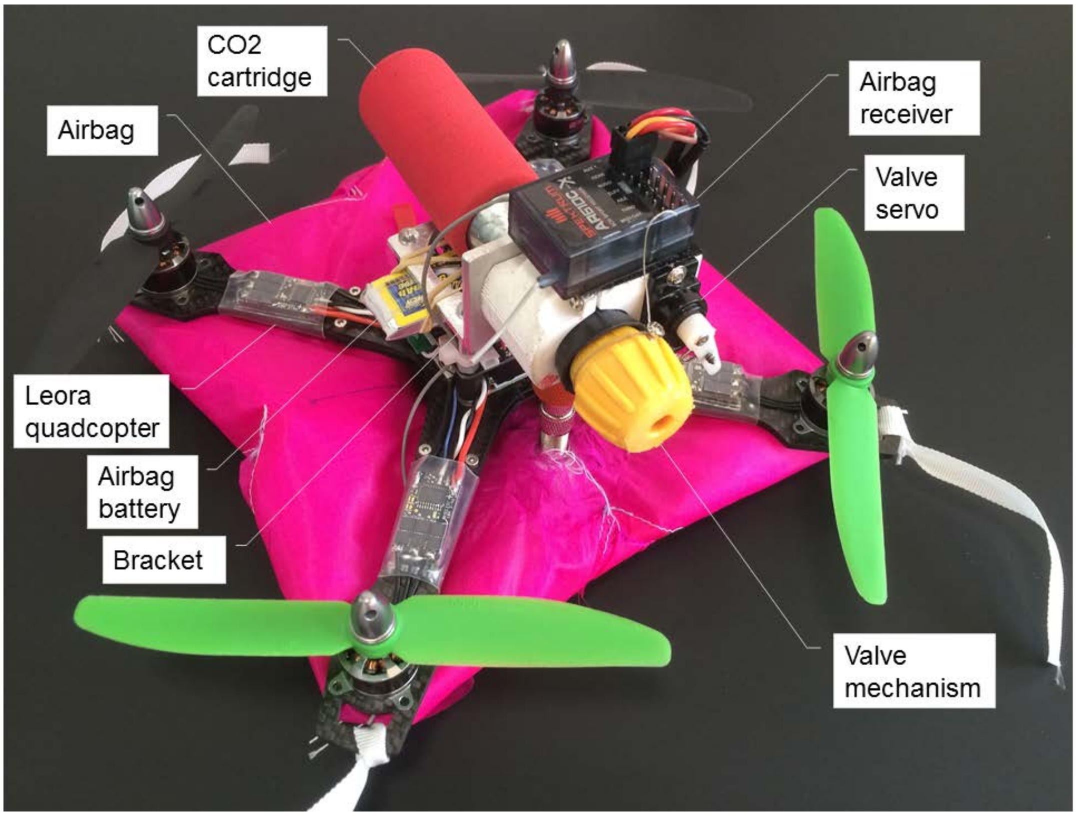


Figure 19 Overview of the x-shaped airbag and its components; component specifications and a weight break-down are in the appendix.

Full-scale testing showed that the airbag reduced kinetic impact energy after free-fall from an altitude of 33.5 meter from 130 joules (assuming no wind resistance) to approximately 20 joules, and impact velocity from 25 m/s to approximately 10 m/s. The cushioning effect of the airbag upon impact was not investigated. The prototype airbag flipped upside down during the test, meaning it would have slowed the drone prior to impact but provided no cushioning. The airbag was activated manually via a stand-alone activation system (separate receiver and battery). A link to video of the experiment is in the appendix.

Figure 20 Field test of the x-shaped airbag (circled). The drone was flown to a height of 33.5 meters and all motors were shut down. About one second later the airbag system was manually activated. It inflated in two seconds, and was fully inflated prior to impact. The airbag reduced the impact kinetic energy from 130 to 20 joules, but landed upside down so no cushioning effect of the airbag was experienced.

These experiments permitted documentation of the proof-of-concept airbag's performance specifications, informed estimates for a fully developed airbag, and answered another research question.

Research question:

2.1. What performance characteristics will the multirotor drone safety device have?

Answer:

2.1. *Once fully developed, the drone airbag could perform very well, reducing impact kinetic energy and providing cushioning prior to impact. See the table for comparison of the proof-of-concept's performance versus the fully developed airbag, and the table comparing airbag performance against a parachute in the discussion section.*

Performance Specification	**Proof-of Concept Airbag**	**Fully Developed Airbag**
Drone type/size	200mm Quadcopter, 200 gram weight without airbag	Multirotor, up to 7 kg (possibly more)
Kinetic energy at terminal velocity	20 joules	Target under 25-200 joules; higher targets may be accepted for larger drones as the airbag could become very large
Airbag cushioning	10 cm, bottom and edges of drone	10+ cm (depending on the drone’s size and KE)
Airbag system total weight	104% of drone’s flying weight (208 grams)	10-15% of drone’s flying weight
Airbag inflation method	Compressed CO2, 16 gram cartridge at 60-80 bar (8 liters volume at 1 bar)	Compressed gas, possibly gas-generating explosive
Airbag inflated volume	2.5 liters	8 to hundreds of liters, depending on drone size
Airbag inflation time	2 seconds	0.1 seconds
Airbag inflation duration	10 seconds	10 seconds
Number of airbags	1, bottom of drone	1, that wraps around drone, or multiple strategically placed at impact locations
Airbag activation method	Manual (stand-alone receiver and battery)	Manual or automatic
Airbag drag generation	Four drag flaps between drone arms	Multiple drag flaps between drone arms
Airbag/drag flaps coefficient of drag	1.1	1.1 or more depending on size of drag flaps

Table 3 X-Shaped, proof-of-concept airbag performance specifications versus those of a fully developed system. The fully developed system should be much lower weight, deploy very rapidly, and feature automatic activation.

Discussion

Social benefit

The sustainability analysis utilized here has benefits and limitations. The primary benefit is that the analysis can be performed quickly, especially when utilizing the Bournemouth University sustainable product development spreadsheet. The sustainability analysis is one of several methods available for determining social benefit. Others include LCA (Life Cycle Assessment) and SROI (Social Return On Investment) (Rothereo, 2007), two valid and well-documented methodologies.

The greatest limitation of the sustainability analysis is the subjective nature of the assessment, and lack of quantification. Yes, the drone parachute increases safety, but exactly how much does this benefit society? There are quantitative methods available (for example, estimate the number of lives saved and count up the added value created by those people), but this model utilizes a rating system instead (low, medium, high impact). The subjective nature of the current method leaves the possibility that I have a biased viewpoint - perhaps I have weighed the safety benefits of the product higher than the environmental or social costs of producing it. A quantitative analysis would be more transparent. However, Twan, who prepared an analysis of eight methods of measuring/estimating social value for the Bill and Melinda Gates Foundation (Twan, 2008) cautions against a *purely* quantitative evaluation. A metric presents no context or nuance. Therefore, future work should include both quantitative and qualitative assessment - measurable facts, discussed and put into context.

The sustainability analysis utilized only considered the product itself; the company, manufacturing site, or the design and distribution aspects in the product analysis as presented in the Bournemouth University model were not included. At this stage of the project it would be difficult to determine the practices of the hypothetical company making drone airbags (do they treat their employees well?) or the manufacturing facility (is it to be built at an environmentally sensitive location?), but this should be considered in the future.

The results of the sustainability analysis predicted that active systems would have the best economic performance. In the case of parachutes, that is what we see in the market - several companies offer parachute systems. Drone airbags are not on the market, perhaps because they are not included in traffic authority rules as parachutes are (Bygningsmin, 2016).

Materials and Sustainable Development as presented by Michael Ashby of Cambridge University (Ashby, 2016) is an alternative methodology to lean product development; it consists of five steps or layers: define the problem, consider the context, research the facts, debate the implications, and reflect on policy. This approach also considers economic, environmental, and social impacts; here they are referred to as manufactured capital, natural capital, and human capital.

Product development

Ethnography was chosen based on research by Tidd and Bessant where it was rated the most effective method for gaining customer/user insight (Bessant, 2013). The ethnography and customer/user interview emphasized how important it was that the safety device be approved by the air traffic authority; if the safety device did not give increased flight access, it would not be implemented (Wiggers, 2016).

The lean product development model was used because it was an iterative model which allowed a flexible process, it was customer/user focused, and it utilized physical prototyping which was within my competences (see the competences map in the appendix). However, there are other suitable product development models that could have been utilized. For example, the more rigid and product-focused process described by Dym (Dym, 2014) which consists of: problem definition, functions and requirements, design alternatives, design modeling, analysis, and optimization, and communicating design outcomes.

The mathematical model where the airbag is considered a rough sphere is a simplification, and represents a worst-case scenario. A real drone airbag should provide the maximum amount of drag possible, and provide cushioning between the drone and person being impacted. This would likely lead to a non-spherical shape. A sphere has relatively low drag (0.2 to 0.35 at the Reynolds numbers associated with 0.35 and 7 kg drones respectively). The X-shaped airbag with drag flaps has higher drag (drag coefficient of 1.1), and more closely follows the shape of a quadcopter frame. Drag coefficients vary depending on velocity, but a conservative, fixed drag coefficient was used for the model. The model represents a scenario where the drone has fallen from a significant height; if the drone was moving at moderate velocity or low altitude relative to a person being impacted, the kinetic energy would be much less. Despite these simplifications, the model was useful as a preliminary design tool - it indicated that, even in a worst-case-scenario, a drone airbag of a realistic size could slow a drone down to below-fatal kinetic energy level.

During full-scale testing, the drone's accelerometer data did not record as expected, so the impact kinetic energy/velocity of the drone had to be estimated from the test video; therefore, there is a significant margin of error in this measurement. The cause of the failure should be investigated and a more accurate method for recording the drone's impact speed should be used. The drone was operational after the test crash, so it is unlikely it was a mechanical failure that caused the lost data.

The estimated threshold for fatal human injury varies significantly, from 25 joules (Cour-Harbo, 2016b) to 200 joules (Radi, 2013a), so the prototype airbag would render an impact non-fatal.

The prototype airbag was activated manually, as the focus of this thesis was the development of a mechanical system; still, it is important to consider how the fully developed airbag would be deployed. It could be activated automatically after detecting a fault or just prior to impact with a person or obstacle. An automated system could react faster than a human operator and facilitate beyond visual line of sight operation. One such system exists on the market, the Mayday by North UAV (UAV, 2016).

Figure 21 Mayday module from North UAV. This stand-alone system uses machine learning to detect “non-standard behavior”, such as unexpected acceleration, and triggers a response such as deploying a parachute. Image credit: (UAV, 2016)

The Mayday module could be tested with an airbag, but it is limited by its onboard sensors. A new system could be developed that monitors and detects faults within the drone’s flight controller and/or senses an impending crash using additional sensors such as currently-available ultrasonic or laser proximity sensors, or, in the future, computer vision systems (Skriver, 2016).

A fully developed airbag system could have the following performance: weight 10-15% of the drone’s weight (similar to the parachutes made by SkyCat as they contain similar components as a parachute), deploy in 0.1 seconds (like car airbags (Wikipedia, 2016)) or the Hovding inflating bicycle helmet (Hovding, 2016)), stay inflated for 10 seconds, and cost similar to a parachute system. It could utilize a low weight gas-generating explosive, such as those used in car airbags, to provide rapid inflation of the airbag (Wikipedia, 2016).

The cushioning effect of the airbag upon impact was not investigated. Prediction models and experimental data exist for other impact categories: blunt ballistic impacts such as less-lethal munitions (B. a. Viano, 2004), baseballs (A. Viano, Polley, and King, 1992), and potato canons (Frank, 2012), automotive impacts, and full-scale aircraft impacts; however, the weight and speed envelope of a multirotor drone are not always within the scope of these models (Magister, 2010).

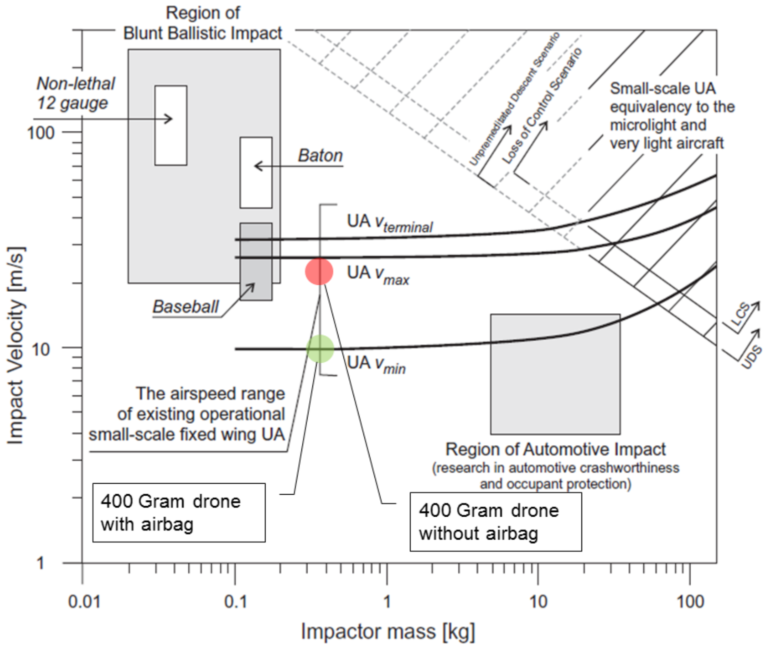


Figure 22 Impact models and data - velocity versus impactor mass, both on logarithmic scales. Drones often occupy velocity and mass regions where established models such as blunt ballistic impact or automotive impact do not apply. For example, the green dot shows the impact velocity of the prototype drone airbag with the airbag deployed; the red dot shows the impact velocity without an airbag - neither are within regions of established models. Developed from: (Magister, 2010)

The blunt impact criteria (B. a. Viano, 2004) considers the kinetic energy (mass, velocity) and characteristic diameter of the impacting object, but does not include the potential for lacerations, which is an important injury mode with drone impacts due to exposed parts (rotors, arms, landing gear etc.) Projects such as DroneImpact at Aalborg University (A. University, 2016b) could lead to methods for assessing drone impact damage to humans.

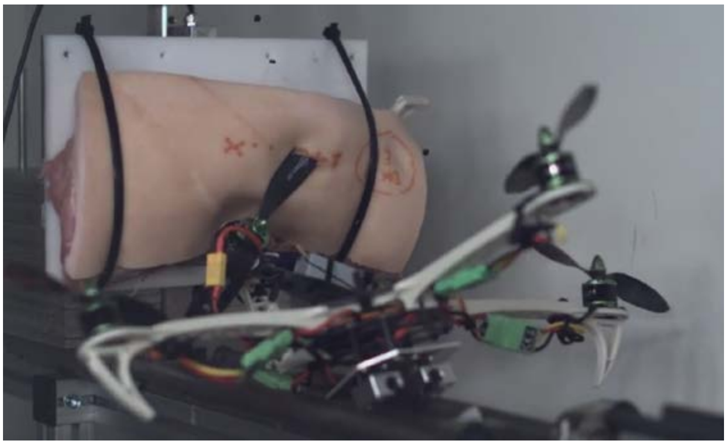


Figure 23 Experiment performed as part of the DroneImpact research project at Aalborg University. A multirotor drone, with propellers spinning, is accelerated on a test sled, into a piece of pork that serves as an analog for the human body. Credit: (A. University, 2016a)

Drone airbags show promise in certain applications, for example, in urban areas with high population densities as detailed in (Dalamagkidis, 2008; Hansman, 2004), indoors, and in situations where drones must operate in close proximity to people or maneuver around obstacles. An airbag system will increase the cost, weight, and aerodynamic drag, and therefore reduce the utility of the drone, so at a certain point the added societal benefit of the airbag's safety will be offset by the reduced usefulness. Therefore, the airbag does not make sense in low-risk operations, such as flights over open ocean or sparsely-populated areas.

The airbag has some unique features when compared to parachutes which makes it suitable for different applications. The main advantages of the airbag are rapid inflation (fractions of a second versus 2-3 seconds for parachutes), the padding effect (which protects people and the drone), reduced drift in the wind after deployment, smaller packaging once deployed that is less likely to get tangled in power lines, and the possibility to stop a fly-away condition. The major disadvantages are that less aerodynamic drag is generated than a parachute (drag coefficient or the airbag was 1.1 compared to 2.4 for a parachute (Chutes, 2015)), which means more kinetic energy upon impact. In addition, under current legislation, there is increased access for operators utilizing a parachute but not an airbag (Bygningsmin, 2016).

Parachute	**Airbag**
+Significantly reduces impact velocity/kinetic energy (drag coefficient up to 2.4 once fully deployed)	-Moderately reduces impact velocity/kinetic energy (drag coefficient around 1.1 with drag flaps deployed)
-Slower inflation time (2-3 seconds)	+Faster inflation time (0.1 seconds possible)
+Weighs 10-15% of drone's flying weight	-Prototype very heavy, but fully developed system could weigh under 15% of the drone's flying weight
/Drag of undeployed system - similar to airbag	/Drag of undeployed system - similar to parachute
-No protection from lacerations by propellers/sharp protrusions	+Protection from lacerations by propellers/sharp protrusions
-Does not protect the drone/payload	+Protects the drone/payload
-Cannot prevent fly-aways	+Could prevent fly-aways (if propellers are covered by the airbag)
+Increased access under current laws	-No increased access under current laws
+Re-usable after deployment	+/-Possibly reusable; depends on inflation method
-Drifts in the wind after deployment	+Less affected by the wind
-Once deployed, possible to get tangled in drone's propellers or power lines	+Will not get tangled in drone's propellers or power lines

Table 4 Comparison of parachute and airbag performance. Each has unique features that make it suited for certain applications.

Future Work

Social benefit

There are many opportunities for further development within this project. The sustainability analysis could be refined, and quantifiable metrics could be developed, such as drone-specific environmental performance indicators (EPIs). The influence of the company, manufacturing site, and product design and product distribution should be included in future analyses.

The sustainability analysis indicates there are opportunities for social benefit within other categories of safety devices. For example, propeller protection (bumpers) could give a social benefit, but the largest risk was the price. If effective, low-cost propeller protection could be developed, adoption would be more likely.

A sustainable approach, considering not just economic, but also social and environmental aspects, could be developed and utilized instead of the current, financial-only accounting methods.

Product development

It would be highly relevant to solicit additional input from stakeholders, including customers/users, and especially those within the traffic authority as they set the standards by which customers/users operate. Perhaps, once drone airbags are more fully developed, the traffic authority will included them in the legislation, allowing operators increased access.

The drone airbag itself will require more development before it becomes attractive for adoption. The weight of the system must be reduced significantly. The x-shaped prototype airbag weighed slightly more than the drone itself (208 grams versus 200 grams for the drone). Most of this weight was associated with the CO2 cartridge (64 grams), the airbag itself (47 grams), and the valve mechanism/servo subsystem (59 grams total). A lighter-weight cartridge could be developed, possibly from filament wound carbon fiber and epoxy, which has a much higher strength to weight ratio than steel (CES, 2016). An airbag material that does not require an inner bladder for sealing would reduce the airbag weight. A light-weight valve mechanism that could resist 60-80 bar pressure but still give a high flow-rate, perhaps activated by a solenoid mechanism, could be sourced or developed. Compressed gas has the advantage that it could be reused multiple times.

Weight reduction may require the use of an inflation mechanism other than compressed gas, such as small quantities of gas-generating explosive as is used in automotive airbags. Research could be done to identify the most attractive explosive - one with light weight, low volatility, and the ability to generate large volumes of gas rapidly, but safe enough that accidental activation would not cause injury. A modular approach, with multiple small airbags placed strategically at the peripheries of the drone, would reduce the concentration of explosive. However, transportation of the system, and possible toxicity of the chemicals used (sodium azide, NaN3) may be an issue (Wikipedia, 2016). This approach would not allow re-use of the airbag after activation, and this, combined with possible toxicity of the chemicals used, would adversely affect the sustainability performance of the system

Materials and fabrication methods for the airbag could be developed further. The prototype airbag was not completely sealed, and lost large volumes of CO2 during inflation (leading to a 2.5 liter airbag when 8 liters of CO2 was available in the canister).

A more detailed cost analysis could be performed, and the value proposition of a drone airbag could be analyzed. These tasks will become easier once the product is more fully developed.

Additional safety features could be added to the system. Airbags should be brightly colored, as the prototype was, to give high contrast against the sky. The system could include warning sounds (alarms, voice commands) as well as flashing lights. This would increase the ‘sheltering effect’ - warning people on the ground of the drone’s presence and allowing them time to get out of the drone’s path.

The shape of the airbag could also be investigated. The prototype airbag covered the bottom of the drone, and, since the center of mass was above the center of pressure, the drone remained upside down after inflation of the airbag - this flaw must be resolved, either by making the system aerodynamically stable, or providing 3D-shaped cushioning all the way around the drone (top, bottom, and sides). Creating 3D shapes from flat panels proved challenging; the ‘unfolding’ function in a computer aided design program (Systemes, 2014) was used, and origami folding software programs were investigated, but none were a complete success. Principals of the design for inflatable structures could be applied, allowing a shape to be developed so the airbag would wrap around the drone, completely encapsulating it upon activation.

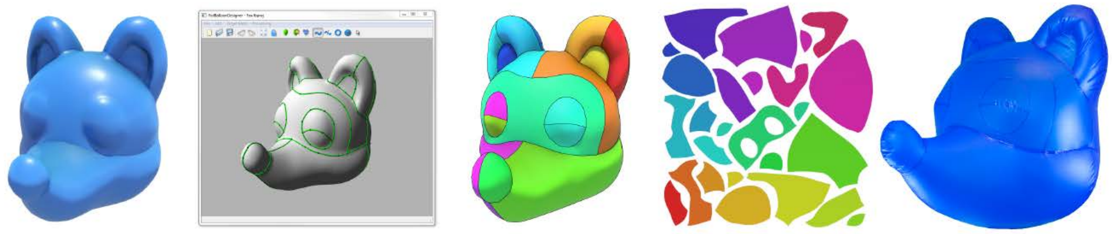


Figure 24 Researchers from ETH Zurich, Disney Research Zurich, and Columbia University have collaborated to develop software that can take a three-dimensional CAD file and generate the flat patterns required to construct an inflatable structure to form the input shape. This software could be utilized to develop a drone airbag that wraps around the drone, fully covering it. These researchers could be contacted for access to the software. Image from: (Skouras, 2012)

The aerodynamics of the airbag could be investigated further - what shape provides the most aerodynamic drag? The inflated shape will likely be complex to provide cushioning around a non-uniform shape, so CFD (computational fluid dynamics), small-scale wind-tunnel and/or full-scale field testing could provide more insight into how to maximize drag (Lund, 2016).

Could the airbag prevent a fly-away situation, and be the first ‘big red button’ (emergency stop) for a flying robot? Perhaps. To provide this function it would be necessary to test if the inflated airbag could stop the rotors without being cut. Durable, cut-resistant airbag materials, such as Aramid, could be investigated.

The dynamics of impact with a person should be studied. Does the airbag deform so much that the drone still impacts the person? How is the energy dissipated during an impact? Should the airbag have built-in weak points or pressure valves that minimize deceleration? Will the airbag burst upon impact? What about the airbag’s behavior after impact - will it bounce, and continue to cause damage?

Incorporation of an airbag into larger drones could also be investigated. A 0.35 kg drone is at the lower limit of a drone that can be fatal, but larger drones have the mass, kinetic energy, and motors powerful enough to be dangerous or fatal.

The patent application by Disney should be analyzed (details are in the post script) (Disney, 2016).

The aim for this thesis was to benefit society, and the drone airbags can only do that if they are adopted into use. There are many ways to approach this. With permission of the FreeD project partners, this thesis could be published under the creative commons attribution 4.0 license (Commons, 2016). This license allows others to share (‘copy and redistribute the material in any medium or format’) and adapt (‘remix, transform, and build upon the material for any purpose, even commercially’) as long as they give “appropriate credit, provide a link to the license, and indicate if changes were made.” This would make the project open source. Tesla has opened a number of their patents in the hopes that it will speed progress and encourage competition within electric car development (Blog, 2014).

There have been many successful products developed using an open source model within the drone industry, including the Iris quadcopter and Pixhawk flight controller (Pixhawk, 2016) which both grew out of the online community DIY Drones. This approach would prevent any one company from being able to take a patent on the technologies presented here, but this could leave the technology in the hands of those less concerned about implementing a sustainable approach. In that case, it might be appropriate to attempt to patent the technology and ensure it is designed, built, and manufactured in an ethical way (for example, using workers paid a fair wage). It might also be possible to collaborate with Disney in the development, and others could license the technology (see details in the post script).

Conclusion

The aim of this thesis was to create social benefit through product development; specifically, by developing a safety device that will reduce human injury from impact by a multirotor drone.

Four research questions were identified, and all were addressed. The sustainability analysis was selected as the social benefit model, and active systems were shown to provide the most social benefit. The lean product development model was chosen, and the performance characteristics of the prototype airbag and a fully developed system were established. Several prototype airbags were built and tested, and the final proof-of-concept airbag was field-tested.

Airbags show promising performance, but will require significant development before they can be widely adopted into use. They have some unique advantages over parachute systems which make them well suited to certain applications.

A fully-developed drone airbag could represent a significant achievement - the first ‘big red button’ (emergency safety stop) for a flying robot.

There are several possible approaches to implementing this work, ranging from open source development to patent and licensing.

I hope I have, in some small way, created social benefit with this thesis, and that drone airbags will eventually be adopted into use where they can provide a benefit to all of us.

Postscript

During the final stages of this thesis, Disney applied for a U.S. patent on drone airbags: *Impact Absorption Apparatus for Unmanned Aerial Vehicle* (US0332739, 2016) (Disney, 2016). The full implications have not yet been analyzed, but it will be discussed briefly here.

This patent application gives validity to the idea of a drone airbag being an economic opportunity. The technologies and approaches suggested are very similar in nature to those developed during this thesis. The patent is quite broad in nature; it mentions protecting multiple types of drones including multirotor, fixed wing, helicopter, and balloons, using single or multiple airbags, and various activation strategies including manual, accelerometer, altimeter, gyroscopes, or motor current sensors. The patent only mentions one inflation method, compressed gas, and does not mention proximity-based sensors for activation (ultrasonic or computer vision systems).

Patent and intellectual property rights specialist Søren Jensen was consulted about the matter (Jensen, 2016). It is possible the patent will not be granted since it is not specific enough. If the current patent is granted, it will only be valid in the U.S. It will still be possible to distribute the work developed in this thesis in an open manner; however, if Disney receives their patent, it will prevent anyone in the U.S. from selling a product like that developed here as it would likely infringe on the Disney patent.

In the future, the full implications of this patent should be considered, as it could have an effect on the implementation of the technology in this thesis.

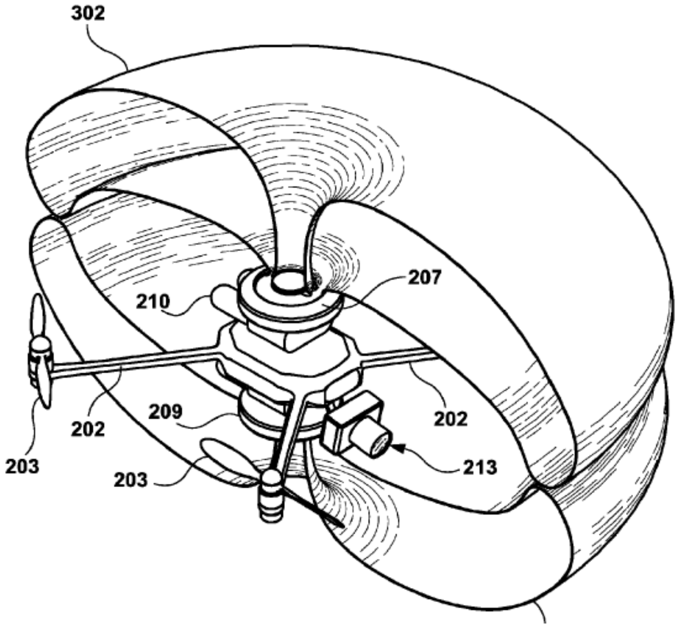


Figure 25 Illustration from the drone airbag patent application made by Disney (Disney, 2016). The approaches in the patent are very similar in nature to those developed in this thesis.

List of figures

List of tables

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Appendix

Testing video index

Master thesis 2016 playlist (19 videos)

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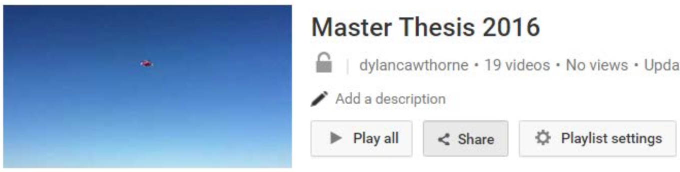


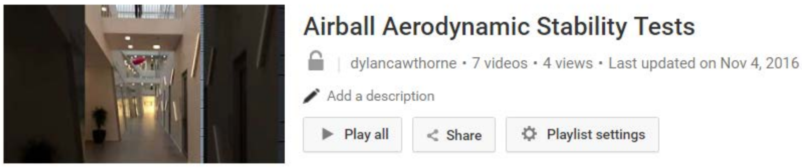
Master Thesis 2016

dylancawthorne • 19 videos • No views • Updated today

Add a description

Aerodynamic stability tests (7 videos)

goo.gl/dIjrFi



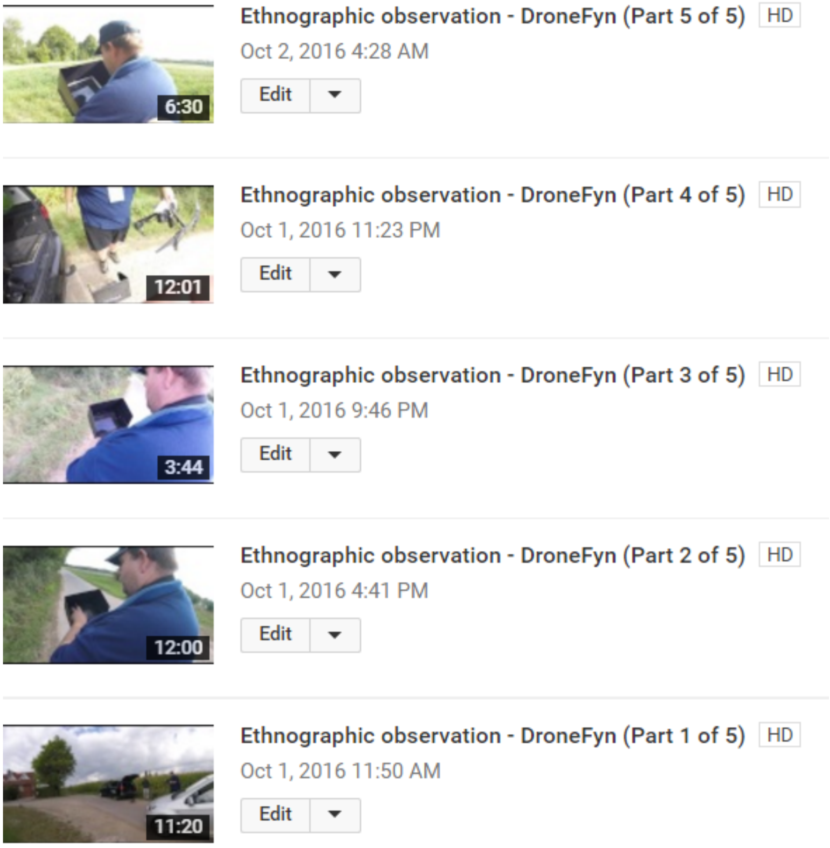
Airball Aerodynamic Stability Tests

dylancawthorne • 7 videos • 4 views • Last updated on Nov 4, 2016

Add a description

Ethnographic observation playlist (6 videos)

goo.gl/iw8aAL



Ethnographic observation - DroneFyn (Part 5 of 5)
Oct 2, 2016 4:28 AM

Ethnographic observation - DroneFyn (Part 4 of 5)
Oct 1, 2016 11:23 PM

Ethnographic observation - DroneFyn (Part 3 of 5)
Oct 1, 2016 9:46 PM

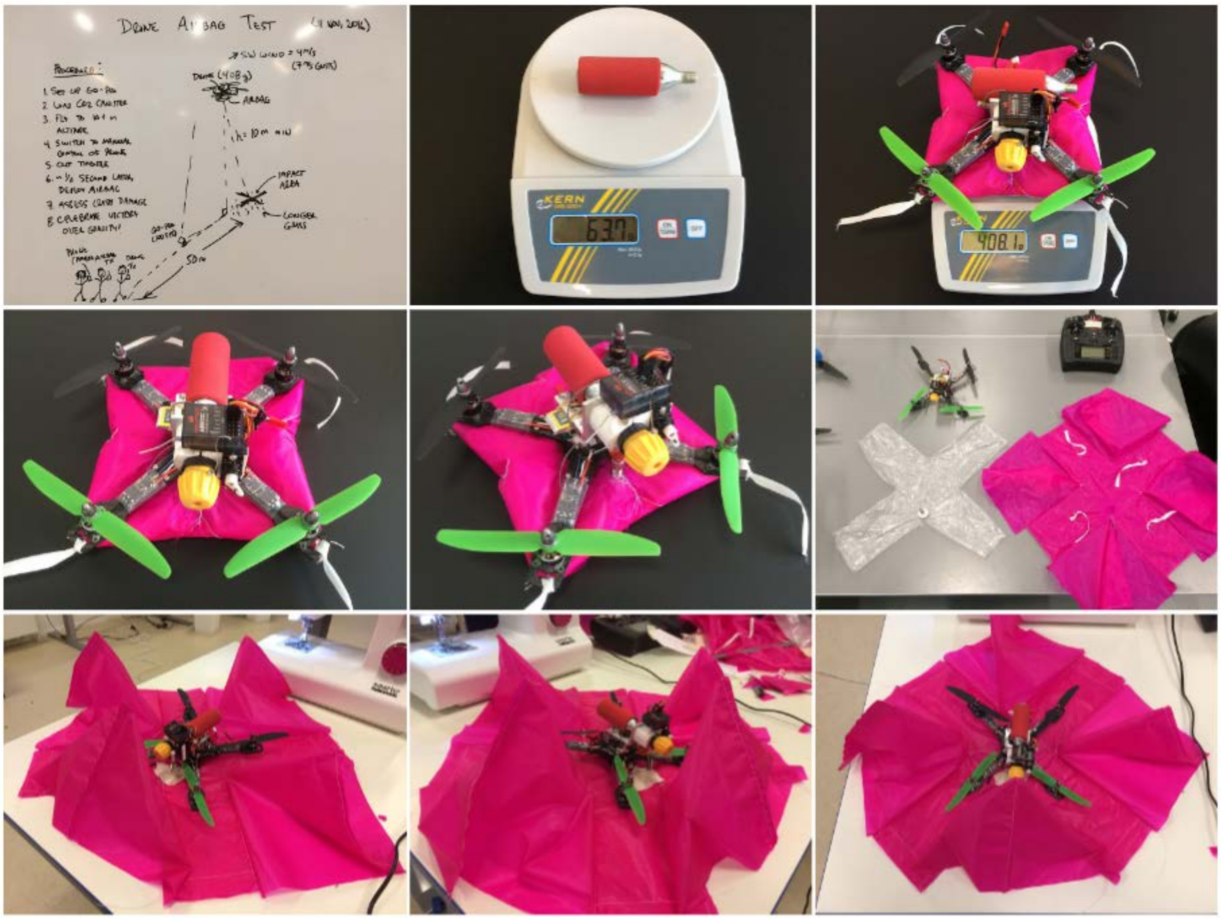
Ethnographic observation - DroneFyn (Part 2 of 5)
Oct 1, 2016 4:41 PM

Ethnographic observation - DroneFyn (Part 1 of 5)
Oct 1, 2016 11:50 AM

Development Pictures

Online photo album

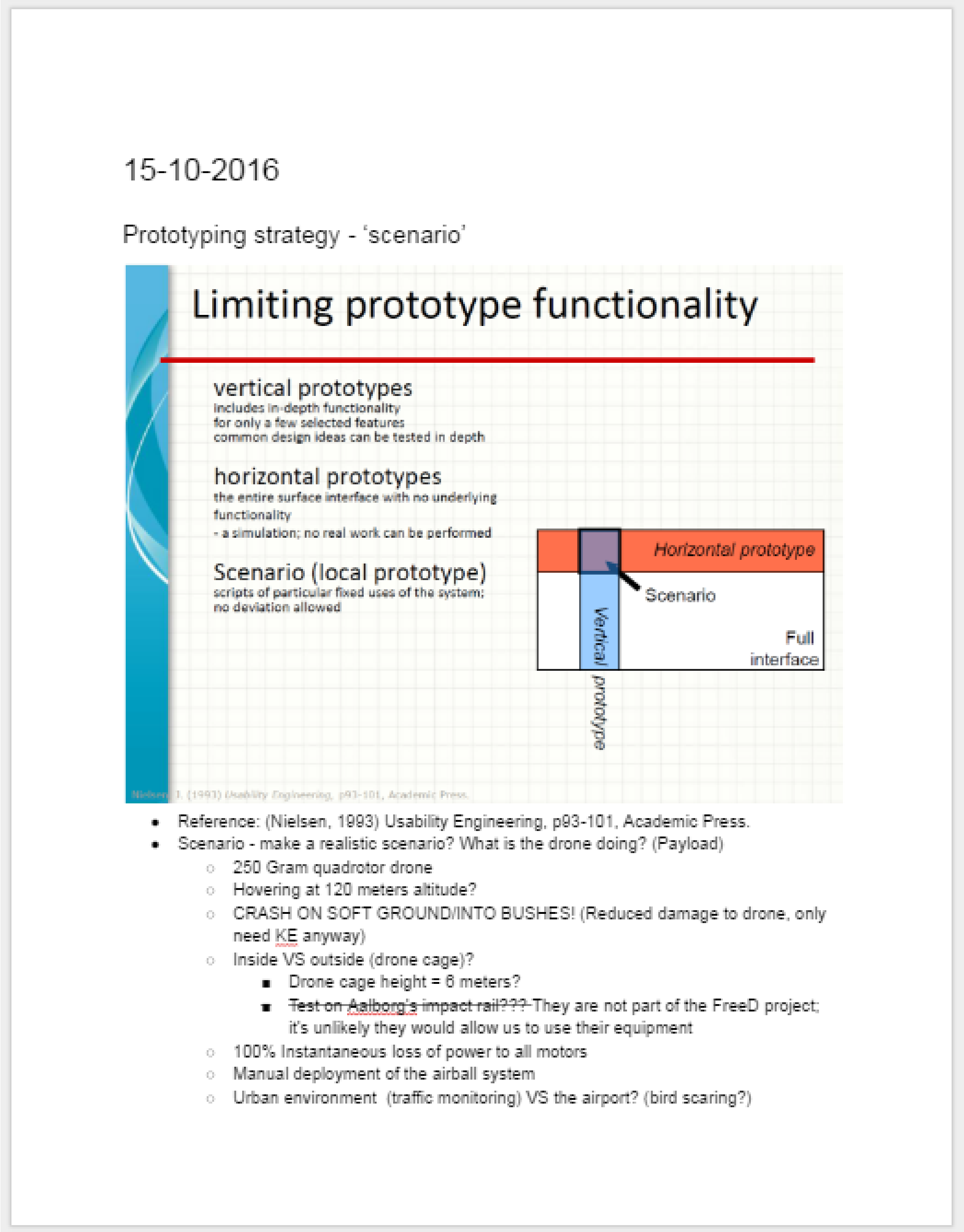
https://goo.gl/photos/ny4ywtRrvgFKKnrt7



Project Journal

Shared google doc

goo.gl/5cokoT



15-10-2016

Prototyping strategy - 'scenario'

Limiting prototype functionality

vertical prototypes
includes in-depth functionality
for only a few selected features
common design ideas can be tested in depth

horizontal prototypes
the entire surface interface with no underlying functionality
- a simulation; no real work can be performed

Scenario (local prototype)
scripts of particular fixed uses of the system;
no deviation allowed

Nielsen, J. (1993) *Usability Engineering*, p93-101, Academic Press.

- Reference: (Nielsen, 1993) Usability Engineering, p93-101, Academic Press.
- Scenario - make a realistic scenario? What is the drone doing? (Payload)
  - 250 Gram quadrotor drone
  - Hovering at 120 meters altitude?
  - CRASH ON SOFT GROUND/INTO BUSHES! (Reduced damage to drone, only need KE anyway)
  - Inside VS outside (drone cage)?
    - Drone cage height = 6 meters?
    - ~~Test on Aalborg's impact rail???~~ They are not part of the FreeD project; it's unlikely they would allow us to use their equipment
  - 100% Instantaneous loss of power to all motors
  - Manual deployment of the airball system
  - Urban environment (traffic monitoring) VS the airport? (bird scaring?)

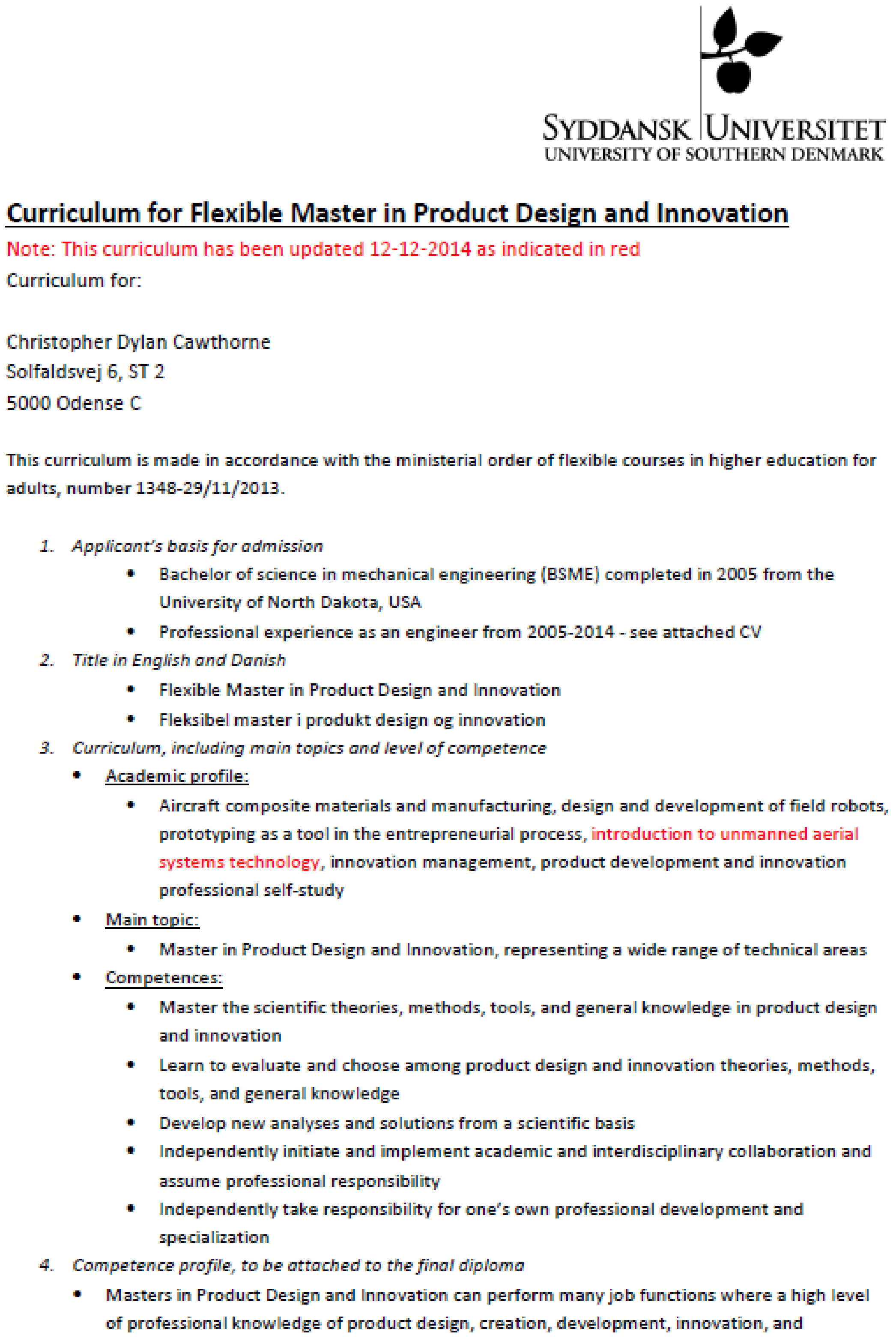
Competence map

This is a list of the tools and methods I have acquired through my study and/or professional experience which I could apply to this project:

- Mechanical and aerodynamic design of drone and drone-related systems
- Lean product development process
- Drone safety/human impact: blunt impact model etc. from previous work *‘Exploring knowledge within unmanned aerial systems mechanical design and its influence on human injury’*
- Pro*votyping*
- Prototyping: vertical, horizontal, scenario
- Digital design and fabrication: 3D printing, laser cutting, CNC machining, CNC hot wire
- ‘Voice of the customer’ tools; ethnography etc.
- Innovation theory: social innovation
- Literature review
- TRIZ - ‘Theory of inventive problem solving’
- Systematic material selection process

  Composite materials

Masters study curriculum



SYDDANSK UNIVERSITET
UNIVERSITY OF SOUTHERN DENMARK

Curriculum for Flexible Master in Product Design and Innovation

Note: This curriculum has been updated 12-12-2014 as indicated in red

Curriculum for:

Christopher Dylan Cawthorne
Solfaldsvej 6, ST 2
5000 Odense C

This curriculum is made in accordance with the ministerial order of flexible courses in higher education for adults, number 1348-29/11/2013.

1. *Applicant's basis for admission*
    - Bachelor of science in mechanical engineering (BSME) completed in 2005 from the University of North Dakota, USA
    - Professional experience as an engineer from 2005-2014 - see attached CV
2. *Title in English and Danish*
    - Flexible Master in Product Design and Innovation
    - Fleksibel master i produkt design og innovation
3. *Curriculum, including main topics and level of competence*
    - Academic profile:
        - Aircraft composite materials and manufacturing, design and development of field robots, prototyping as a tool in the entrepreneurial process, introduction to unmanned aerial systems technology, innovation management, product development and innovation professional self-study
    - Main topic:
        - Master in Product Design and Innovation, representing a wide range of technical areas
    - Competences:
        - Master the scientific theories, methods, tools, and general knowledge in product design and innovation
        - Learn to evaluate and choose among product design and innovation theories, methods, tools, and general knowledge
        - Develop new analyses and solutions from a scientific basis
        - Independently initiate and implement academic and interdisciplinary collaboration and assume professional responsibility
        - Independently take responsibility for one's own professional development and specialization
4. *Competence profile, to be attached to the final diploma*
    - Masters in Product Design and Innovation can perform many job functions where a high level of professional knowledge of product design, creation, development, innovation, and

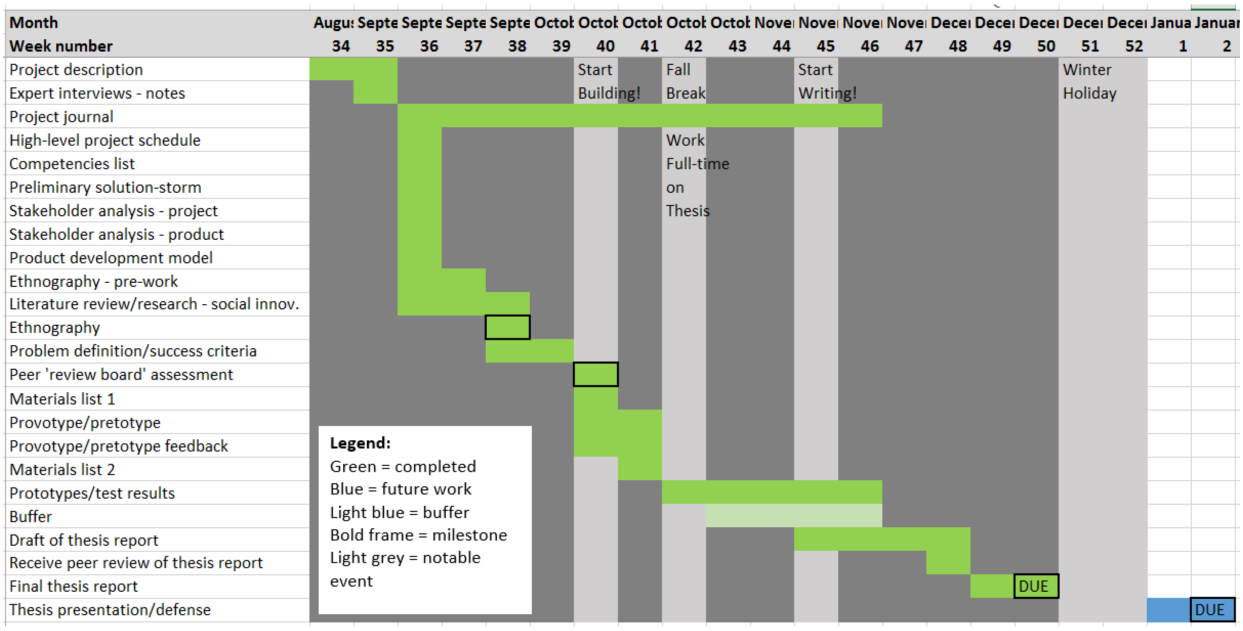
implementation are required. Graduates can thus solve complex technical problems and implement complex product designs. The graduate is also able to take a holistic approach to product design and innovation, incorporating varying technical specialties as well as economic, entrepreneurial, user-based, and managerial perspectives. The graduate is able to create and develop complex product designs using creativity and the latest research-based knowledge, continuing the further development of the subject, both practically and on a theoretical basis.

5. *Overview of the educational elements of the study*
    - Educational elements indicating semester start and ECTS points:

Educational Institution	Course	Semester Start	ECTS Points
University of Washington, Seattle - USA	Aircraft composite materials	Spring 2006	TBD By study board
University of Washington, Seattle – USA	Aircraft composite manufacturing	Fall 2006	TBD By study board
University of Washington, Seattle - USA	Aircraft composite tooling	Spring 2007	TBD By study board
SDU	Design and development of field robots	Summer 2014	7.5
SDU	Prototyping as a tool in the entrepreneurial process	Fall 2014	5
SDU	Introduction to unmanned aerial systems technology	Spring 2015	5
SDU	Innovation management (PART-TIME MBA PROGRAM)	Fall 2015	5
SDU	Product development and innovation professional self-study	Spring 2016	5
SDU	Thesis	Fall 2016	20

- Educational institutions:
    - Courses taken from the masters of science in mechanical engineering program from the University of Washington, and the product development and innovation, part-time master in business administration, and the robot systems programs from the University of Southern Denmark
- Items to be complete:
    - All items must be completed as specified. In case of deviation, the education shall be completed within 6 years
- Order of completion:
    - Relevant courses shall be completed in the order in which they are listed in the chart specifying ECTS points (see above)

Schedule



Month	**Augu:**	**Septe**	**Septe**	**Septe**	**Septe**	**Octok**	**Octok**	**Octok**	**Octok**	**Octok**	**Novei**	**Novei**	**Novei**	**Novei**	**Decei**	**Decei**	**Decei**	**Decei**	**Decei**	**Janua**	**Januar**
Week number	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**	**50**	**51**	**52**	**1**	**2**
Project description	🟩	🟩					Start		Fall			Start						Winter			
Expert interviews - notes		🟩					Building!		Break			Writing!						Holiday			
Project journal			🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩								
High-level project schedule			🟩						Work												
Competencies list			🟩						Full-time												
Preliminary solution-storm			🟩						on												
Stakeholder analysis - project			🟩						Thesis												
Stakeholder analysis - product			🟩																		
Product development model			🟩																		
Ethnography - pre-work			🟩	🟩																	
Literature review/research - social innov.			🟩	🟩	🟩																
Ethnography					🟩																
Problem definition/success criteria					🟩	🟩															
Peer 'review board' assessment							🟩														
Materials list 1							🟩														
Provotype/pretotype							🟩	🟩													
Provotype/pretotype feedback							🟩	🟩													
Materials list 2								🟩													
Prototypes/test results									🟩	🟩	🟩	🟩	🟩								
Buffer										░	░	░	░								
Draft of thesis report												🟩	🟩	🟩	🟩						
Receive peer review of thesis report															🟩						
Final thesis report																🟩	DUE				
Thesis presentation/defense																				🟦	DUE

Legend:
Green = completed
Blue = future work
Light blue = buffer
Bold frame = milestone
Light grey = notable event

Sustainability Analysis Inputs

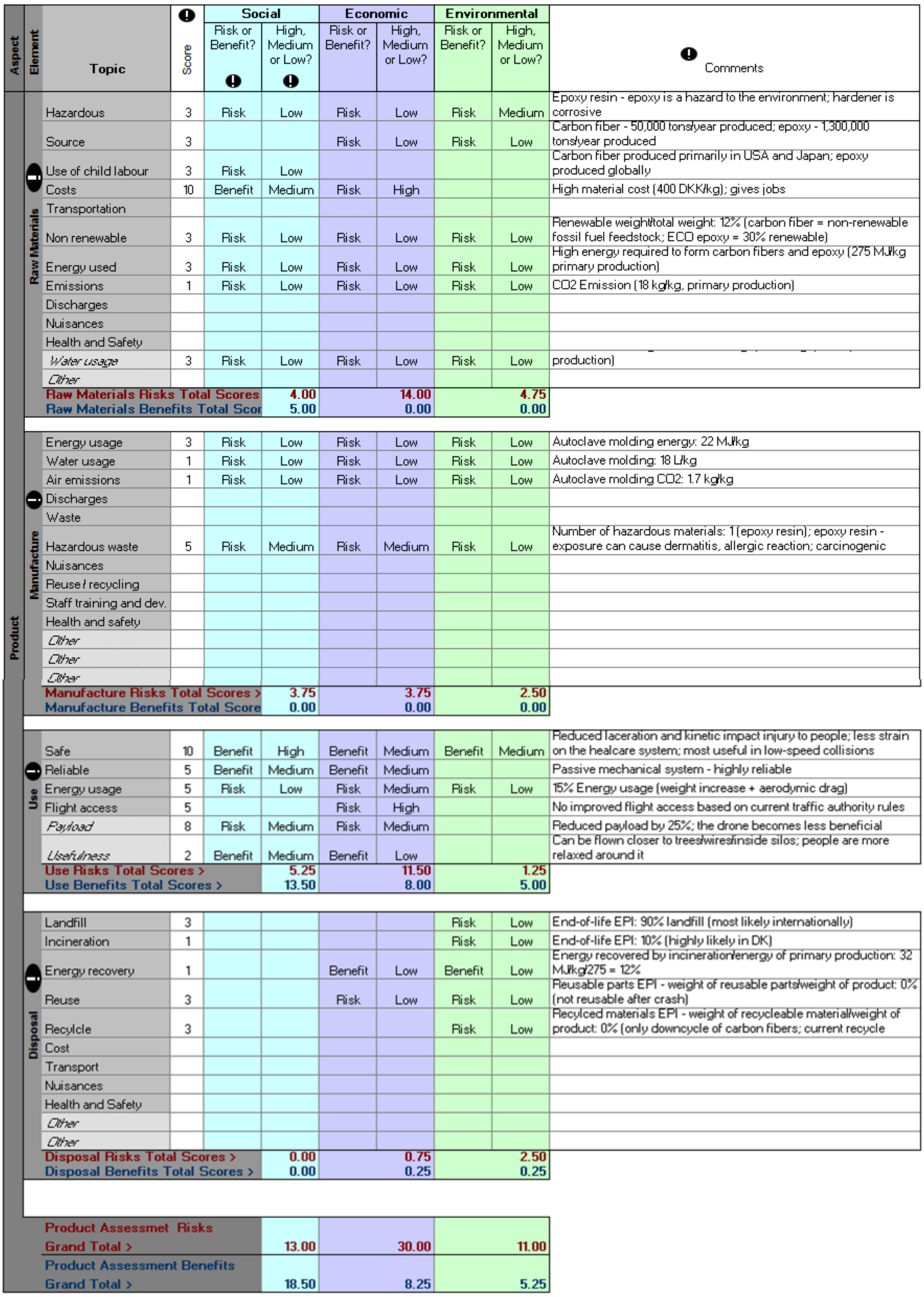
Parachute

Analysis is based on the SkyCat drone parachute systems (SkyCat, 2016).

Aspect	Element	Topic	Score	Social: Risk or Benefit?	Social: High, Medium or Low?	Economic: Risk or Benefit?	Economic: High, Medium or Low?	Environmental: Risk or Benefit?	Environmental: High, Medium or Low?	Comments
Product	Raw Materials	Hazardous	1	Risk	Low	Risk	Low	Risk	Low	Small LIPO battery
		Source	2			Risk	Low	Risk	Low	Nylon - 3,700,000 tons/year produced; carbon fiber - 50,000 tons/year produced; epoxy - 1,300,000 tons/year produced
		Use of child labour	3	Risk	Low					Nylon produced globally; carbon fiber produced primarily in USA and Japan; epoxy produced globally
		Costs	10	Benefit	Medium	Risk	Medium			Nylon - low material cost (28 DKK/kg); carbon fiber - high material cost (400 DKK/kg); gives jobs
		Transportation								
		Non renewable	3	Risk	Low	Risk	Low	Risk	Low	Renewable weight/total weight: 5% (carbon fiber = non-renewable fossil fuel feedstock; ECO epoxy = 30% renewable)
		Energy used	2	Risk	Low	Risk	Low	Risk	Low	Nylon - 120 MJ/kg, carbon fibers and epoxy - 275 MJ/kg primary
		Emissions	1	Risk	Low	Risk	Low	Risk	Low	CO2 Emission: Nylon - 8 kg/kg; carbon fiber + epoxy - 18 kg/kg (primary production)
		Discharges								
		Nuisances								
		Health and Safety								
		Water usage	1	Risk	Low	Risk	Low	Risk	Low	Water used during raw material mfg.: Nylon - 185 L/kg; carbon fiber + epoxy - 1300 L/kg (primary production)
		Other								
		Raw Materials Risks Total Scores >			**2.75**		**7.50**		**2.50**	
		Raw Materials Benefits Total Scores			**5.00**		**0.00**		**0.00**	
	Manufacture	Energy usage	1	Risk	Low	Risk	Low	Risk	Low	Nylon extrusion: 6 MH/kg; composite autoclave molding energy: 22 MJ/kg
		Water usage	3	Risk	Low	Risk	Low	Risk	Low	Nylon extrusion: 180 L/kg; composite autoclave molding: 18 L/kg
		Air emissions	1	Risk	Low	Risk	Low	Risk	Low	Nylon extrusion - 0.5 kg/kg; composite autoclave molding CO2: 1.7 kg/kg
		Discharges								
		Waste								
		Hazardous waste	3	Risk	Medium	Risk	Medium	Risk	Low	Number of hazardous materials: 1 (epoxy resin); epoxy resin - exposure can cause dermatitis, allergic reaction; carcinogenic
		Nuisances								
		Reuse / recycling								
		Staff training and dev.								
		Health and safety								
		Other								
		Other								
		Other								
		Manufacture Risks Total Scores >			**2.75**		**2.75**		**2.00**	
		Manufacture Benefits Total Scores :			**0.00**		**0.00**		**0.00**	
	Use	Safe	10	Benefit	High	Benefit	High	Benefit	Medium	Reduced kinetic impact injury to people - may save lives (impact energy reduced to 150 J, non-likely fatal); less strain on the healcare system
		Reliable	3	Benefit	Medium	Benefit	Medium			1 moving part + wireless connection; moderate reliability
		Energy usage	8	Risk	Low	Risk	Medium	Risk	Low	5-10% Energy usage increase; small increase in aerodynamic drag
		Flight access	10			Benefit	High			Improved flight access based on current traffic authority rules (can fly over people with their permission)
		Payload	9	Risk	Medium	Risk	Medium			Reduced payload by 10-15%; the drone becomes less beneficial
		Usefulness	2	Benefit	Low	Benefit	Low			People are more relaxed under it
		Use Risks Total Scores >			**6.50**		**8.50**		**2.00**	
		Use Benefits Total Scores >			**12.00**		**22.00**		**5.00**	
	Disposal	Landfill	3					Risk	Low	End-of-life EPI: 90% landfill (most likely internationally)
		Incineration	1					Risk	Low	End-of-life EPI: 10% (highly likely in DK)
		Energy recovery	3			Benefit	Low	Benefit	Low	Energy recovered by incineration/energy of primary production: 40% (Nylon - 80 MJ/kg/120 = 66%; carbon fiber + epoxy - 32 MJ/kg/275 = 12%)
		Reuse	3			Benefit	Medium	Benefit	Low	Reusable parts EPI - weight of reusable parts/weight of product: 100% (reusable after crash)
		Recylcle	3					Benefit	Medium	Recylced materials EPI - weight of recycleable material/weight of product: 50% (Nylon)
		Cost								
		Transport								
		Nuisances								
		Health and Safety								
		Other								
		Other								
		Disposal Risks Total Scores >			**0.00**		**0.00**		**1.00**	
		Disposal Benefits Total Scores >			**0.00**		**2.25**		**3.00**	
		Product Assessmet Risks Grand Total >			**12.00**		**18.75**		**7.50**	
		Product Assessment Benefits Grand Total >			**17.00**		**24.25**		**8.00**	

Propeller protection

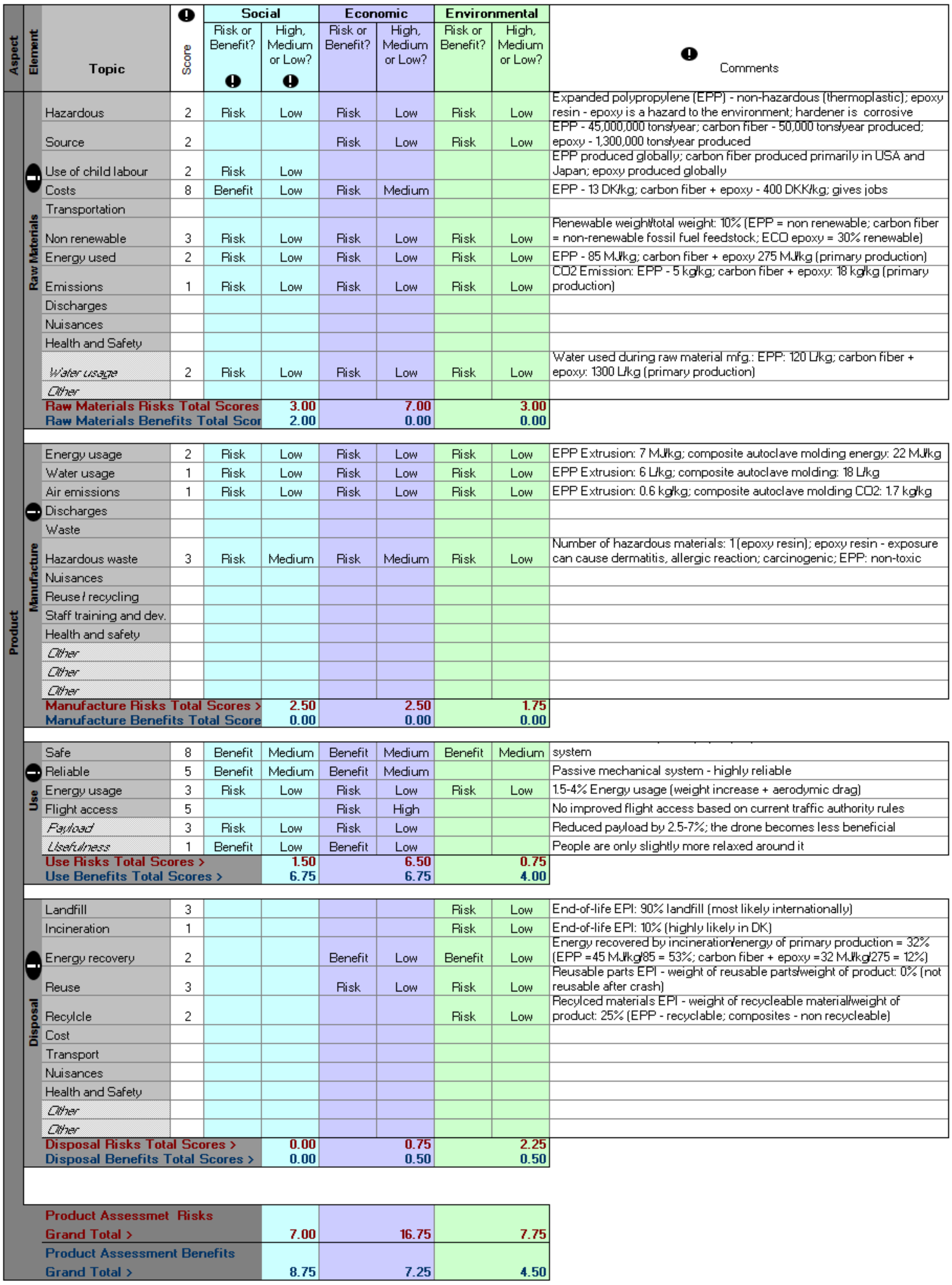
Analysis is based on the carbon fiber bumpers of the Aibot X6 drone (Aibot X6, 2016).



Aspect	Element	Topic	Score	Social		Economic		Environmental		Comments
				Risk or Benefit?	High, Medium or Low?	Risk or Benefit?	High, Medium or Low?	Risk or Benefit?	High, Medium or Low?	
Product	Raw Materials	Hazardous	3	Risk	Low	Risk	Low	Risk	Medium	Epoxy resin - epoxy is a hazard to the environment; hardener is corrosive
		Source	3			Risk	Low	Risk	Low	Carbon fiber - 50,000 tons/year produced; epoxy - 1,300,000 tons/year produced
		Use of child labour	3	Risk	Low					Carbon fiber produced primarily in USA and Japan; epoxy produced globally
		Costs	10	Benefit	Medium	Risk	High			High material cost (400 DKK/kg); gives jobs
		Transportation								
		Non renewable	3	Risk	Low	Risk	Low	Risk	Low	Renewable weight/total weight: 12% (carbon fiber = non-renewable fossil fuel feedstock; ECO epoxy = 30% renewable)
		Energy used	3	Risk	Low	Risk	Low	Risk	Low	High energy required to form carbon fibers and epoxy (275 MJ/kg primary production)
		Emissions	1	Risk	Low	Risk	Low	Risk	Low	CO2 Emission (18 kg/kg, primary production)
		Discharges								
		Nuisances								
		Health and Safety								
		Water usage	3	Risk	Low	Risk	Low	Risk	Low	production)
		Other								
		Raw Materials Risks Total Scores			**4.00**		**14.00**		**4.75**	
		Raw Materials Benefits Total Scor			**5.00**		**0.00**		**0.00**	
	Manufacture	Energy usage	3	Risk	Low	Risk	Low	Risk	Low	Autoclave molding energy: 22 MJ/kg
		Water usage	1	Risk	Low	Risk	Low	Risk	Low	Autoclave molding: 18 L/kg
		Air emissions	1	Risk	Low	Risk	Low	Risk	Low	Autoclave molding CO2: 1.7 kg/kg
		Discharges								
		Waste								
		Hazardous waste	5	Risk	Medium	Risk	Medium	Risk	Low	Number of hazardous materials: 1 (epoxy resin); epoxy resin - exposure can cause dermatitis, allergic reaction; carcinogenic
		Nuisances								
		Reuse / recycling								
		Staff training and dev.								
		Health and safety								
		Other								
		Other								
		Other								
		Manufacture Risks Total Scores >			**3.75**		**3.75**		**2.50**	
		Manufacture Benefits Total Score			**0.00**		**0.00**		**0.00**	
	Use	Safe	10	Benefit	High	Benefit	Medium	Benefit	Medium	Reduced laceration and kinetic impact injury to people; less strain on the healcare system; most useful in low-speed collisions
		Reliable	5	Benefit	Medium	Benefit	Medium			Passive mechanical system - highly reliable
		Energy usage	5	Risk	Low	Risk	Medium	Risk	Low	15% Energy usage (weight increase + aerodymic drag)
		Flight access	5			Risk	High			No improved flight access based on current traffic authority rules
		Payload	8	Risk	Medium	Risk	Medium			Reduced payload by 25%; the drone becomes less beneficial
		Usefulness	2	Benefit	Medium	Benefit	Low			Can be flown closer to trees/wires/inside silos; people are more relaxed around it
		Use Risks Total Scores >			**5.25**		**11.50**		**1.25**	
		Use Benefits Total Scores >			**13.50**		**8.00**		**5.00**	
	Disposal	Landfill	3					Risk	Low	End-of-life EPI: 90% landfill (most likely internationally)
		Incineration	1					Risk	Low	End-of-life EPI: 10% (highly likely in DK)
		Energy recovery	1			Benefit	Low	Benefit	Low	Energy recovered by incineration/energy of primary production: 32 MJ/kg/275 = 12%
		Reuse	3			Risk	Low	Risk	Low	Reusable parts EPI - weight of reusable parts/weight of product: 0% (not reusable after crash)
		Recylcle	3					Risk	Low	Recylced materials EPI - weight of recycleable material/weight of product: 0% (only downcycle of carbon fibers; current recycle
		Cost								
		Transport								
		Nuisances								
		Health and Safety								
		Other								
		Other								
		Disposal Risks Total Scores >			**0.00**		**0.75**		**2.50**	
		Disposal Benefits Total Scores >			**0.00**		**0.25**		**0.25**	
		Product Assessmet Risks Grand Total >			**13.00**		**30.00**		**11.00**	
		Product Assessment Benefits Grand Total >			**18.50**		**8.25**		**5.25**	

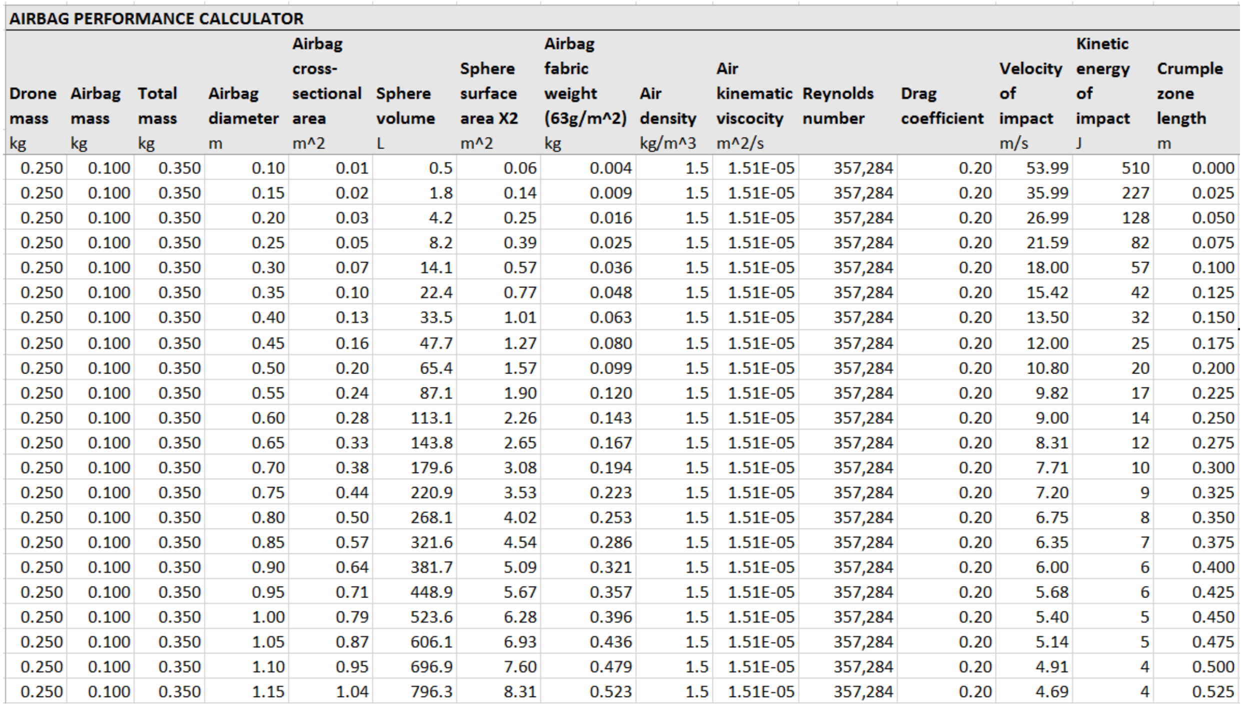
Crumple zones and foam padding

Analysis is based on carbon fiber crumple-zone arms and EPP foam padding.



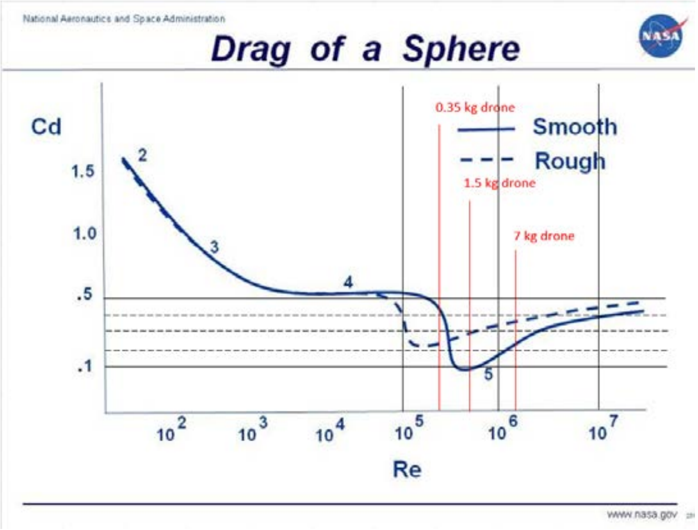
Aspect	Element	Topic	❗ Score	Social: Risk or Benefit? ❗	Social: High, Medium or Low? ❗	Economic: Risk or Benefit?	Economic: High, Medium or Low?	Environmental: Risk or Benefit?	Environmental: High, Medium or Low?	❗ Comments
Product	Raw Materials	Hazardous	2	Risk	Low	Risk	Low	Risk	Low	Expanded polypropylene (EPP) - non-hazardous (thermoplastic); epoxy resin - epoxy is a hazard to the environment; hardener is corrosive
		Source	2			Risk	Low	Risk	Low	EPP - 45,000,000 tons/year; carbon fiber - 50,000 tons/year produced; epoxy - 1,300,000 tons/year produced
		Use of child labour	2	Risk	Low					EPP produced globally; carbon fiber produced primarily in USA and Japan; epoxy produced globally
		Costs	8	Benefit	Low	Risk	Medium			EPP - 13 DK/kg; carbon fiber + epoxy - 400 DKK/kg; gives jobs
		Transportation								
		Non renewable	3	Risk	Low	Risk	Low	Risk	Low	Renewable weight/total weight: 10% (EPP = non renewable; carbon fiber = non-renewable fossil fuel feedstock; ECO epoxy = 30% renewable)
		Energy used	2	Risk	Low	Risk	Low	Risk	Low	EPP - 85 MJ/kg; carbon fiber + epoxy 275 MJ/kg (primary production)
		Emissions	1	Risk	Low	Risk	Low	Risk	Low	CO2 Emission: EPP - 5 kg/kg; carbon fiber + epoxy: 18 kg/kg (primary production)
		Discharges								
		Nuisances								
		Health and Safety								
		Water usage	2	Risk	Low	Risk	Low	Risk	Low	Water used during raw material mfg.: EPP: 120 L/kg; carbon fiber + epoxy: 1300 L/kg (primary production)
		Other								
		Raw Materials Risks Total Scores			**3.00**		**7.00**		**3.00**	
		Raw Materials Benefits Total Scor			**2.00**		**0.00**		**0.00**	
	Manufacture	Energy usage	2	Risk	Low	Risk	Low	Risk	Low	EPP Extrusion: 7 MJ/kg; composite autoclave molding energy: 22 MJ/kg
		Water usage	1	Risk	Low	Risk	Low	Risk	Low	EPP Extrusion: 6 L/kg; composite autoclave molding: 18 L/kg
		Air emissions	1	Risk	Low	Risk	Low	Risk	Low	EPP Extrusion: 0.6 kg/kg; composite autoclave molding CO2: 1.7 kg/kg
		Discharges								
		Waste								
		Hazardous waste	3	Risk	Medium	Risk	Medium	Risk	Low	Number of hazardous materials: 1 (epoxy resin); epoxy resin - exposure can cause dermatitis, allergic reaction; carcinogenic; EPP: non-toxic
		Nuisances								
		Reuse / recycling								
		Staff training and dev.								
		Health and safety								
		Other								
		Other								
		Other								
		Manufacture Risks Total Scores >			**2.50**		**2.50**		**1.75**	
		Manufacture Benefits Total Score			**0.00**		**0.00**		**0.00**	
	Use	Safe	8	Benefit	Medium	Benefit	Medium	Benefit	Medium	system
		Reliable	5	Benefit	Medium	Benefit	Medium			Passive mechanical system - highly reliable
		Energy usage	3	Risk	Low	Risk	Low	Risk	Low	1.5-4% Energy usage (weight increase + aerodymic drag)
		Flight access	5			Risk	High			No improved flight access based on current traffic authority rules
		Payload	3	Risk	Low	Risk	Low			Reduced payload by 2.5-7%; the drone becomes less beneficial
		Usefulness	1	Benefit	Low	Benefit	Low			People are only slightly more relaxed around it
		Use Risks Total Scores >			**1.50**		**6.50**		**0.75**	
		Use Benefits Total Scores >			**6.75**		**6.75**		**4.00**	
	Disposal	Landfill	3					Risk	Low	End-of-life EPI: 90% landfill (most likely internationally)
		Incineration	1					Risk	Low	End-of-life EPI: 10% (highly likely in DK)
		Energy recovery	2			Benefit	Low	Benefit	Low	Energy recovered by incineration/energy of primary production = 32% (EPP =45 MJ/kg/85 = 53%; carbon fiber + epoxy =32 MJ/kg/275 = 12%)
		Reuse	3			Risk	Low	Risk	Low	Reusable parts EPI - weight of reusable parts/weight of product: 0% (not reusable after crash)
		Recylcle	2					Risk	Low	Recylced materials EPI - weight of recycleable material/weight of product: 25% (EPP - recyclable; composites - non recycleable)
		Cost								
		Transport								
		Nuisances								
		Health and Safety								
		Other								
		Other								
		Disposal Risks Total Scores >			**0.00**		**0.75**		**2.25**	
		Disposal Benefits Total Scores >			**0.00**		**0.50**		**0.50**	
		Product Assessmet Risks Grand Total >			**7.00**		**16.75**		**7.75**	
		Product Assessment Benefits Grand Total >			**8.75**		**7.25**		**4.50**	

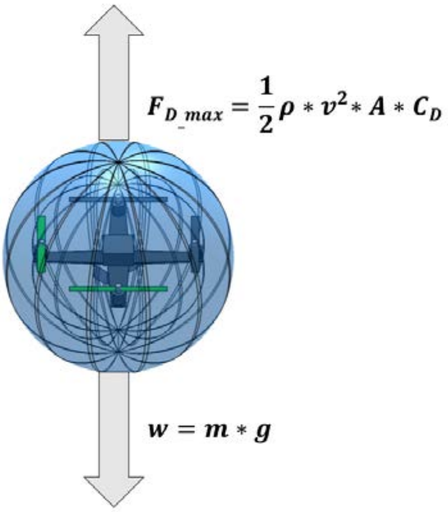
Airbag performance mathmatical model



AIRBAG PERFORMANCE CALCULATOR

Drone mass	Airbag mass	Total mass	Airbag diameter	Airbag cross-sectional area	Sphere volume	Sphere surface area X2	Airbag fabric weight (63g/m^2)	Air density	Air kinematic viscocity	Reynolds number	Drag coefficient	Velocity of impact	Kinetic energy of impact	Crumple zone length
kg	kg	kg	m	m^2	L	m^2	kg	kg/m^3	m^2/s			m/s	J	m
0.250	0.100	0.350	0.10	0.01	0.5	0.06	0.004	1.5	1.51E-05	357,284	0.20	53.99	510	0.000
0.250	0.100	0.350	0.15	0.02	1.8	0.14	0.009	1.5	1.51E-05	357,284	0.20	35.99	227	0.025
0.250	0.100	0.350	0.20	0.03	4.2	0.25	0.016	1.5	1.51E-05	357,284	0.20	26.99	128	0.050
0.250	0.100	0.350	0.25	0.05	8.2	0.39	0.025	1.5	1.51E-05	357,284	0.20	21.59	82	0.075
0.250	0.100	0.350	0.30	0.07	14.1	0.57	0.036	1.5	1.51E-05	357,284	0.20	18.00	57	0.100
0.250	0.100	0.350	0.35	0.10	22.4	0.77	0.048	1.5	1.51E-05	357,284	0.20	15.42	42	0.125
0.250	0.100	0.350	0.40	0.13	33.5	1.01	0.063	1.5	1.51E-05	357,284	0.20	13.50	32	0.150
0.250	0.100	0.350	0.45	0.16	47.7	1.27	0.080	1.5	1.51E-05	357,284	0.20	12.00	25	0.175
0.250	0.100	0.350	0.50	0.20	65.4	1.57	0.099	1.5	1.51E-05	357,284	0.20	10.80	20	0.200
0.250	0.100	0.350	0.55	0.24	87.1	1.90	0.120	1.5	1.51E-05	357,284	0.20	9.82	17	0.225
0.250	0.100	0.350	0.60	0.28	113.1	2.26	0.143	1.5	1.51E-05	357,284	0.20	9.00	14	0.250
0.250	0.100	0.350	0.65	0.33	143.8	2.65	0.167	1.5	1.51E-05	357,284	0.20	8.31	12	0.275
0.250	0.100	0.350	0.70	0.38	179.6	3.08	0.194	1.5	1.51E-05	357,284	0.20	7.71	10	0.300
0.250	0.100	0.350	0.75	0.44	220.9	3.53	0.223	1.5	1.51E-05	357,284	0.20	7.20	9	0.325
0.250	0.100	0.350	0.80	0.50	268.1	4.02	0.253	1.5	1.51E-05	357,284	0.20	6.75	8	0.350
0.250	0.100	0.350	0.85	0.57	321.6	4.54	0.286	1.5	1.51E-05	357,284	0.20	6.35	7	0.375
0.250	0.100	0.350	0.90	0.64	381.7	5.09	0.321	1.5	1.51E-05	357,284	0.20	6.00	6	0.400
0.250	0.100	0.350	0.95	0.71	448.9	5.67	0.357	1.5	1.51E-05	357,284	0.20	5.68	6	0.425
0.250	0.100	0.350	1.00	0.79	523.6	6.28	0.396	1.5	1.51E-05	357,284	0.20	5.40	5	0.450
0.250	0.100	0.350	1.05	0.87	606.1	6.93	0.436	1.5	1.51E-05	357,284	0.20	5.14	5	0.475
0.250	0.100	0.350	1.10	0.95	696.9	7.60	0.479	1.5	1.51E-05	357,284	0.20	4.91	4	0.500
0.250	0.100	0.350	1.15	1.04	796.3	8.31	0.523	1.5	1.51E-05	357,284	0.20	4.69	4	0.525





$$F_{D\_max} = \frac{1}{2}\rho * v^2 * A * C_D$$

$$w = m * g$$

Stoichiometry calculations

CO2 Volume calculation - 16g @ 1 atm and 20 degrees C

Molar mass of CO2:

$$M = 12\,g/mol + (16\,g/mol * 2) = 44\,g/mol$$

Mol of CO2:

$$n = m/M = 16\,g\,/\,44\,g/mol = 0.36\,mol$$

Ideal gas law:

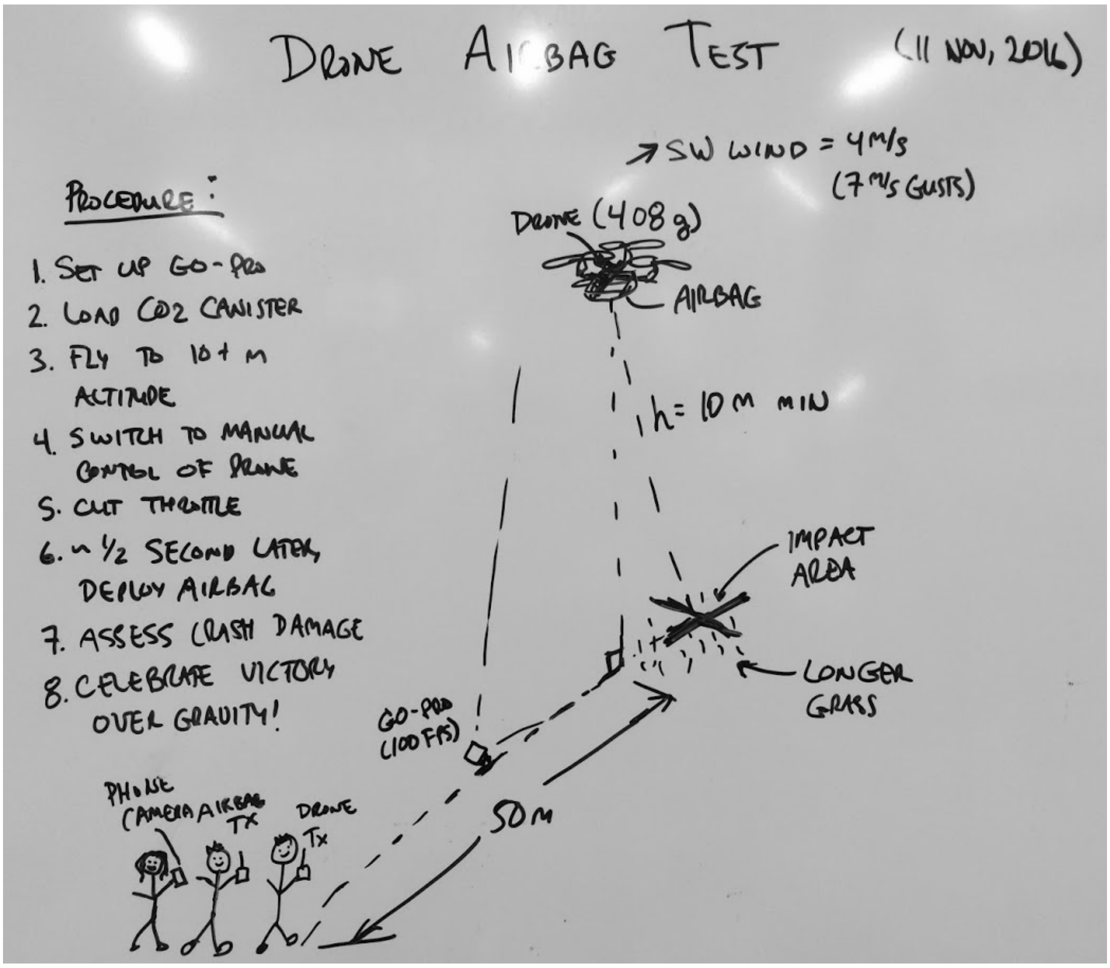
$$PV = nRT$$
$$V = nRT\,/\,P = [(0.36\,g/mol)(0.08206\,L * atm/mol * K)(293\,K)]\,/\,(1\,atm)$$
$$V = 8.7\,L(@\text{ STP})$$

Gas weight VS volume (Nitrogen and air are lightest):

- N2 = 14 X 2 = 28 grams / mole
- CO2 = 12 + 16 + 16 = 44 grams / mole
- Air (78% nitrogen, 21% oxygen etc.) = N2 and O2 = (14 + 14) X 78% + (16 + 16) X 21% = 28.5 grams / mole

Drone airbag test plan

The full-scale prototype test plan. The purpose of the experiment was to determine how much the impact velocity of the drone was reduced with the airbag deployed. The experiment is documented in a video - there is a link in the appendix.



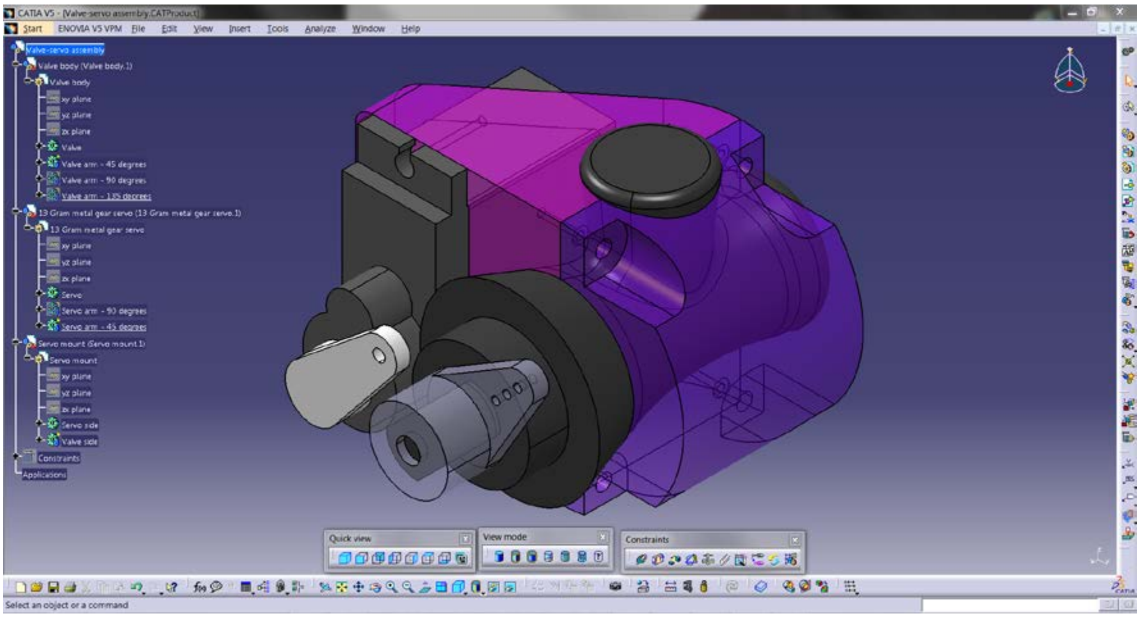
DRONE AIRBAG TEST (11 NOV, 2016)

PROCEDURE:

1. SET UP GO-PRO
2. LOAD CO_2 CANISTER
3. FLY TO 10+ M ALTITUDE
4. SWITCH TO MANUAL CONTROL OF DRONE
5. CUT THROTTLE
6. ~ 1/2 SECOND LATER, DEPLOY AIRBAG
7. ASSESS CRASH DAMAGE
8. CELEBRATE VICTORY OVER GRAVITY!

Valve mechanism CAD

CATIA V5 Computer aided design software was used to model the drone and its components. Digital design allowed for easy duplication and modification as the product developed. The CAD models are included as digital attachments.



Airbag prototype airbag components/weights

Component details and weight break-down of X-shaped airbag system. The system weighs slightly more than the drone, doubling the flying weight.

Component	**Details**	**Weight (grams)**
CO2 Cartridge	16 gram, Biltema part 27527 (Biltema, 2016)	64
Airbag and plastic inner bladder	Zero-porosity parachute material, 70 gram/m^2 (Para Service, 2016)	47
Valve mechanism	Modified bicycle inflation valve, Biltema part 27527 (Biltema, 2016) and custom 3D printed parts	43
Bracket	Aluminum angle, 3mm thickness	14
Servo	Turnigy TGY-9018MG, metal gear micro servo (HobbyKing, 2016)	16
Receiver	Spektrum AR610C (HobbyKing, 2016)	10
Battery	Lipo, 1S (3.3v), 520 mAh (HobbyKing, 2016)	14
	Total system weight	**208**