# Fully automated rudder pedal system for ultralight aircraft

Ana Beric and Simon Strand

DIVISION OF PRODUCT DEVELOPMENT | DEPARTMENT OF DESIGN SCIENCES
FACULTY OF ENGINEERING LTH | LUND UNIVERSITY
2019

MASTER THESIS

BLACKWING

# Fully automated rudder pedal system for ultralight aircraft

Ana Beric and Simon Strand

# Fully automated rudder pedal system for ultralight aircraft

Copyright © 2019 Ana Beric and Simon Strand

*Published by*
Department of Design Sciences
Faculty of Engineering LTH, Lund University
P.O. Box 118, SE-221 00 Lund, Sweden

Subject: Product Development (MMKM05)
Division: Product Development
Supervisor: Per Kristav
Co-supervisor: Per-Erik Andersson
Examiner: Axel Nordin

# Abstract

The Swedish ultralight aircraft manufacturer, Blackwing Sweden AB, has requested a reinvention of their adjustable mechanism for the rudder pedal system in the BW600RG aircraft. The current manual system is insufficient in terms of a non-ergonomic adjustment process which requires for the aircraft to be stationary. The ambition of this project was to deliver a concept covering a fully automated adjustment mechanism which can be initiated at a stationary state as well as during flight. In addition, the concept was to acquire an airworthiness certification which is necessary for implementation in the aircraft. By following the principles of Ulrich & Eppinger's design process, a concept which satisfies the main project goal was developed. The results from the validation analysis showcased that the proposed solution is functional, while a few additional actions of work are necessary in order to fully incorporate it. These actions include: selecting fasteners, selecting a linear actuator of suitable size and lastly, designing a mounting rig for the linear actuator. By completing the additional requirements, a strength-test can be performed which subsequently allows for certification and thus for implementation of the fully automated rudder pedal system in the BW600RG aircraft.

**Keywords:** Actuator, Rudder, BW600RG, Certification, System

# Sammanfattning

De svenska tillverkarna av ultralätta mikroflygplan, Blackwing Sweden AB, har lämnat en förfrågan gällande uppdatering av den justerbara mekanismen tillhörande roderpedal-systemet i flygplansmodellen BW600RG. Det nuvarande manuella systemet anses bristfälligt sett till den icke ergonomiska justeringsprocessen som för övrigt kräver att flygplanet är stationärt. Målet med detta projekt var att framföra ett koncept med en fullt automatiserad justeringsmekanism som kan initieras i stationärt läge så väl som under flygning. Vidare erfordras att konceptet uppfyller kraven för flygplanscertifiering vilket är nödvändigt för att konceptet skall kunna implementeras i flygplanet. Genom att följa principerna i Ulrich & Eppingers utvecklingsprocess genererades ett koncept som möter huvudmålen i projektet. Resultaten från analyserna visar att den föreslagna lösningen är funktionell men att vidare arbete krävs för att införliva den i flygplanet. Dessa åtgärder omfattas bland annat av val av fästelement, val av lämplig storlek på ställdon samt utformning av ett fäste för själva ställdonet. Genom att fullborda de slutliga åtgärderna kan ett hållfastighetstest utföras på konceptet vilket ligger till grund för flygplanscertifiering. Således möjliggörs realisering av konceptet i flygplansmodellen BW600RG.

**Nyckelord:** Ställdon, Roder, BW600RG, Certifiering, System.

# Acknowledgements

This thesis project would not have been possible without the help from the following people.

Thank you Per Kristav, our supervisor at LTH, for always being available and always encouraging us.

Thank you Tomas Norlander & Niklas Anderberg at Blackwing, for valuable input.

Thank you Mårten, Patrik and the rest of the production team, for assisting with assembling and disassembling the rudder pedal system.

Thank you Bert Berglund, for helping with the waterjet cutting of structural plates.

Thank you Axel Nordin, our examiner at LTH, for assisting in the analysis and providing valuable input.

Thank you Cilla Perlhagen for your administrative help.

Thank you, our friends and families for your support during the thesis project.

Thank you, Ryszard Wierzbicki and Svante Bouvin at Industrial Production, for helping us with the prototype.

Thank you Cornelia Svensson, our opponent, for valuable input.

Lund, May 2019
Ana Beric & Simon Strand

# Table of contents

# 1 Introduction

*This chapter introduces the master thesis and the company at which the project was performed. The courses of actions throughout the project report are based on problem statements including an initial brief, goals, resources and delimitations as well as a detailed description of the current solution.*

Presented below is an introduction of Blackwing Sweden and the problem statement which is continuously evaluated throughout the report by following the working principles in Ulrich & Eppinger's Development Process (U&E).

## 1.1 Blackwing Sweden

The master thesis will be performed at Blackwing Sweden which, according to themselves, produces the world's most advanced ultralight aircraft. The company was established in 2011 by Niklas Anderberg & Yngve Anderberg.

The point of departure for the development of Blackwing was a student project carried out at Kungliga Tekniska Högskolan (KTH), where Niklas took his Master of Science degree in Vehicle Engineering. After his degree, while working at SAAB, Niklas was given the opportunity to participate in a project initiated by KTH where the project aim was to develop a fuel-efficient aircraft. The project was later transmitted over to SAAB from KTH where the aircraft was to be manufactured. However, as time went on, SAAB lost interest in the project and Niklas decided to proceed by himself with additional help from his dad Yngve. This was the starting point of Blackwing.

Dedication and hard work led to the first demonstration aircraft being presented in 2015 and since then, Blackwing has been praised and awarded by the aviation industry for its two-seated ultralight aircraft. Moreover, Blackwing has been awarded the prominent Red Dot Design Award, which is an international design competition for those who would like to distinguish their business activities through design. The competition is separated into three categories: “product design”, “communication design” and “design concepts”. The finest designs are evaluated and selected by a competent expert jury, which awarded Blackwing the Red Dot Design Award 2016 in the category “product design” among 79 other competitors such as Ferrari and Airbus. In addition, Blackwing was awarded the Flieger Award, selected by the German Aviation community in both 2016 and 2019 for the best new ultralight aircraft.

Blackwing distinguishes themselves from competitors primarily by choice of material. Approximately 90 percent of the aircraft is made out of composite material with carbon fibre reinforcements. Remaining parts which require high accuracy in structural design from which it mustn’t deviate are made of light aluminum. Examples of such parts are pedals and additional joint components. The combination of material selection results in a rigid but lightweight fuselage, which enables for a more powerful (and thus heavier) engine to be installed. Hence why Blackwing is recognized as one of the strongest and fastest aircrafts ever tested in the 600 kg category. The benefits of aircrafts produced by Blackwing justifies (or excuses) the price being approximately 25 percent above the price of competitor products which aims the market towards flight academies and wealthy seniors (mostly senior men from Germany with previous history in the military). As of now, they have distributors located in Sweden, Germany, Poland, France and South Africa.

Blackwing is a fairly small company with eleven employees (2017). Apart from being the CEO, Niklas is also responsible for all structural calculations with its accompanied work of administration. Furthermore, 3D-modelling and drawings of aircraft components is executed by the mechanical engineer Tomas Norlander who is the main supervisor of the thesis project. Tomas has done an impressive job modelling all of the Blackwing aircrafts by himself apart from a short time during the company start-up. At the beginning of 2011, Tomas chose to disrupt his Master of Science degree in Mechanical Engineering at Lunds Tekniska Högskola. After a couple of years as an employee at Blackwing Sweden he is now aiming towards completing the degree while still contributing with his expertise at Blackwing. Remaining employees at Blackwing Sweden are involved mainly with production.

## 1.2 Problem statement

### 1.2.1 Initial brief

Blackwing aims to develop a fully automated rudder pedal system to replace their current manual solution. The ambition is to reconstruct the system so it can be adjusted without manual effort from the user, i.e., by initiating an electrically controlled adjustment mechanism. Considering the extent of this project, there are constraints in terms of time and resources which are taken into consideration by the mentors at Blackwing. If a solution with fully automated rudder pedal system is not developed, the company wishes for a mechanical solution that at least allows for an automated adaption. Lastly, if none of the earlier mentioned is achieved, the company will accept a manual solution if it's considered more ergonomically favorable compared to the current system.

If time permits, the company wishes for a prototype to be built based on the chosen concept. The prototype shall provide additional value and justice in both strength and function. The latter shall be confirmed by strength tests for certification in their aircraft.

### 1.2.2 Current solution

The 3D-model of the current aircraft and the workspace of relevance is depicted in Figure 1-2.

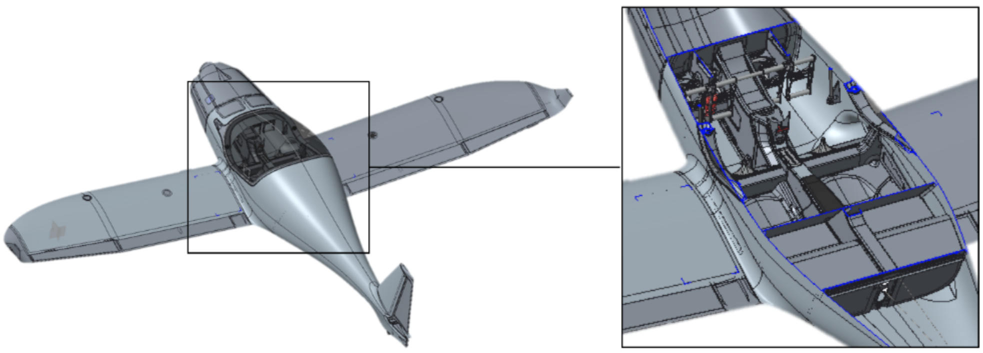

Figure 1: 3D-model of the BW600RG aircraft

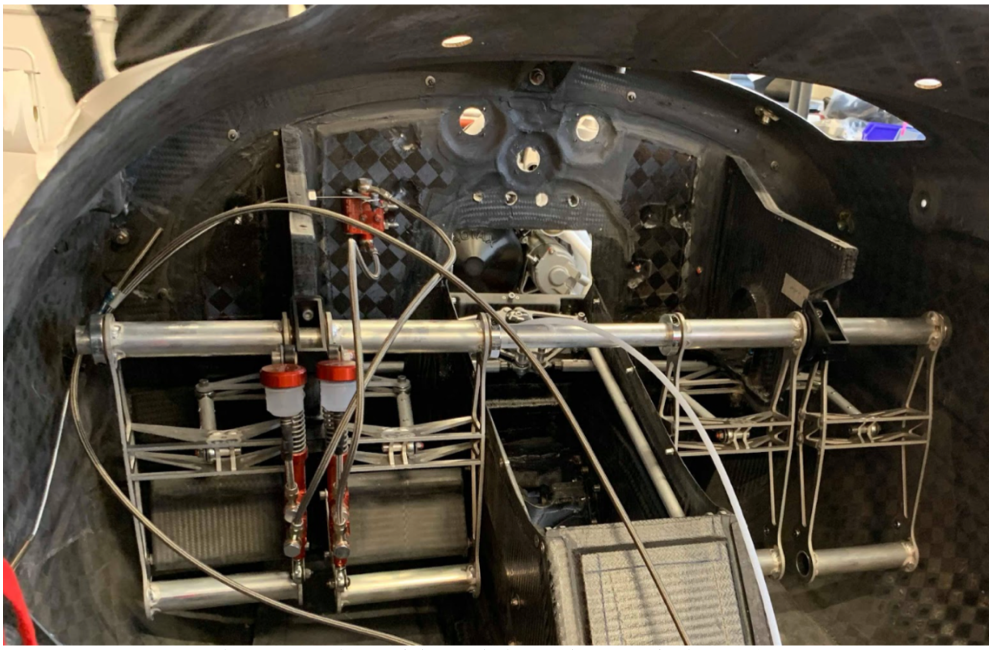

Figure 2: A photo of the cockpit (workspace of relevance).

One of the steering control units on an aircraft is the rudder pedal system, which controls the movement around the yaw-axis, see Figure 3.

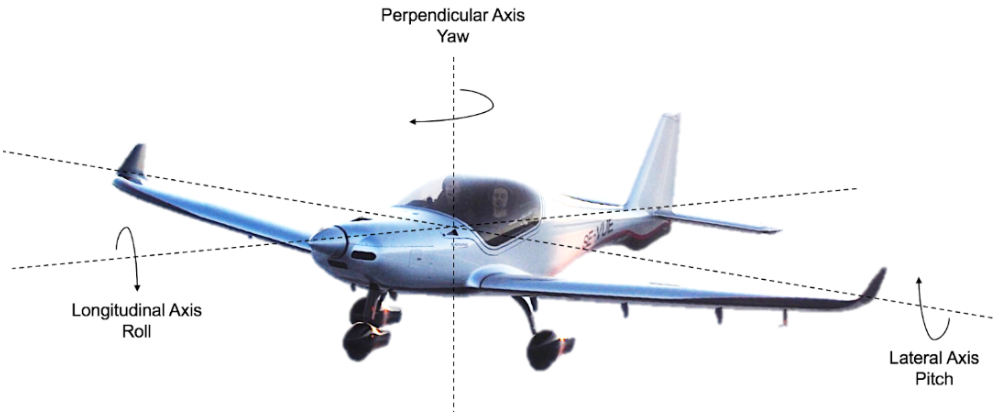


Figure 3: Aircraft principal axes applied on the BW600RG aircraft [1, Figure 3].

The carbon fiber composites in the aircraft are manufactured by either Prepreg Hand lay-up with autoclave, or as such composites with additional sandwich structure reinforcements. Prepreg is an abbreviation for pre-impregnated laminates, i.e. thermoset/thermoplastic matrix materials which are reinforced with carbon fibers beforehand. A regular (wet) hand-layup process without Prepregs is a so called “In-process reinforcement impregnation”, where the matrix and fibers are applied sequentially and must be worked thoroughly in order for defects to not appear. Moreover, it may be hazardous in terms of exposure through inhalation and direct contact with uncured matrices. Prepregs are, on the other hand, not hazardous since they come as finished fabrics (mostly weaves) and thus they are easily applied in moulds. Unlike wet hand lay-up, prepreg composites require autoclave for curing which makes it a very expensive technique. Nevertheless, it achieves outstanding mechanical properties required for the current industry. By using additional cores, the bending stiffness is increased while maintaining a low density. The structure most commonly consists of a foam core with additional composite layers on each side, which constitutes the Sandwich structure, see Figure 4.

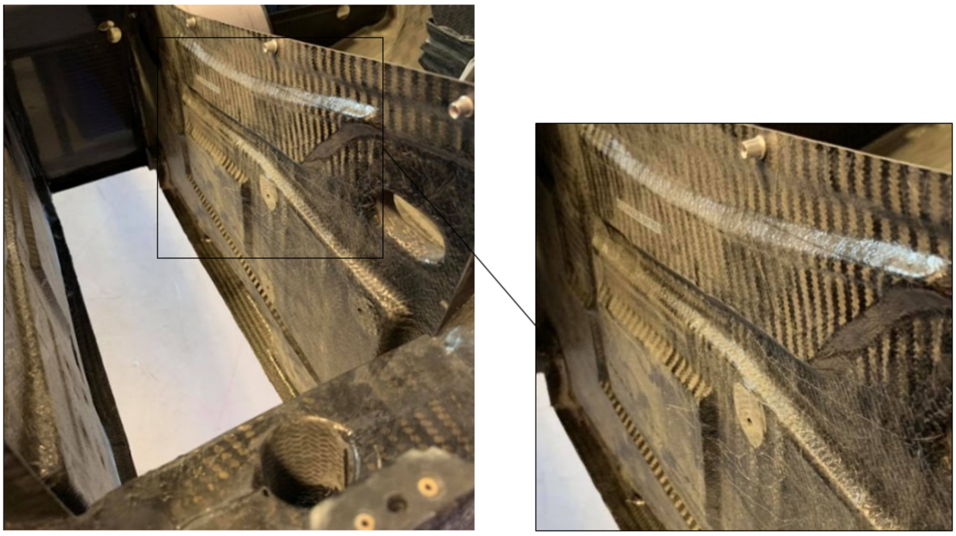

Figure 4: Sandwich structure within the NW (Nosewheel Console).

The design of the rudder pedal system features several components. Presented below is an overall explanation of how the rudder is controlled by interaction with the pedals.

**Pedals**

The pedals are attached to a beam which serves as the pivot point, see Figure 5. When the pilot interacts with a pedal, a rotation around the pivot point is induced. The pedals are made of aluminum and are connected with the pedal yoke through a rod joint.

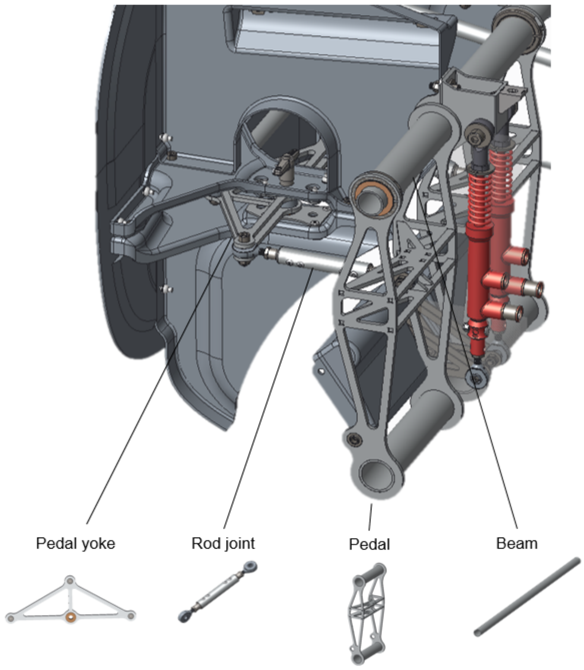


Figure 5: 3D-model of the rudder pedal system.

**Pedal yoke**

The rotational movement of the pedals is transferred through the rod joints to an aluminum pedal yoke, which has its rotation axis through the lock-pin mechanism, see Figure 6-7. The yoke is connected to The Nosewheel Yoke within the NW through an additional rod joint. The lock-pin mechanism is accompanied with structural support in the vertical and transverse direction, such as “The Shark tail”, “The Center Structure” and “The Clamp”, which are made of Carbon Fiber Reinforced Plastics (CFRP) and are mounted onto the firewall.

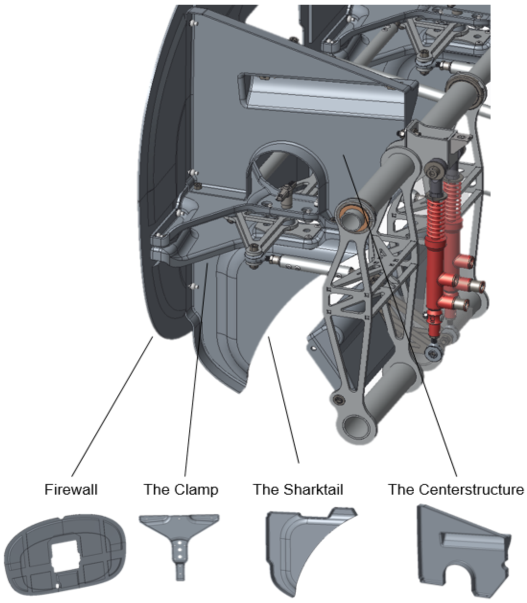


Figure 6: 3D-modell of the rudder pedal system.

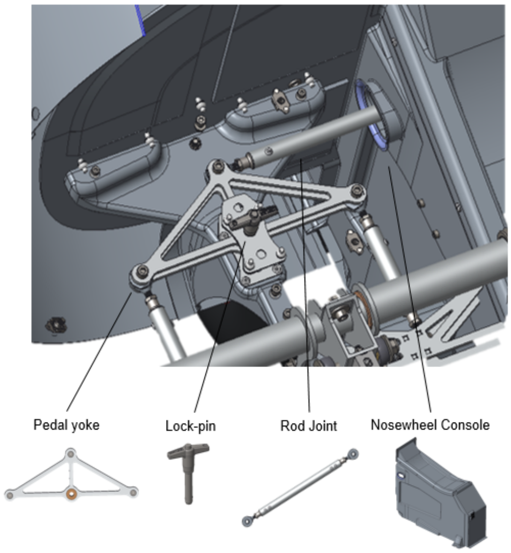


Figure 7: 3D-model of the rudder pedal system.

**Nosewheel Console**

The NW (see Figure 8) serves as housing for an additional yoke, the Nosewheel Yoke, which is connected to the rudder blade through wires and rod joints. Rotation of the Pedal Yoke is translated to The Nosewheel Yoke through the rod joint, which subsequently puts the rudder in motion due to the wire connection. Moreover, the rod joint connection also causes the nosewheel to rotate.

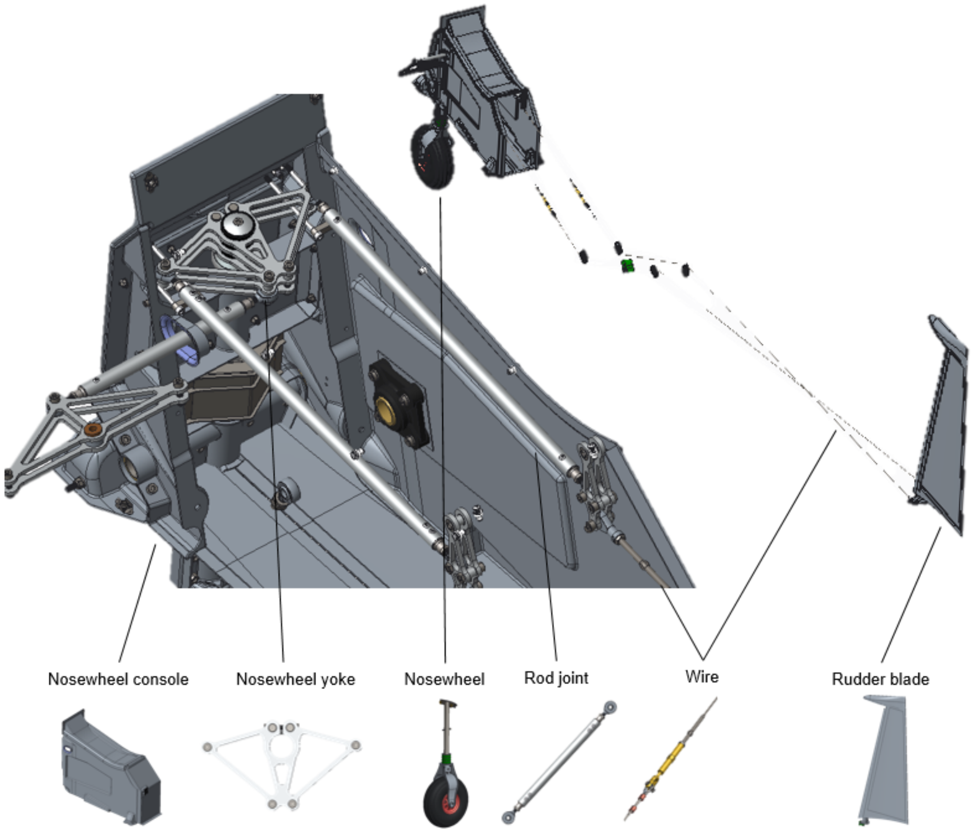


Figure 8: 3D-model of the rudder pedal system.

**Firewall**
The Firewall is a thin screen made of CFRP placed in the transverse direction in order to separate the cockpit region from the aircraft engine, see Figure 9. The firewall is reinforced with sandwich material on individual surfaces in order to endure deformations.

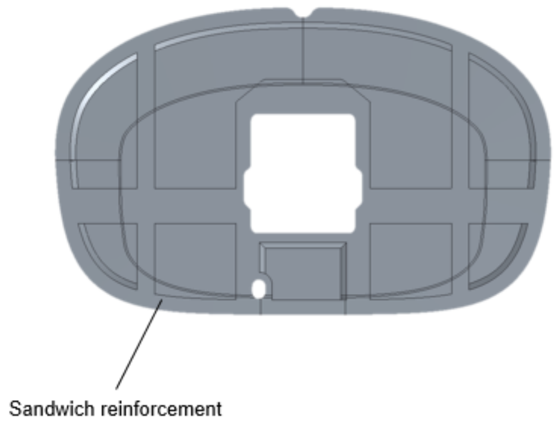


Figure 9: 3D-model of the firewall.

The current system features a lock-pin mechanism, see Figure 10, which has three available positions.

Figure 10: The lock-pin mechanism

There is only one alternative for the user to interact with the lock-pin mechanism in order to adjust the position of the rudder pedals. The adjustment requires the aircraft to be stationary since it is impossible to access the area below the control panel during flight mode. The degree of exposure is a limitation and the user is restricted to sense (by hand) when locating the pin. The adjustment includes following steps:

- Step out of cockpit, see Figure 11

Figure 11: Ana sitting in the cockpit

- Reach down below control panel and locate the pin, see Figure 12.

Figure 12: Reaching below the control panel

- Pull out the pin to unlock system
- Manually move pedals into one of the three positions
- Locate the pin positioning and insert it in order to lock the system, see Figure 13.


Figure 13: Sideway view of interaction with lock-pin during adjustment.

### 1.2.3 Goals

This master thesis aims to develop a mechanical solution concept for an automated adjustable rudder pedal system. To achieve this, following partial goals are essential:

- Gain deeper knowledge about design methods in the current aircraft industry
- Understand the user expectations to identify requirements.
- Understand the environment in which the system will be integrated.
- Develop concepts which are to be screened and further evaluated with the finite element method.
- Evaluate the final result with an incidence of constructive criticism with additional recommendations for further development.

### 1.2.4 Resources

Blackwing provided the thesis work with necessary equipment for the project as well as a workplace at their office and access to their production in Eslöv. Both Tomas and Niklas contributed with their knowledge and experience throughout the thesis work.

### 1.2.5 Delimitations

The project will encounter several delimitations which can be decomposed into five main challenges: trade-offs, dynamics, details, time pressure and economics.

#### *1.2.5.1 Trade-offs*

Weight and cost are the two most important parameters which are considered throughout the whole project. Due to the complexity of the aircraft configuration, custom made parts would normally be considered a necessity. However, it is desirable for Blackwing to reuse existing solutions in order to maintain a low variety of components, moulds, fastenings etc. Moreover, it is of importance to use intuition when the design is carried out with respect to solely weight reduction. If the complexity of such a detail exceeds what is thought of as acceptable, the economic consequences may not be disregarded.

#### *1.2.5.2 Dynamics*

The aircraft is under continuous development and subsequent issues arise whenever an incremental measurement changes, which leads to a constantly changing environment in which the concept will be implemented. The adaptability for modifications is therefore decisive in this project.

#### *1.2.5.3 Details*

The concept will encounter plenty of details which will affect the rigidity, weight and cost of the overall system. Choices such as the selection of motion systems for the generated concepts are crucial and will demand careful thinking in order to balance the three aspects mentioned previously.

#### *1.2.5.4 Time pressure*

Considering the scope of the project along with a limited number of people being involved, the primary focus is to deliver an effective solution for the problem. Hence why cost calculations will not be included in this project.

#### *1.2.5.5 Economics*

Blackwing is still in its start-up phase with limited resources in terms of equipment and financial aid. This implies that the final solution must satisfy Blackwing’s current manufacturing methods in order to maximize their profit and maintain a competitive price on their aircraft.

# 2 Methodology

The thesis project was carried out with respect to guidelines in U&E. The choice of approach is based on U&E's broad ability of adaptation, mainly due its highly decomposed schematics. These characteristics were considered necessary because of delimitations in the project, since they enable the user to customize a project plan without compromising the final quality assurance. In addition, the requirements mentioned in the brief such as incremental improvements of an already existing product, are directly applicable to subprocesses in U&E. Hence, it is the preferable choice of approach. Figure 14 shows the main phases included in a generic U&E. Aside from "Production Ramp-Up", all phases will be elaborated.

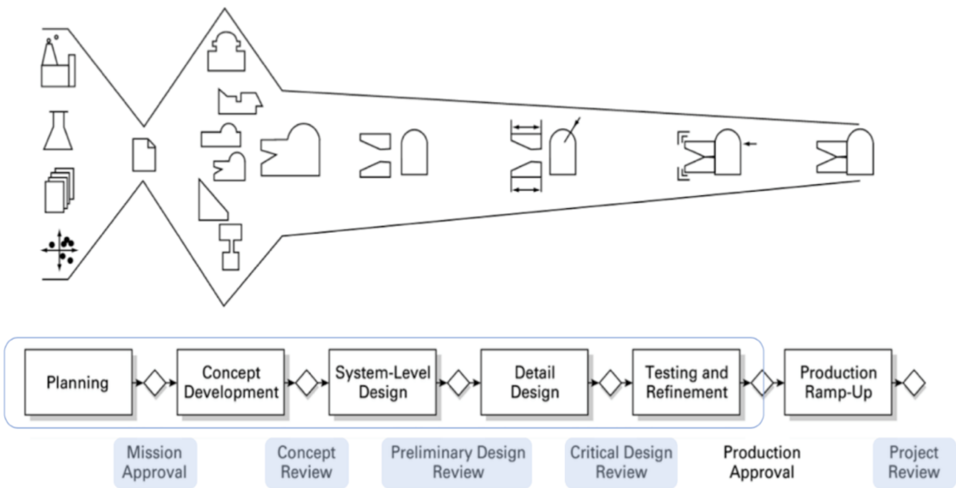


Figure 14: The 6 phases in Ulrich and Eppinger's Development Process and the delimitation for the current project [2, Figure 14].

In the concept development phase, the customer needs will be identified followed by interpretation of these into raw data. Technical requirements will also be considered in order to complete the product specifications which are brought to use when generating the concept solutions. Among these, only a few ideas will be voted for further concept testing and refinement, which answers for evaluation of the final solution.

## 2.1 Planning

The time schedule for the project, including each phase of the U&E design process except from Production Ramp-up, is depicted in Figure 15.

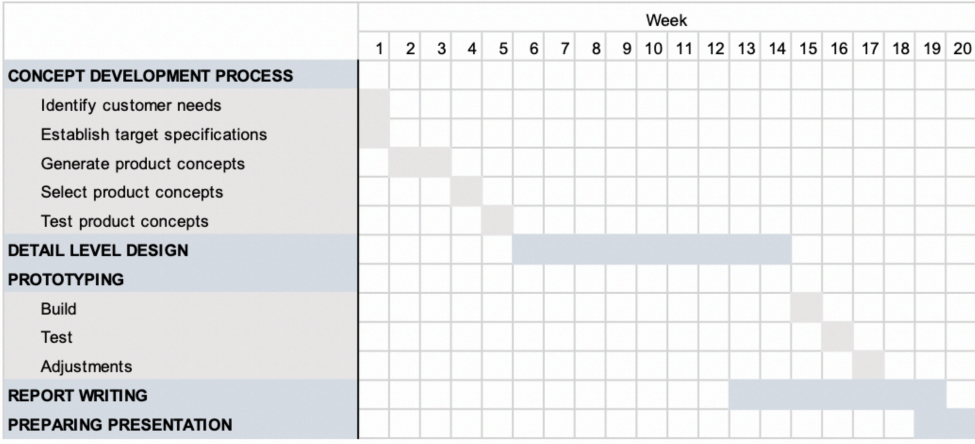


Figure 15: Initial time schedule for the project.

# 3 Concept development

The process of developing concepts is initiated by a Mission Statement and is usually completed by a Downstream Development Plan (see Figure 16). However, the latter will not be taken into consideration since the final solution will require additional development before the Production Ramp-up becomes relevant.

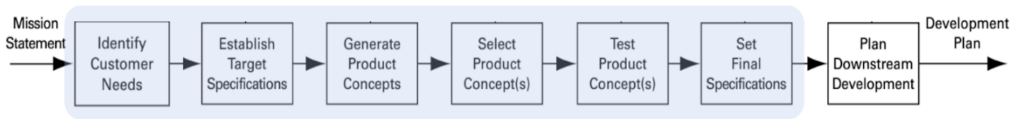


Figure 16: The concept development process and the delimitation for the current project.

The Mission Statement is a formal summary which provides an overview of the aim in the project as well as involved parts which are to be affected by it. A Mission Statement for the fully automated rudder pedal system does not deviate from the summary for the aircraft as a whole, other than having modifications in the “Product Description”, “Benefit Proposition” and “Assumptions/Constraints” (see Figure 17).

| | |
|---|---|
| **Product description** | Fully automated rudder pedal system |
| **Benefit proposition** | The absence of manual effort during adjustment of system |
| **Key Business Goals** | Profitable in Sweden |
| **Primary market** | Top segment within micro light aircrafts |
| **Secondary markets** | Flight schools |
| **Assumptions and constraints** | • Increases the standard and instills luxury<br>• Additional weight |
| **Stakeholders** | Flight & Safety Design Sweden AB |

Figure 17: Mission Statement for aircraft with a fully automated rudder pedal system.

## 3.1 Identifying customer needs

### 3.1.1 Raw data

The raw data mainly consists of statements collected from customers (seniors from Germany with previous history in the military as well as teachers and students in flight schools) who have expressed their dissatisfaction with manual adjustment of the current rudder pedal system. In addition, employees among the production team secure endorsement of the customer feedback by also stating that the mechanism requires improvement as they wish for it to become less tedious. The statements are acquired from the supervisors who have personal contact with employees as well as the customers who leaves feedback continuously. Observations of the product in use were carried out by the authors in order to gather further understanding of issues that a user may experience, see Figure 10-13.

In conclusion, customers and employees primarily pronounce that

- It is rather cumbersome to open the hatch on the fuselage near the cockpit window merely to reach the pin.
- The maneuvering area is too cramped, only the arm used for adjusting the mechanism can fit.
- It is difficult to locate the pin and, in addition to that, position it rightfully after adjusting the pedals since one cannot catch sight of the obscured maneuvering area.
- It's opined insufficient that the aircraft needs to be stationary in order to carry out the adjustment.
- The amount of manual effort required to carry out the adjustment doesn't answer to a technical exclusivity expected with the price paid for the product.

### 3.1.2 Interpretation of raw data into customer needs

The customer and employee statements are interpreted into needs as seen in Table 1.

Table 1: Raw data interpreted into customer needs.

| CUSTOMER STATEMENT | INTERPRETED NEED |
|---|---|
| *It is rather cumbersome to open the hatch on the fuselage near the cockpit window merely to reach the pin.*<br><br>*The maneuvering area is too cramped, only the arm used for adjusting the mechanism can fit.* | The adjustment mechanism is accessible in a firsthand manner.<br><br>The adjustment mechanism is suitably fitted in the provided area of implementation. |
| *It is difficult to locate the pin and, in addition to that, position it rightfully after adjusting the pedals since one cannot catch sight of the maneuvering area.*<br><br>*The amount of manual effort required to carry out the adjustment doesn't answer to a technical exclusivity expected with the price paid for the product.* | The adjustment mechanism operates automatically after initiation. |
| *It's opined insufficient that the aircraft needs to be stationary in order to carry out the adjustment* | Adjustment of pedals can be carried out during flight mode. |

### 3.1.3 Certification requirements

Difference is made between the customer needs and the needs acquired from Blackwing, as the latter is expressed as engineering characteristics. The customer needs initiate the inquiry of the product whereas potential modifications which are to be implemented on the adjustment mechanism are restricted by the configuration of the current aircraft. The fuselage and internal architecture is not to be changed whilst smaller brackets and attachments can be somewhat customized and fitted. Furthermore, the final solution must satisfy requirements denoted in German Airworthiness Requirements LTF-UL 2018 to receive a flying certificate. These requirements imply load impact endurance, limited deformations and safety factors, among others. A certificate signifies the airworthiness of an aircraft in a particular category which, in the case of Blackwing, implies a maximum 600 kg take-off mass. The certificate is a confirmation that the aircraft is manufactured according to an approved design and that the design guarantees compliance with airworthiness requirements. This report will exercise the LTF-UL 2018 German Civil Airworthiness Requirements at the request of Blackwing, as guidelines for fulfilling certification criteria for the rudder pedal system. The certification requirements brought to use are listed below:

**LTF-UL 301 Loads:**
Strength requirements are specified in terms of limits loads (the maximum loads to be expected) and ultimate loads (limit loads multiplied by prescribed factors of safety).

**LTF-UL 303 Factor of safety:**
Unless otherwise provided, a factor of safety of 1.5 must be used.

**LTF-UL 305 Strength and deformation:**
The structure must be able to support limit loads without detrimental, permanent deformation. At any load up to limit loads, the deformation may not interfere with safe operation. This is particularly true for the controls. The structure must be able to support ultimate loads without failure for at least three seconds. However, when proof of strength is shown by dynamic tests simulating actual load conditions, the three second limit does not apply.

**LTF-UL 307 Strength requirements for materials and structural analysis:**
Material strength properties must be based on enough tests of material meeting specifications to establish design values on a statistical basis. The design must be chosen so that the probability of any structure being understrength because of material variations is extremely rare.

**LTF-UL 397 Loads introduced through pilot force:**
The control systems for the direct control of the aircraft about its longitudinal, lateral, or yaw-axis (main control system) and other control systems affecting flight behaviour and supporting points must be designed to withstand as far as to the stops (these included) limit loads arising from the following pilot forces shown in Table 2.

Table 2: Control system, actuation force and method of force application. See Figure 3 for additional understanding of Aircraft Principal Axes.

| **Control** | **Actuating force [N]** | **Method of force application (assuming single lever control systems)** |
|---|---|---|
| Pitch | 350 | Push and pull of control stick |
| Roll | 200 | Move of control stick sideways |
| Yaw and other foot controls | 900 | Apply forward pressure on one rudder pedal |

**LTF-UL 399 Dual control systems:**
Dual control systems must be designed for

- The pilots acting together in the same direction
- The pilots acting in opposition

Each pilot applies 0.75 times the load in specified in load case LTF-UL 397 Table 2.

In summary, the certification requirements are listed below:

- Structure will remain unaffected in terms of strength even if material variety occurs.
- Structure will not undergo plastic deformation during limit load impact, furthermore, it will not fail during the first three seconds of ultimate load impact.
- A safety factor of 1,5 is implemented in the structure, $F, Limit \cdot 1{,}5 = F, Ultimate$
- The structure is designed to withstand the limit load of 900 N arising from the pilot force on the rudder pedal.

When certified, there are two remaining factors which significantly influence the aircraft as a whole, namely the weight and the cost. The weight restriction is essential for Blackwing in order to compete on the market since the weight impinges the performance notedly. Moreover, Blackwing strongly highlights the request of product design adaptation towards manufacturing methods available at the company. These include milling and prepreg layup with autoclave and are advocated in order to avoid outsourcing. This is an immediate consequence of cost limitations. At last, Blackwing attaches great importance in misalignment between the pedals which, regardless of positioning, is allowed to be 3 mm at most. The limit is acquired by Blackwing based on intuition since it’s perceived as nonexistent by the user. When exceeded, the spacing becomes notable and may instill inaccuracies. The new solution must also enable for the pedals to move within an interval of 50 mm in the direction of travel. In conclusion, the needs acquired from Blackwing are listed below

- The weight is (as far as) unchanged in comparison to existing adjustment mechanism.
- The product design is adapted towards manufacturing methods available at Blackwing.
- The maximum allowed misalignment between the pedals is 3 mm.
- Pedals can be moved within an interval of 50 mm in the direction of travel

### 3.1.4 Organization of needs in hierarchy and establishment of relative importance

During the customer interviews, it was rather obvious that the most important change wished for was an easily accessed, automated system. If it was to be acquired, the prevailing issues will not cease with the straightforward usability since the production team clearly addresses dissatisfaction towards the space shortage in product installation. Nevertheless, these issues have been resolved as yet, which is why they are not of fundamental character even if experienced as cumbersome. Moreover, the adjustment mechanism should be enabled during flight mode in order to fulfill the requirements of an ideal product from a user perspective. It is, however, a wish rather than an essential attribute of the concept which contributes to instilling luxury and quality assurance. The hierarchy and relative importance of the customer needs (strengthened by valuable opinions of the employees) is thereby concluded as follows, where the statements in bold cannot be compromised whilst the asterisks mark the relative importance of the residuaries:

- **The adjustment mechanism operates automatically** (1)
- **The adjustment mechanism is accessible in a firsthand manner** (2)
- ** Adjustment of pedals can be carried out during flight mode (3)
- * The adjustment mechanism is suitably fitted in the provided area of implementation and is thereby easy to install (4)

As for the certification requirements, they cannot be disregarded at any cause. In similarity, the needs acquired from Blackwing are equally important since it will affect either the performance or profit. Thus, none of the mentioned are to be compromised:

- **Certification requirements**
  - Structure will remain unaffected in terms of strength even if material variety occurs (5)
  - Structure will not undergo plastic deformation during limit load impact, furthermore, it will not fail during the first three seconds of ultimate load impact (6)
  - A safety factor of 1,5 is implemented in the structure, F, $, Limit \cdot 1.5 = F$, Ultimate (7)

- The structure is designed to withstand the limit load of 900 N arising from the pilot force on the rudder pedal (8)

- **The weight is (as far as) unchanged in comparison to existing adjustment mechanism** (9)
- **The product design is adapted towards manufacturing methods available at Blackwing** (10)
- **The maximum allowed misalignment between the pedals is 3 mm** (11)
- **Pedals can be moved within an interval of 50mm in the direction of travel** (12)

## 3.2 Establishment of product specifications

A list of metrics is prepared in order to specify an agreement of unambiguous manner on how the needs are to be met. Having the customer needs expressed in tangible metrics and associated units (if at all possible) clearly defines the assignments ahead which must be addressed. It constitutes the final product specifications together with requirements acquired from Blackwing which are somewhat well-defined already in terms of metrics and units. Thenceforth, the table is completed with marginally accepted values which are to be pursued and used as guidelines ahead in the project. The marginally accepted values are justified below:

Specification #1:
A fully automated system implicates no human interaction aside from initiation. Human interaction is considered appropriately expressed in "*amount of times*" since SI units aren't adequate for the cause.

Specification #2:
The user must reach the trip of the system effortlessly in order for it to be accessible in a first-hand manner, thus, it is expressed in *distance*. A suitable unit is within the area of use and does not interfere with the dashboard or other interior equipment.

Specification #4:
The volume of assembled components must be marginally within predefined maneuvering area for the installation process to be at ease. The choice of unit is, however, initially based on intuition since an ill-considered concept formation is a contributory factor to the problem.

Specification #10:
The concept formation must, at all times, be carried out with respect to weight reduction. The concept is immediately rejected if the weight margins are exceeded, which according to Blackwing takes place around 1.5 kg.

Specification 3, 5, 6, 8 and 11 cannot be translated into quantifiable metrics and are therefore not further expressed in the table. The remaining specifications, i.e. 7, 9 and 12, are already considered well-defined by Blackwing. The product specifications are concluded in Table 3.

Table 3: Product specifications interpreted from customer needs and certification requirements.

| SPEC | NEED | METRIC | UNIT | VALUES |
|---|---|---|---|---|
| 1 | 1 | Number of interactions between user and adjusted pedals | amount of time(s) | 1 |
| 2 | 2 | Distance between user and trip of system | m | 0,5 |
| 3 | 3 | Adjustment mechanism is compatible with an aircraft in flight mode | | |
| 4 | 4 | Length x Width x Height | $m^3$ | 0.026 |
| 5 | 5 | Structure will remain unaffected in terms of strength even if material variety occurs. | | |
| 6 | 6 | Structure will not undergo plastic deformation during limit load impact | | |
| 7 | 6 | Amount of time to withstand failure during ultimate load | s | 3 |
| 8 | 7 | A safety factor of 1,5 is implemented in the structure | | |
| 9 | 8 | Limit load arising from the pilot force on the rudder pedal which structure must withstand | N | 900 |
| 10 | 9 | Weight deviation | kg | 1,5 |
| 11 | 10 | Must be manufactured by milling and prepreg lay-up (with autoclave) | | |
| 12 | 11 | Maximum allowed misalignment between pedals | m | 0,003 |
| 13 | 12 | Length interval in direction of travel in which pedals can be moved | m | 0,05 |

## 3.3 Concept generation

The concepts that are described in this section suggest how the established product specifications are to be met and satisfied through embodied working principles. In order to proceed with a final solution which is fit for testing, deeper knowledge such as further understanding of the problem must be gained. Incorporating this with existing and new solutions which are to be somewhat combined will finally result in concepts ready for evaluation, see Figure 17.

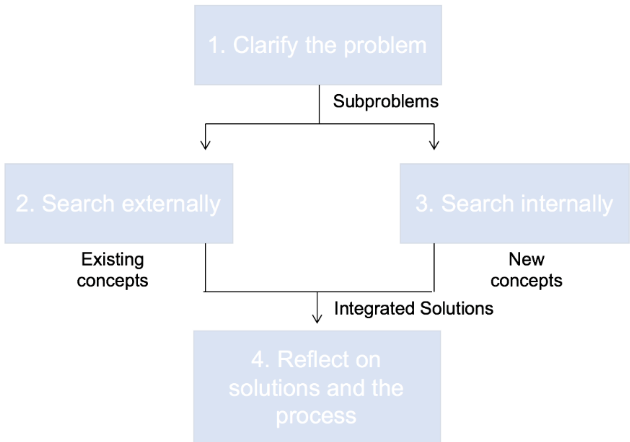


Figure 17: The Concept Generation process.

### 3.3.1 Clarifying the problem

Further understanding of the problem is acquired through a method named Functional Decomposition, which implies decomposing the general, holistic understanding into subproblems. In Figure 18, functions are represented with a set of elements embodied by a "Black Box". The elements are attributes of the product and describe the product expectations in terms of performance. Along with the Input Energy, the "Black Box" will result in an Output which corresponds to the main purpose initiating the inquiry at first.

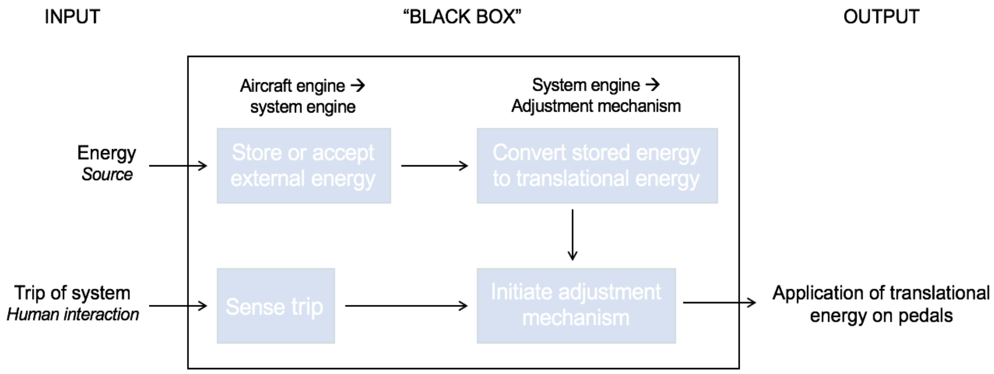


Figure 18: Functional Decomposition of the Problem Statement.

## 3.3.2 External and internal search

**External search**

The elements within the Black Box (see Figure 18) constitute the basis for the external search, i.e. the benchmarking. Solutions for the decomposed subproblems are to prefer rather than a holistic solution. The pedal adjustment mechanisms that are available on the market are of manual character or are considered too heavy and uncertain, thus, they are not competitive nor do they contribute to an improvement. The elements in Figure 18 are concluded in two main functions, namely "Linear Motion Systems" and associated "Energy Sources", which subsequently will be incorporated in the Internal Search. Only the benchmark observations which are relevant for the concepts presented as Internal Search will be mentioned in the report.

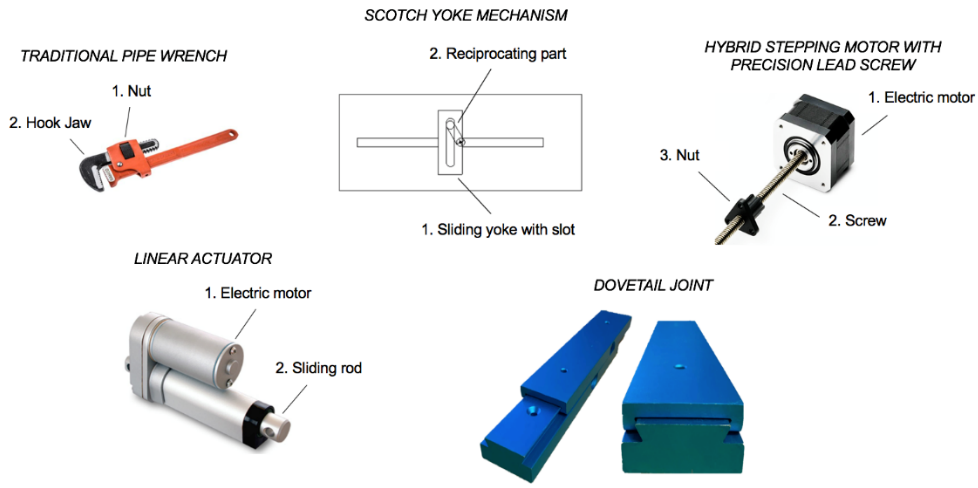


Figure 19: Benchmark observations relevant for the concepts presented in the Internal Search [3-6, Figure 19]

- Traditional pipe wrench: A traditional pipe wrench is originally designed to turn a threaded pipe. Even if not considered relevant at first, the pipe wrench has an easy way of creating a linear motion. When the nut is set in rotation, the hook jaw is forced in motion due to the cogs.

- Scotch Yoke mechanism: The Scotch Yoke mechanism implies a conversion of a reciprocating rotational movement into linear motion (or vice versa). The reciprocating part is constantly rotating and thus forcing the yoke to move back and forth due to their direct coupling in the slot.

- Hybrid stepping motor with a precision lead screw: The electric motor contributes to the circular motion of the screw, which subsequently forces the nut to straight line motion.

- Linear actuator: A linear actuator creates a rectilinear motion in contrast to a conventional motor. Linear actuators have many areas of applications, such as industrial automation applications, medical equipment, vehicles and equipment for disabled people, among others.

One main issue that was brought to attention during the phase of benchmarking is the risk of failure due to load applied by the pilot on the pedals, which is concluded in Specification #9. The limit load is, at this state in the project, assumed to be a resultant force obtained from forces acting in the x, y and z-direction, since nothing more specific is denoted in the German Airworthiness Requirements LTF-UL 2018. This results in the requirement of having an additional support for load absorption and/or translation. Figure 19 shows a Dovetail Joint which is a joinery technique that provides good resistance for separation in the y and z-direction while still enabling movement in the direction of travel [7].

**Internal search**

Presented below are the proposed solutions to the functions acquired from Figure 18. The concepts are sketches of initial character and are meant to represent ideas that will need further evaluation and development in order to fully meet all established product specifications (if at all possible).

**Concept 1: The Pipe Wrench**

The Pipe Wrench concept adds a rack and a servo motor into an unmodified area of implementation, see Figure 20. The rack is coupled with the existing pedal yoke which rotates around the pin but moves along the rack on the direction of travel when the gear is rotating due to the servo-motor.

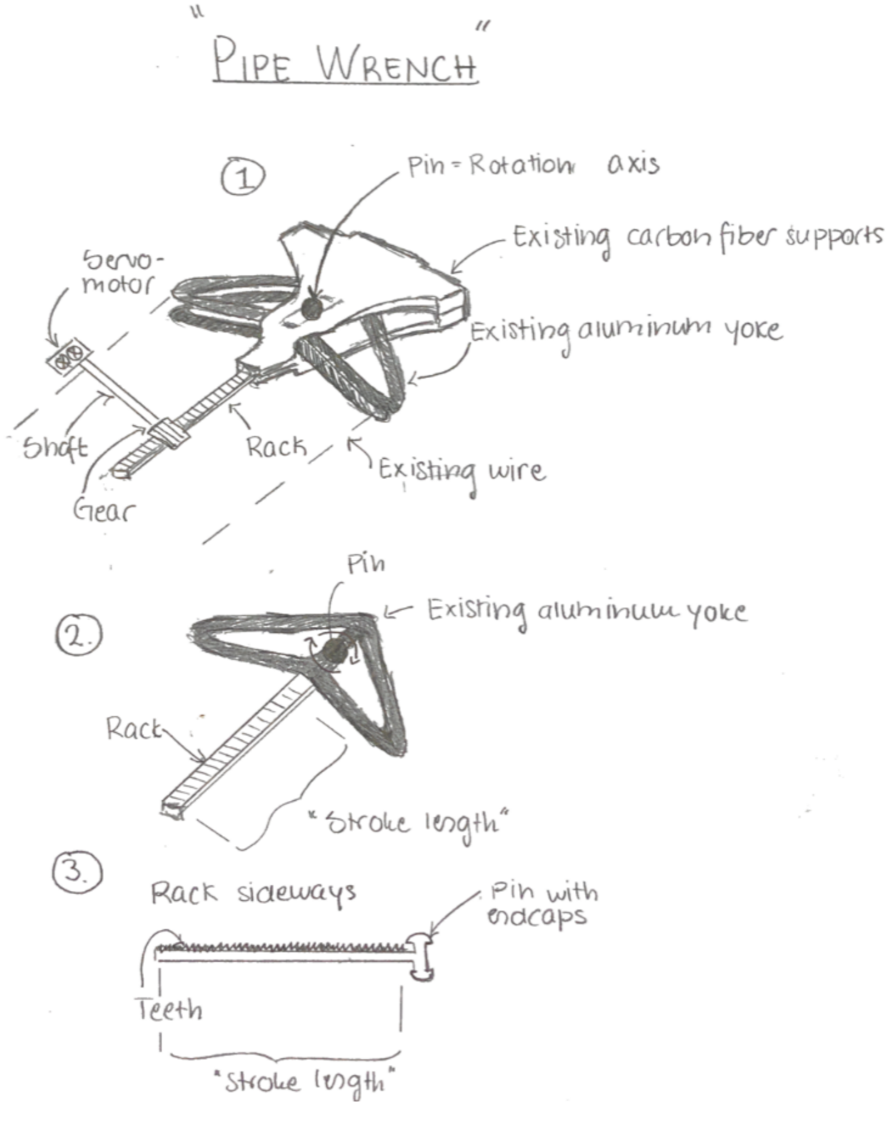


Figure 20: Concept 1, The Pipe Wrench

**Concept 2: Scotch Yoke**

In similarity with Concept 1, the area of implementation is unmodified, see Figure 21. A scotch yoke mechanism, which is coupled with the pedal yoke, is placed between the carbon fiber supports. When initiated by a motor, the reciprocating part (a pin) will be set into rotation which translates into a linear movement of the pedal yoke.

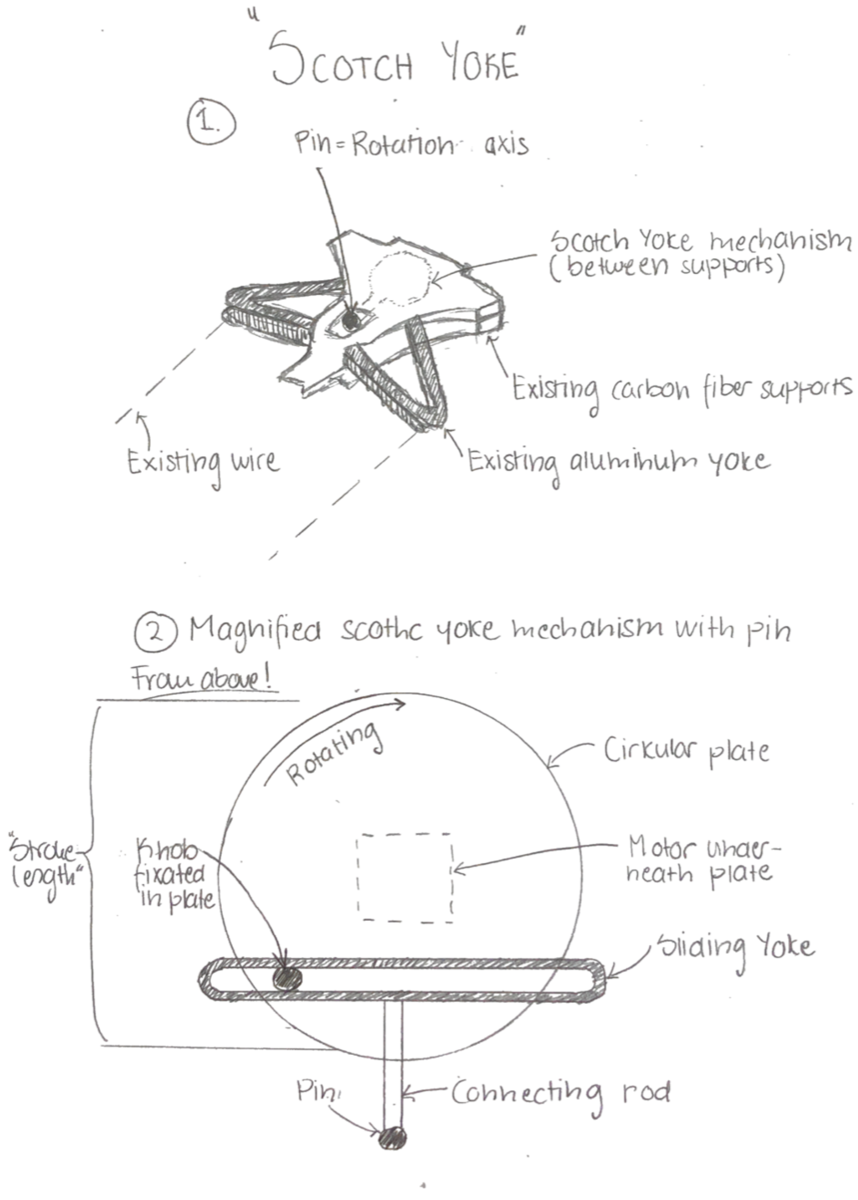


Figure 21: Concept 2, Scotch Yoke.

**Concept 3: Dovetail Joint #1**

The first Dovetail concept will require some modifications of the surrounding details. For example, the carbon fiber supports must be removed in order to make place for the Dovetail joint, see Figure 22. The middle dovetail provides a fastening for the pedal yoke and is set in linear movement when the screw is rotating due to the motor.

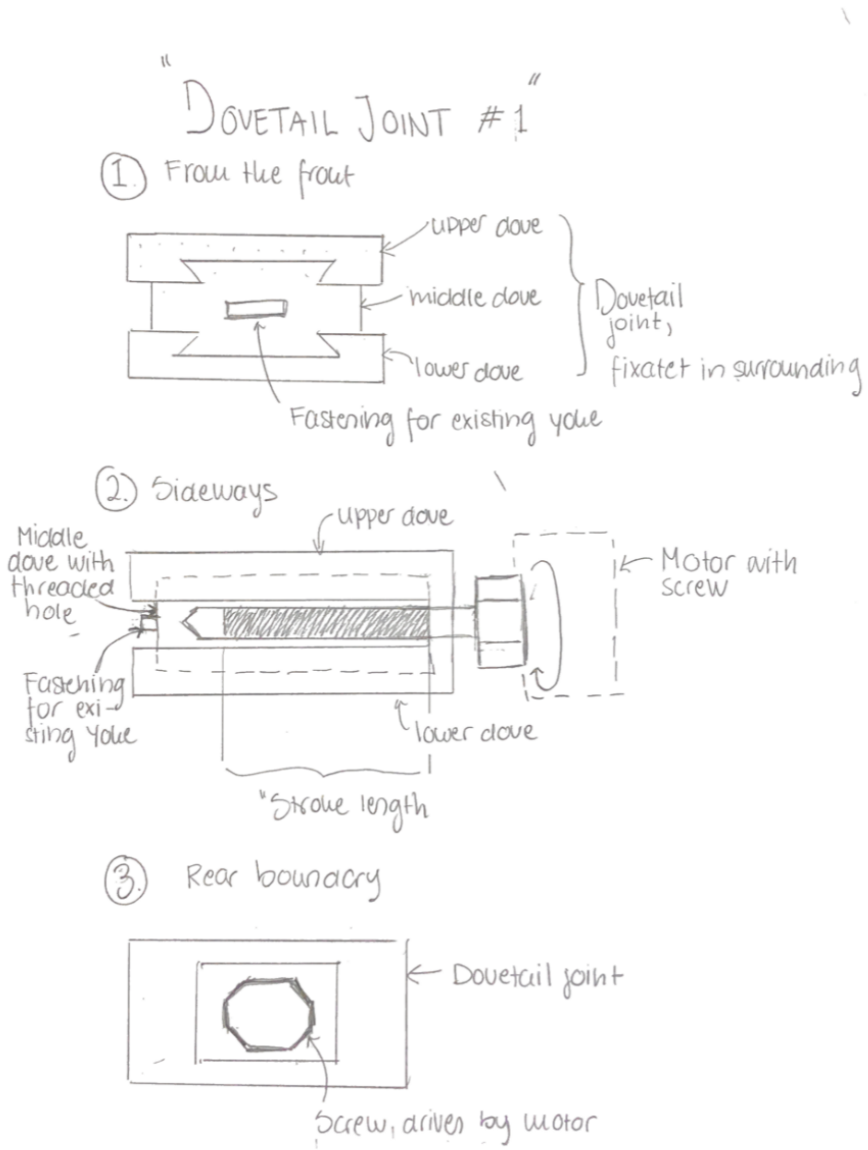


Figure 22: Concept 3, Dovetail Joint #1

**Concept 4: Racing Pedal Box**

The Racing Pedal Box consists of a link which connects the linear motion of the actuator to the pedal yoke, see Figure 23. When the rod is set in movement, it rotates the link around a fixed point which subsequently transfers the pedal yoke along an arc. Due to the short distance (50 mm), the arc is considered negligible and thus a linear approximation of the motion is approved.

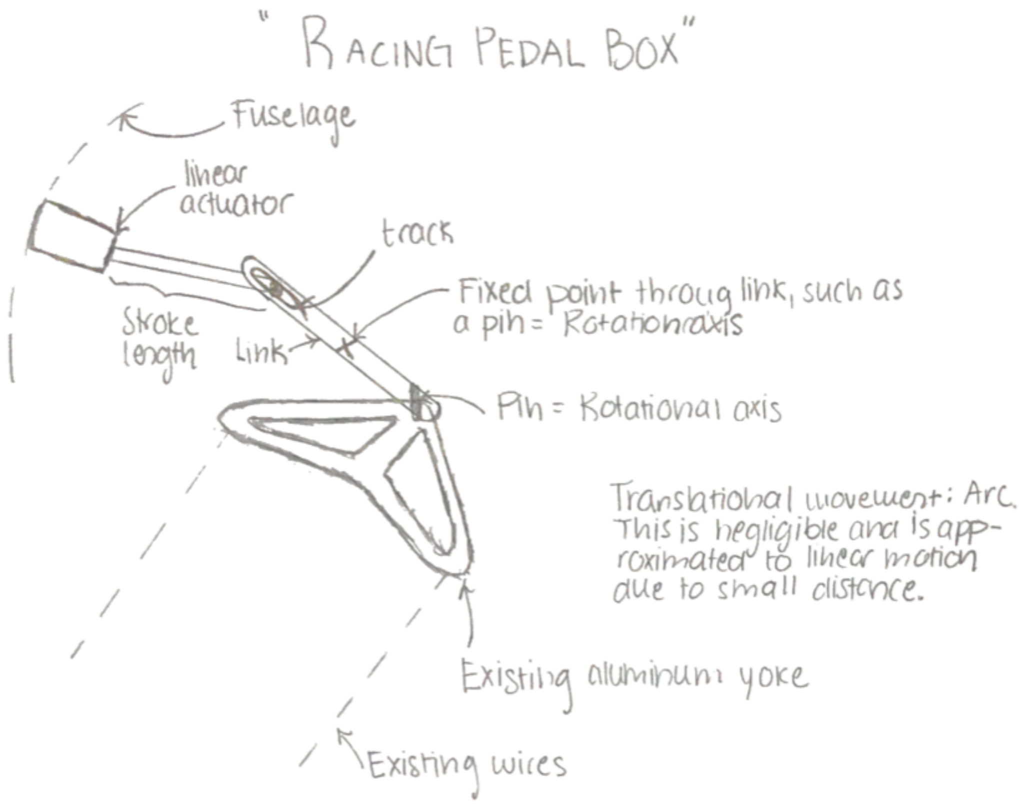


Figure 23: Concept 4, Racing Pedal Box.

**Concept 5: Dovetail Joint #2**

The second Dovetail concept is a combination of concept three and four, see Figure 24. A link connects the linear motion of the actuator to the middle dovetail joint, which is coupled with the pedal yoke. When the rod is set in movement, it rotates the link around a fixed point which subsequently moves the middle dove and thus the pedal yoke.

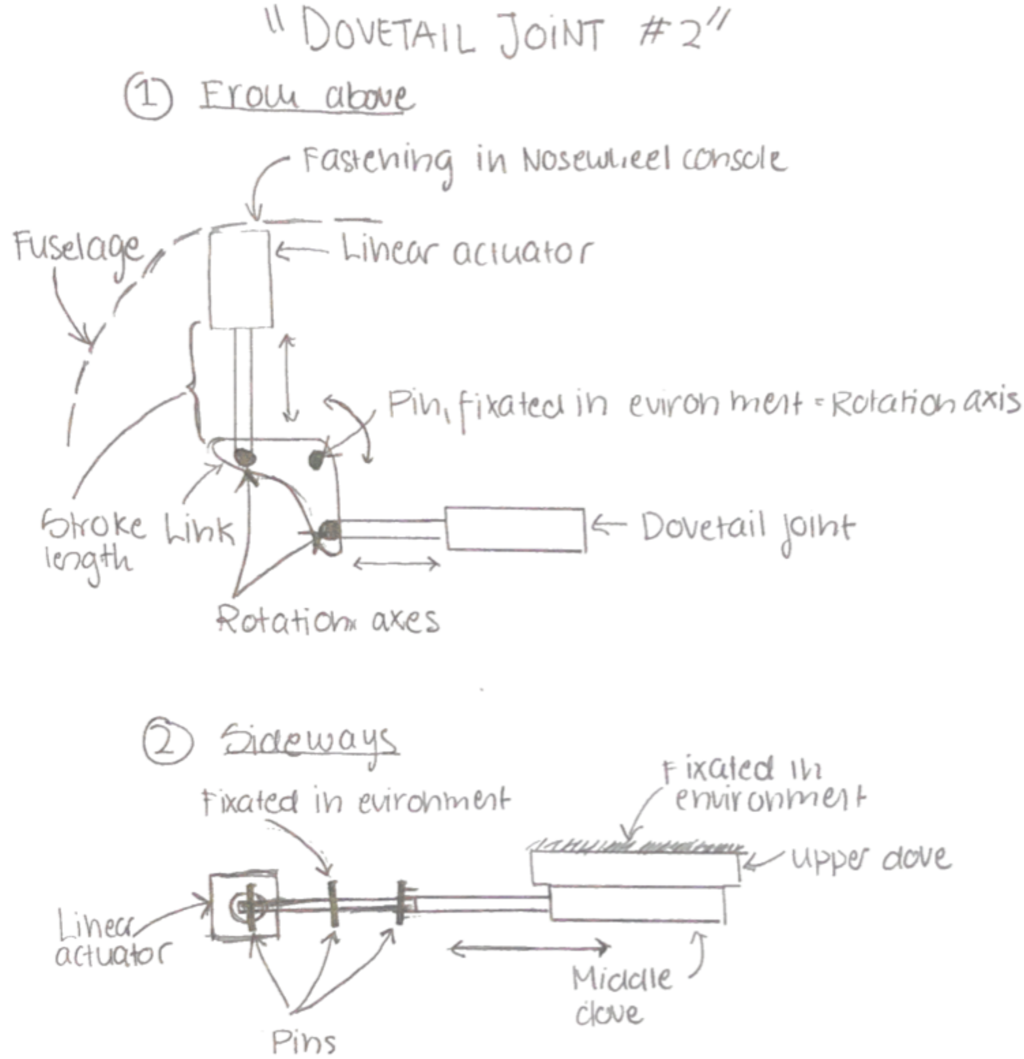


Figure 24: Concept 5, Dovetail Joint #2.

**Concept 6: Dovetail Joint #3**

The third Dovetail Concept consists of the dovetail joint which is additionally supported by aluminum plates in order to provide attachments in the area of implementation, see Figure 25. When the motor is initiated, the screw is set in rotation which translates to a linear movement of the middle dove nut. The pedal yoke is coupled with the middle dove nut and thus it is moved in the direction of travel.

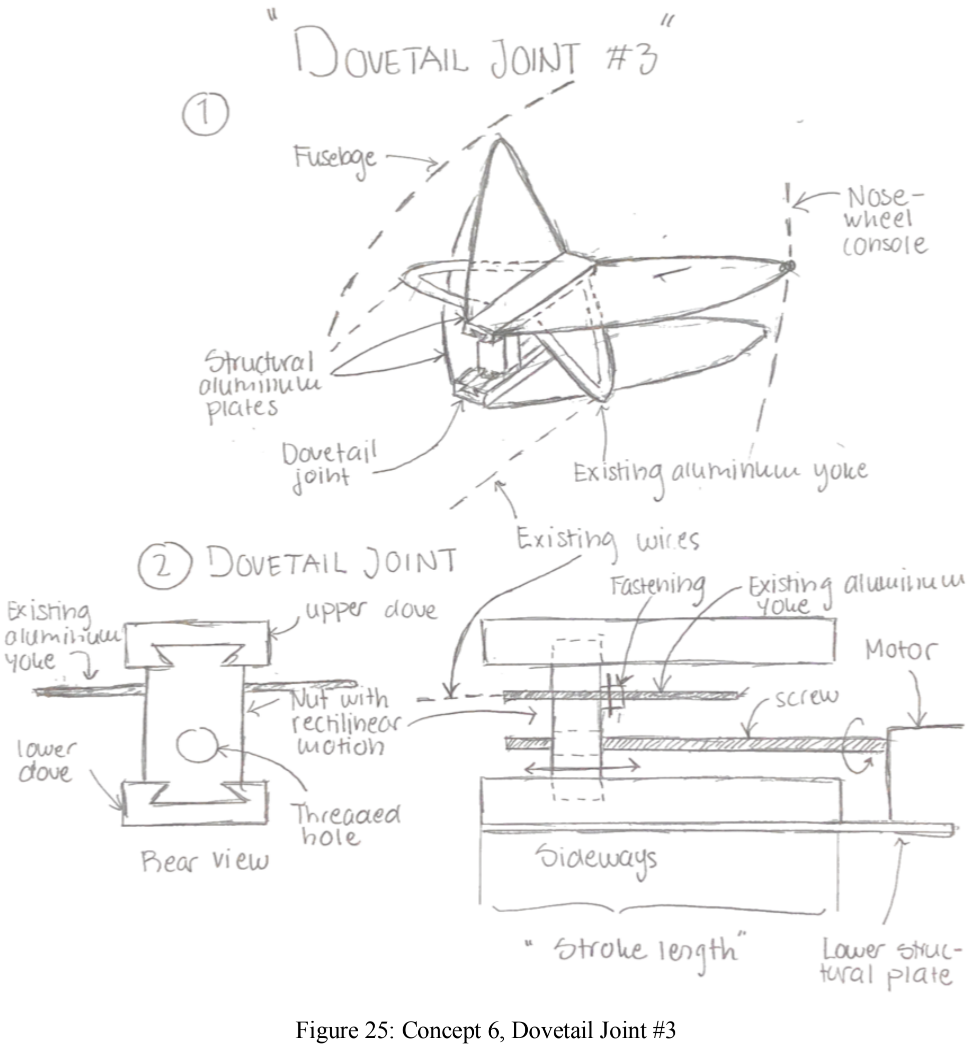


Figure 25: Concept 6, Dovetail Joint #3

**Concept 7: Pivot**

Two aluminum plates, with the pedal yoke coupled in between them, are attached to the NW on the right hand side, see Figure 26. This constitutes a point around which the assembly will rotate (the Pivot Point). A linear actuator is to be found at the left hand side which provides the movement. When the rod is initiated, it forces the plates back and/or forth in a circular motion which subsequently moves the pedal yoke. Due to the short distance (50 mm), the arc is considered negligible and thus a linear approximation of the motion is approved.

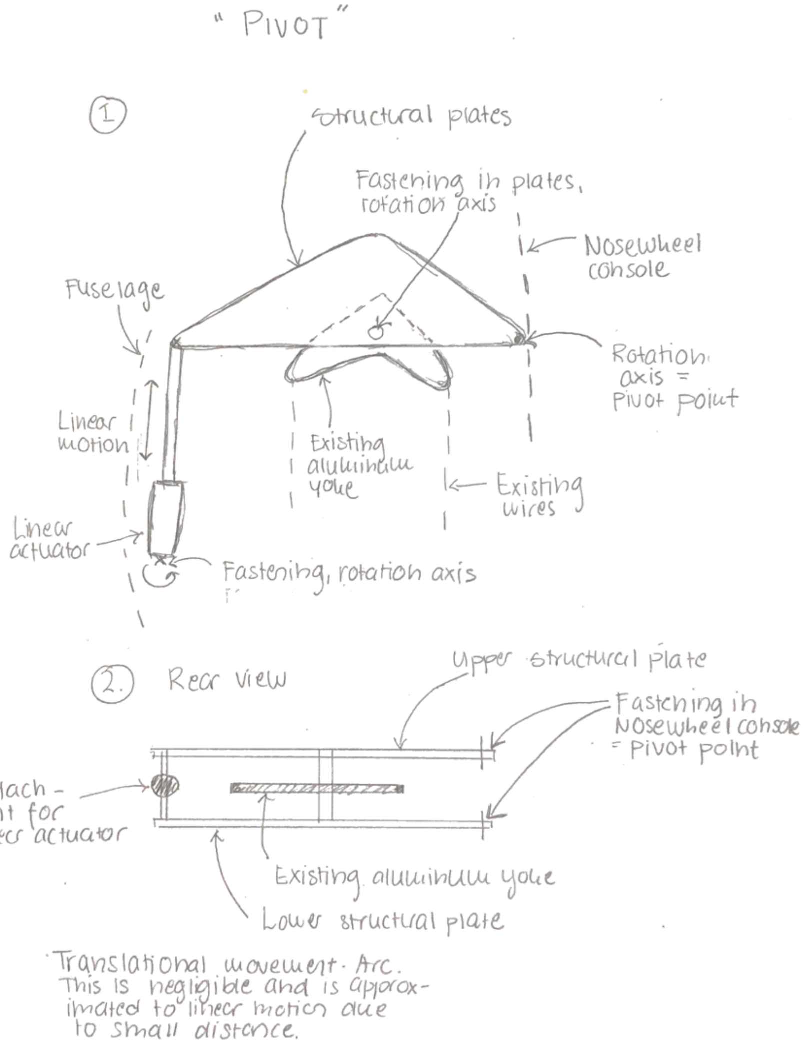


Figure 26: Concept 7, The Pivot.

## 3.4. Concept screening

The process of Concept Screening is carried out by comparing the relative strength and weakness of the concepts with respect to the established product specifications and the current solution (the reference concept). The concepts selected with the screening method are to be further investigated and developed in the Analysis section before enabling the choice of the final solution. The screening is solely based on intuition, discussions and assumptions as to how well the concepts will be perceived by Blackwing, i.e. there are no analyses for strengthening the result, see Table 4.

Table 4: Concept Screening for further evaluation of chosen concepts

| | CONCEPTS | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| SELECTION CRITERIA (Product Specifications) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | REF |
| Number of interactions between user and adjusted pedals | + | + | + | + | + | + | + | 0 |
| Distance between user and trip of system | + | + | + | + | + | + | + | 0 |
| Adjustment mechanism is compatible with an aircraft in flight mode | + | + | + | + | + | + | + | 0 |
| Length x Width x Height | - | 0 | + | - | - | - | - | 0 |
| Structure will remain unaffected in terms of strength even if material variety occurs | - | - | + | - | - | + | + | 0 |
| Structure will not undergo plastic deformation during limit load impact | - | - | - | - | - | + | + | 0 |
| Amount of time to withstand failure during ultimate load | ? | ? | ? | ? | ? | ? | ? | 0 |
| A safety factor of 1,5 is implemented in the structure | + | + | + | + | + | + | + | 0 |
| Limit load arising from the pilot force on the rudder pedal which structure must withstand | - | - | - | - | - | + | + | 0 |
| Weight deviation | - | - | - | - | - | - | - | 0 |
| Must be manufactured with milling and prepreg lay-up (with autoclave) | - | - | + | + | + | + | + | 0 |
| Maximum allowed misalignment between pedals | 0 | 0 | 0 | - | 0 | 0 | - | 0 |
| Length interval in direction of travel in which pedals can be moved | + | + | + | + | + | + | + | 0 |
| PLUSES | 5 | 5 | 8 | 6 | 6 | 9 | 9 | |
| EQUALS | 1 | 2 | 1 | 0 | 1 | 1 | 0 | |
| MINUSES | 6 | 5 | 3 | 6 | 5 | 2 | 3 | |
| NET | -1 | 0 | 5 | 0 | 1 | 7 | 6 | |
| RANK | 6 | 5 | 3 | 5 | 4 | 1 | 2 | |
| CONTINUE? | No | No | No | No | No | Yes | Yes | |

**DOVETAIL JOINT #3**

The main purpose of the concept is to utilize a dovetail slider mechanism, which is excellent for withstanding transverse and vertical loads while providing a precise rectilinear motion. The dovetail slider is accompanied with an engine which regulates the motion of the dove nut, see Figure 26. It is of great importance to position the engine so that it is solely exposed to axial loads (direction of travel), since linear motion devices are great for enduring such load scenarios but are significantly weaker when exposed to radial forces. However, it is impossible to place the engine in front of the dovetail slider because of the pedal yoke interfering, therefore, the engine must be placed either above or below. Considering the positioning, the height of the engine will be a crucial parameter, by the virtue of the lever-arm effect. An increasing engine height would increase the distance between dovetail tracks and thus increase the lever-arm effect. Because of this, a compact engine with the smallest dimensions possible with capability of withstanding load requirements is sought. The stepping motor is the only linear motion system among the benchmark results which satisfies mentioned criteria. In addition, is it beneficial since it enables replacement of the original lead nut with the middle dove nut instead.

The selection of the stepping motor depends on the static and dynamic load, which will act in compression due to the concept design. The dynamic load, i.e. the load impacting the motor while it is active and thus moving the pedal assembly (the adjustment process), can be approximated since the mass of the pedal assembly is known to be around 5-8 kg. However, the static load in the direction of travel is unknown at this state of the project since the loadcase given by Specification 9 is assumed to be a resultant force from components in the x, y and z-direction. Thereof, the selection will satisfy the dynamic load while the static load criteria is met with intuition.

Due to lack of information regarding static load for stepper motors, the initial source of failure is assumed to be the lead screw, i.e., the critical static load. Based on that assumption, one can determine the critical load $F_c$ by utilizing Equation (1) [8, Equation (1)]. The calculated $F_c$ is to be compared with the static loadcase which is to be obtained from the concept analysis ahead, in order to ensure that the stepper motor meets the requirements for the static load in axial direction. The selected motor is a NEMA 17 with an M6 lead screw from Thomson Linear Motion, which can operate a dynamic load of 100 N [9]. The choice of engine translates into the following critical compressive load:

Critical compressive load: $F_c = 10^4 \cdot f_b \cdot \frac{d^4}{L^2}$ (1)

Where,

fb = the end bearing factor, i.e., fixity of the lead screw

d = the root diameter of the lead screw

L = the unsupported length of the screw, i.e., length between motor to lead nut (in the current case).

Due to uncertainty of the end bearing factor fb, the worst case scenario is chosen for evaluation. The root diameter d of the M6 lead screw is known as 4.773 mm [10]. Moreover, the unsupported length L between the stepper motor and the lead nut is 110 mm at most. Accordingly, the critical compressive load is determined:

$$F_c = 10^4 \cdot 2.5 \cdot \frac{4.773^4}{110^2} = 1072 \text{ N}$$

In conclusion, the load that is to be compared with the axial load obtained from the future concept analysis is 1072 N.

The concept design enables mounting in the fuselage and in the intersection area between the NW and the firewall, see Figure 27. An arrangement of structural plates links the dovetail track to the mounting areas, which is preferable in terms of load impact endurance. Even if symmetry is wished for, the bottom plate must deviate from the upper in order to prevent interference with the pedals. The structural arrangement, along with mounting brackets designed to fit the fuselage and the intersection area, constitutes a moderately rigid construction. At last, four bushings are added in order to ensure construction stability. The bushings shall reduce potential radial forces acting on the stepping motor as well as reduce the probability of disorientation of the dovetail sliders. By implementing this concept, The Sharktail and the Center structure become useless and can therefore be removed from the internal architecture. The Dovetail Joint #3 is henceforward abbreviated to The Dove.

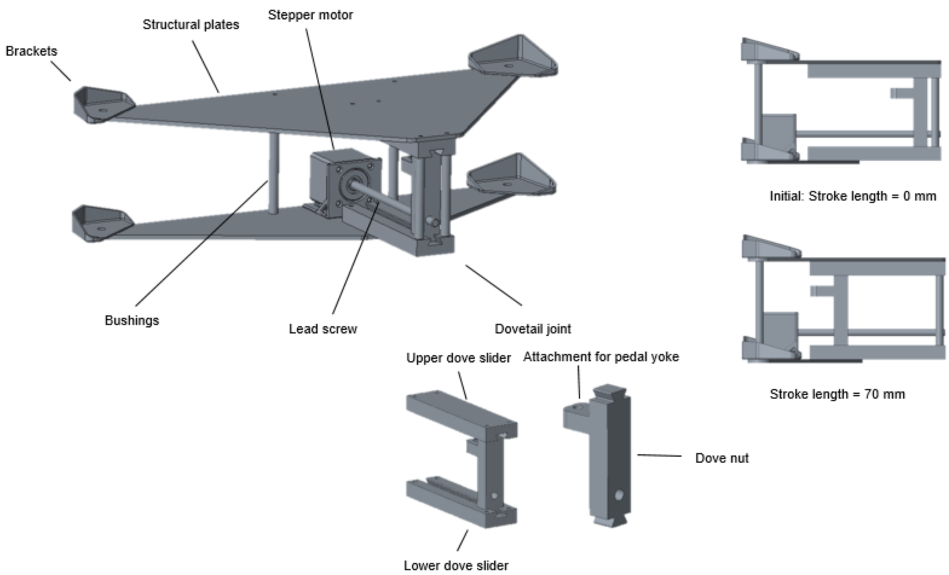


Figure 26: The Dove concept

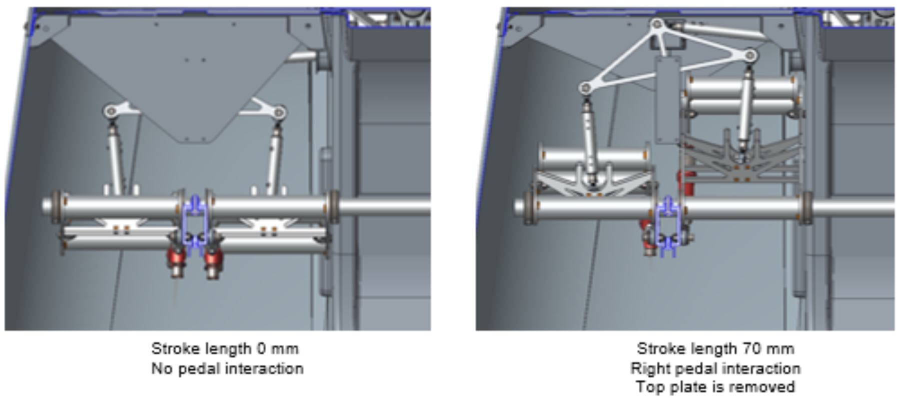


Figure 27: The Dove concept implemented in the aircraft.

Material data:

- Brackets: CFRP
- Structural plates and dovetail joint: aluminum
- Bushings: structural steel
- Lead screw: stainless steel

**THE PIVOT**

The main component of the Pivot concept, see Figure 28, is the linear actuator, which regulates the motion in the system and is excellent for withstanding axial loads. More specifically, it is excellent for withstanding axial loads in tension. Linear actuators have less capacity in compression due to internal bearing arrangement, type of internal screw (buckling is a cause for failure on small screws in compression) etc. [11], which motivates the positioning of the linear actuator in the concept design. It is positioned favorably with respect to the capacity, so that it's exposed to tension in the direction of travel when the pilot interacts with the pedals, see Figure 29.

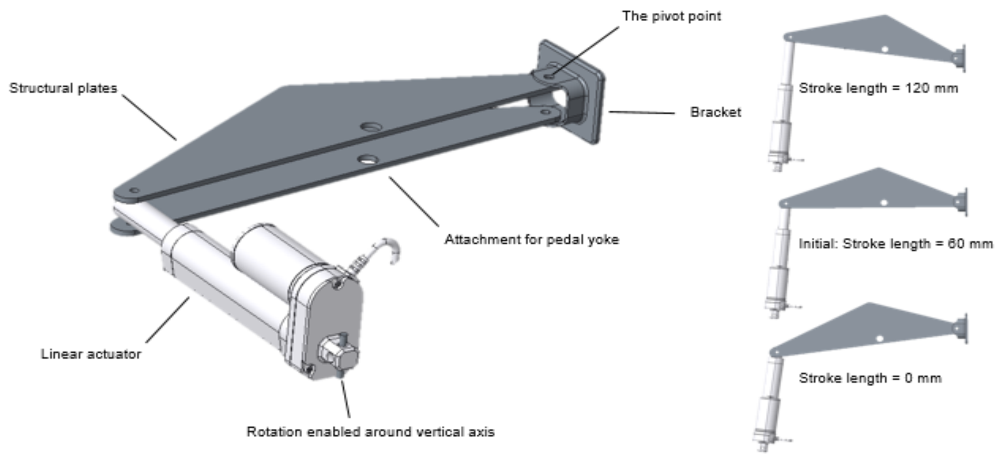


Figure 28: The Pivot concept

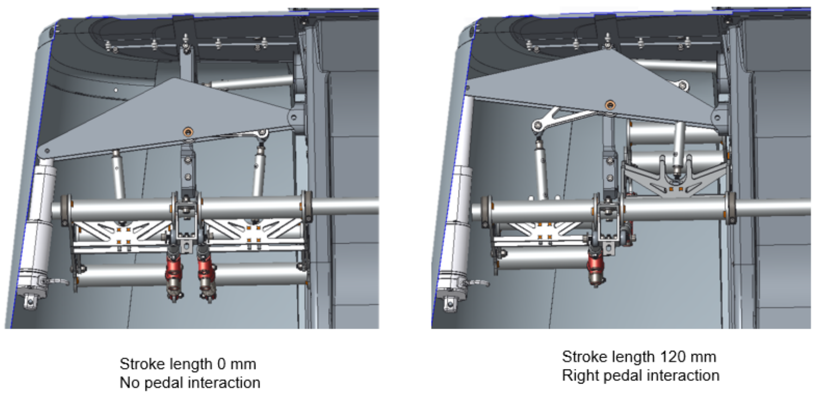


Figure 29: The Pivot concept implemented in the aircraft

Nevertheless, the linear actuator is significantly weaker when exposed to radial forces which is why it is accompanied with supportive plates for load endurance in the transverse direction. The plates work as an extension of the existing pedal yoke as they are coupled through the initial position of the lock-pin. Furthermore, the plates are fastened onto the NW through a bracket. These two points coincide horizontally, whilst the latter constitutes the pivot point of the system motion. The actuator, which is connected to the plates on the leftmost side, will rotate the plates (and the pedal yoke) around the pivot point. The conversion of the linear motion from the rod into rotation of the plates requires a fastening of the actuator in the fuselage that enables rotation around its vertical axis.

The arc path along which the pedal yoke will be moved is about 50 mm and is approximated to linear motion because of insignificant deviation perceived by the pilot of the latter, thus, Specification 13 is met. However, the misalignment that occurs between the pedals due to the arc motion is of significant character and must therefore be taken into consideration. In order to meet Specification 12 which allows a maximum misalignment of 3mm, a so called "thread model" is used, which is a sketch constituted by lines along the pattern of movement in the system, see Figure 30-31.

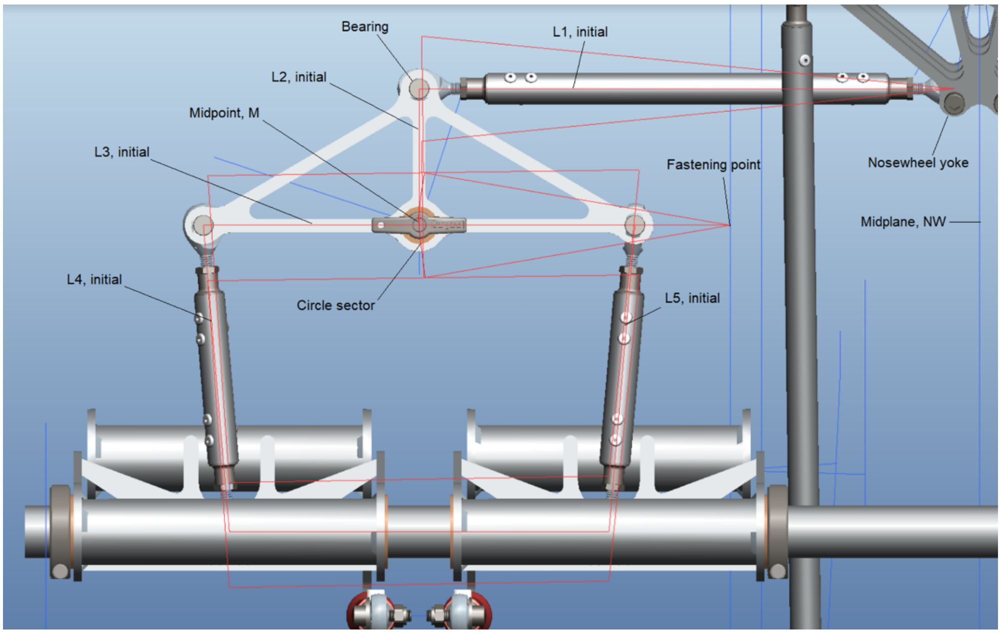

Figure 30: Thread model applied on the 3D-model.

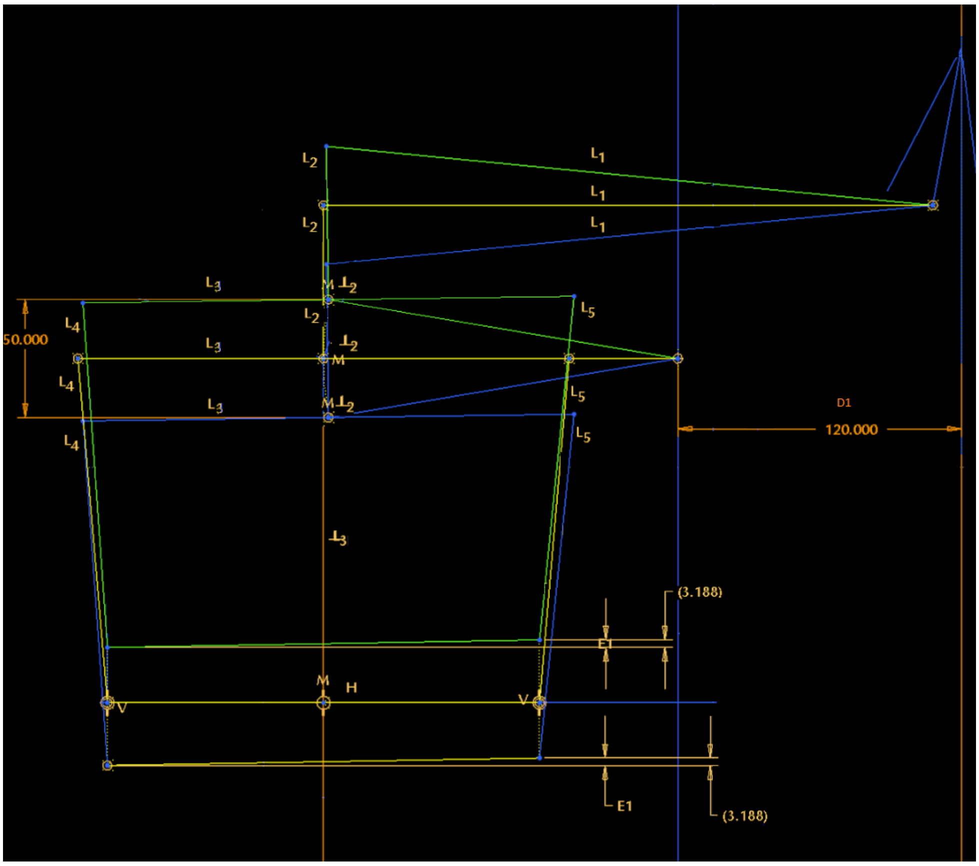

Figure 31: Thread model for positioning of the fastening point for plates.

The fastening point of the plates in the bracket is simply the midpoint of a circle sector and is positioned the distance D1 from the midplane in the NW, see Figure 31. When the pedal yoke is moved along the arc, it can rotate around the fastening point in the rod joint (L1) due to the bearing, which means that the angle between L1 and L2 is varying. In contrast, the angle between L2 and L3 is always orthogonal since L2 and L3 are the stiffeners in the pedal yoke. As the pedal yoke moves along the arc, it translates from the leftmost point in a circle (constituted by the circle sector) to the right. The line L2 will therefore not remain orthogonal with respect to L1, but is still orthogonal with respect to L3. In order to keep the orthogonal relationship between the latter, L3 can no longer be horizontal and thus the misalignment of the pedals (which are connected to L4 and L5) will appear. The misalignment will depend on where the midpoint of Line L3 is positioned, which is always coinciding with the arc in the circle sector. Since the adjustment distance 50 mm is determined, the parameter affecting the appearance of the arc and thus the misalignment is D1. D1 is suitably chosen to 120 mm which results in the maximum misalignment of the pedals being 3.2 mm (see E1). E1 can be decreased if D1 decreases, but that would result in the bracket interfering with the internal architecture of the NW which is why Blackwing approves of the slight deviation from Specification 12.

The selection of the linear actuator is carried out in similarity with the stepping motor in the previous section, i.e. based on the static and the dynamic load. The dynamic load, which can be approximated due to known weight data of the pedal assembly, meets the temporarily chosen actuator which can operate a dynamic load of 250 N. Moreover, it can operate a static load of 2500 N [12], which cannot be validated before the forces acting on the concept have been evaluated.

At last, in order to achieve the adjustment length of 50 mm, an actuator stroke length is acquired by the principle of similarity [13], see Figure 32 followed by equation (2).

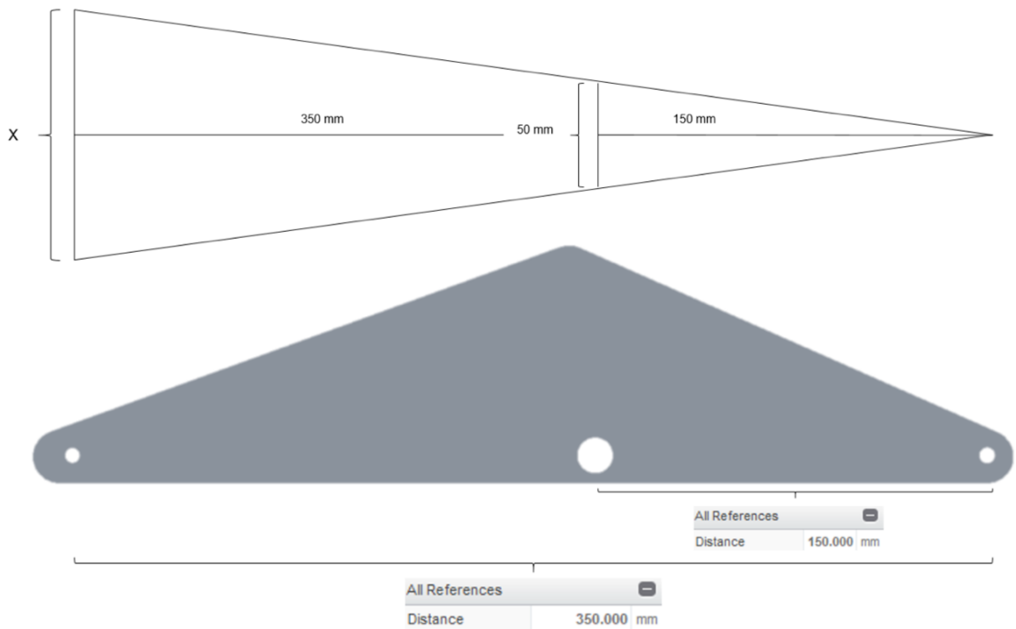

Figure 32: The principle of similariy applied on the upper structural plate.

The stroke length is obtained accordingly:

$$\frac{50}{150} = \frac{x}{350} \rightarrow X = 117 \text{ mm} \quad (2)$$

The stroke length is approximated to 120mm since the industry standard for stroke lengths vary by 10 mm intervals. By implementing this concept, The Sharktail and the Center structure become useless and can therefore be removed from the internal architecture.

Material data

- Bracket: CFRP
- Structural plates: aluminum

# 4 Concept testing and refinement

*In this segment, a detailed description of the analysis procedure is presented. The Primary Analysis is based on the Finite Element Method which is carried out in ANSYS Workbench and is showcased for each concept chosen for further evaluation in the previous chapter. The results will set the foundation for further development of the concepts, which will undergo an additional analysis for final validation.*

Presented below are justifications as to how and why the settings of the analysis will be applied.

In order to receive a certification, the rudder pedal system must endure two different scenarios of load application. At first, the symmetric behavior of the rudder pedal system must be brought to attention. The first scenario (LTF-UL 399), i.e. dual application of forces, implies impact from the pilot as well as the passenger. These forces will counteract each other by virtue of symmetric behavior, whereas a force applied solely by the pilot will be more crucial due to asymmetry when put in comparison. Thus, it is only of interest to analyze the force applied solely by the pilot (LTF-UL 397).

Furthermore, depending on interaction with the left or right pedal, a transverse load will be induced directed towards either the fuselage or the NW. In case of the Dove, for which the transverse load impacts both the fuselage and the NW, it is only of interest to investigate the left pedal interaction which contributes to a load directed towards the NW in compression. The fuselage is known to be stiffer and more impact resistant which is a result of the (by far) thicker layers of carbon fiber in the fuselage than in the NW. In case of the Pivot, which is solely attached to the NW in terms of load absorption, the transverse load will act on the same component either in compression or tension depending on left or right pedal interaction. Carbon fiber reinforcements are more sensitive to compression which makes the left pedal interaction the most crucial yet again.

The primary analysis will be carried out separately for each concept. Due to large and complex geometries, it will be segmented in order to examine the subsystems. The purpose of segmentation is to, in an effective manner, obtain an accurate load case by minimizing the number of components required in the primary concept analysis. This is a necessity since the excess of information will affect the time lapse significantly. The first segmentation will feature a pedal analysis, where the ambition is to retrieve the force acting on the rod joint connection between pedal and yoke. The second segmentation will feature a yoke analysis, for which the goal is to extract the resulting force acting on the pin joint between yoke and the adjustment mechanism (the implemented concept). In the last sequence of the approach, an analysis which is comparatively extensive is performed, featuring the concept along with surrounding components of interest together with the reaction forces extracted from the first and second segmentation. The aim is to analyze the structural behavior of the overall system and to answer whether the established product specifications can be met or not.

With the limit load as an input, the results will be treated as guidelines for structural improvements. Subsequently, a secondary analysis will be carried out on the developed concepts which constitutes the selection criteria for the final Concept Scoring, a method for comparison and choosing the winning concept. A final validation will be carried out on the solution with a nonlinear analysis to ensure that nonlinear effects have an insignificant impact on the system. At last, the solution will undergo a topology optimization as an act of weight reduction and final refinement.

Geometry simplifications will be performed which aim to reduce the time lapse for the analyses. Removal of draft angles and insignificant holes will be performed in order to achieve uncomplicated contact settings and thus avoiding convergence issues. Moreover, the prepreg components will be simplified and simulated by surfaces instead of solids, whereas the sandwich materials will be simulated by surfaces as well but with additional thickness. This is possible by utilizing the Parallel Axis Theorem, which provides an estimation of the surface thickness required for a single CFRP plate to act as a supplement for the sandwich. Presented below are the calculations, see equations (3) - (8) [14, Equation (3-4)].

Parallel axis theorem: $I_G = I_0 + d^2 \cdot A$ (3)

Second moment of area for plate cross section: $I = \frac{b \cdot h^3}{12}$ (4)

$$I_{Sandwich} = \sum_1^2 \frac{b \cdot h^3}{12} + d^2 \cdot b \cdot h \quad (5)$$

$$I_{Supplement} = \frac{b \cdot h^3}{12} \quad (6)$$

$$I_{Sandwich} = I_{Supplement} \quad (7)$$

The sought supplementary plate thickness H can now be estimated by subtracting b from each side and by inserting remaining known variables from Figure 33. Note that the sigma notation has the upper limit of summation set to two due to the fact there are two carbon fiber layers in a sandwich.

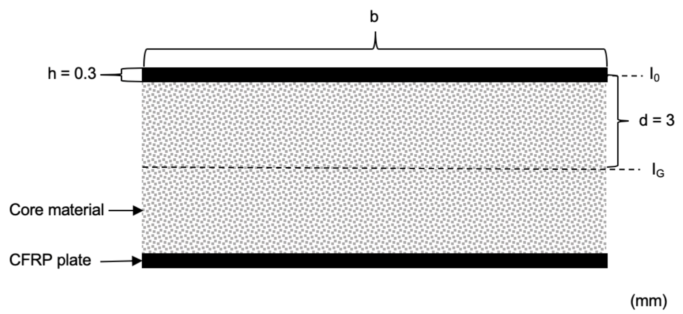


Figure 33. The sandwich material with an internal core fronted with Prepreg layers on each side.

$$H = \sqrt[3]{12 \cdot 2 \cdot \left(\frac{h^3}{12} + d^2 \cdot h\right)} \rightarrow \sqrt[3]{12 \cdot 2 \cdot \left(\frac{0.3^3}{12} + 3^2 \cdot 0.3\right)} = 4 \text{ mm} \quad (8)$$

In conclusion, the thickness of prepreg composites is set to 2 mm, whereas the thickness of sandwich components is set to 4 mm.

## 4.1 Preparatory analysis: The segmentation

In order to acquire reaction forces which are to be used in the analyses, the current solution, i.e. the manual adjustment mechanism, is brought to use in the segmentation. The reaction forces extracted from the segmentation represents the forces which must be endured by the new concepts.

### 4.1.1 Pedals

In the first segmentation, the pedals are hinged at a pivot point on a beam which is simulated by application of two Remote Displacement conditions (C and D) in the edge contact surfaces, see Figure 34. The Remote Displacement condition locks the rigid body motion in all directions but leaves the pedals free to rotate around the pivot point. Furthermore, the rod joint connection between the pedal and the yoke is simulated by application of a Remote Displacement condition (B) as well, but with movement locked in the direction of travel. The force (A) is applied at the area of interaction between the pilot and the pedal, with values acquired from LTF-UL 397. The resulting force, which is to be used in the Primary Analysis, is extracted from the rod joint connection and is approximately 2200 N contrary to the direction of travel.

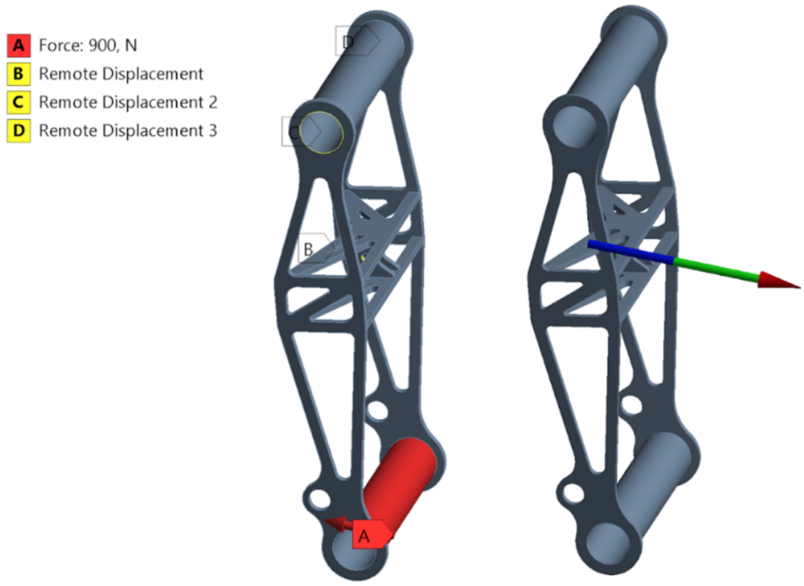

Figure 34: Boundary conditions and force extraction in the first segmentation.

### 4.1.2 Yoke

In the second segmentation, the yoke is prevented from rotation around its rotation axis (the pin used for manual adjustment of the pedals) in order to acquire reaction forces. It is simulated with a Bonded Condition, which prevents separation in all degrees of freedom. Furthermore, the yoke is placed between an upper and lower bracket (used for the incremental adjustment of the pin), connecting the yoke with the surrounding aircraft components. A Fixed Support is applied to the brackets, see Figure 35, which simulates their attachment to the surrounding. An additional rod joint, which connects the yoke to the NW, is simulated with a Remote Displacement condition by locking the motion in the transverse direction. The force extracted from the first segmentation (2200 N) is applied on the area of interaction between the rod joint and the yoke. In addition, it must be brought to attention that the pilot force applied on the pedal will contribute to a force acting in the z-direction as well, which is a result of the pedals being hinged in a pivot point. Hence why, a supplementary force component is added in the z-direction, which is estimated to be around 100 N according to Blackwing.

At last, the reaction forces are extracted at the pin joint. The extracted force was approximately 2200 N in the direction of travel, 3550 in the transverse direction and 160 in the vertical direction.

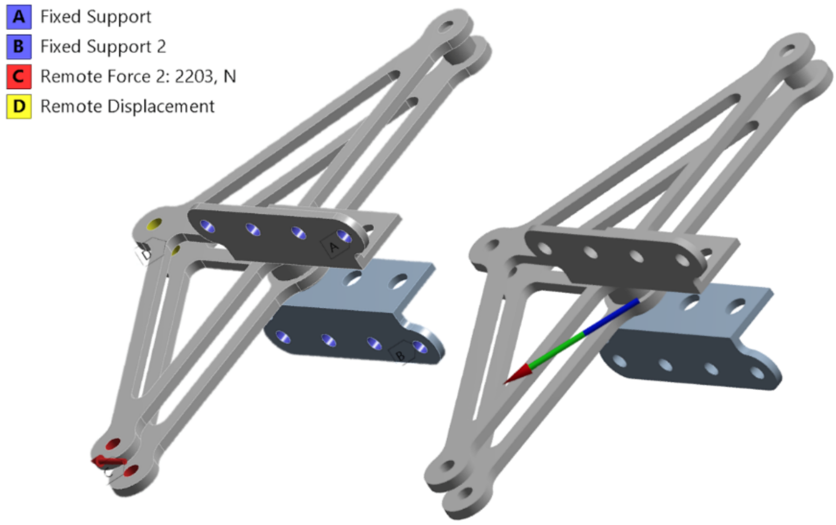


Figure 35: Boundary conditions and force extraction in the second segmentation

## 4.2 Primary analysis

### 4.2.1 Material data

ANSYS Workbench standard materials will be utilized due to lack of further material information. The materials brought to use for the components are aluminum, stainless steel, structural steel and epoxy carbon woven (230 GPa).

### 4.2.2 Geometry preparation

At first, the CAD model is uploaded in DesignModeler (a software within ANSYS Workbench) in order to modify the carbon fiber components into surfaces. This modification enables the use of shell elements rather than solids and also enables application of individual face thicknesses, which is performed at sandwich material components. Components made by regular prepreg layup are 2 mm thick, except for the hatch on the NW which is only 1 mm thick. Individual faces corresponding to sandwich material components have the estimated thickness of 4 mm, see Figure 36.

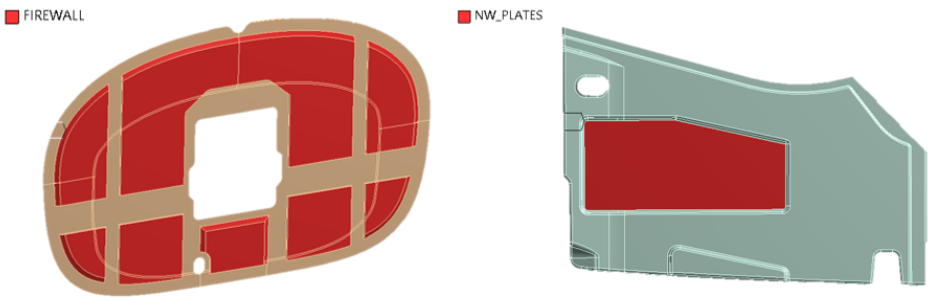


Figure 36: Individual faces corresponding to sandwich material components with an estimated thickness of 4 mm.

### 4.2.3 Boundary Conditions and Connections

Boundary conditions are applied in order to simulate the external relationship between the components of importance and the environment which is not imported in the analysis. In contrast, Connections represent the internal relationship between the appearing components. Presented below is the justification for how the connections have been chosen.

- Bolted joints: Bolted joints are assumed to be strong enough to prevent slipping between and/or parting from surfaces, thus, they are simulated with a Bonded Connection.

- Carbon fiber composites: Details made of carbon fiber composites are generally glued to each other, which makes the Bonded Connection usable yet again.

- Bushings: Bushings will be simulated by rigid circular beam connections which are applied in ANSYS Workbench instead of importing excessive information such as screws, bushings etc. in order to decrease the time lapse.

- Components for uniform direction loads: Components which are meant to solely withstand single direction loads, will be connected with No Separation that allows planar sliding but prevents any other separation.

## 4.2.4 The initial Dove

### *4.2.4.1 Boundary conditions, additional connections and meshing*

**Boundary conditions**

- Fixed Support is applied at the edge around the firewall, under the NW and on the side of the brackets (see Figure 37), in order to simulate the attachment to the fuselage and the aircraft floor panel.

- The forces extracted from the segmentation are applied at the nut where the pedal yoke is intended to be attached. The resultant force is 4179,5 N.

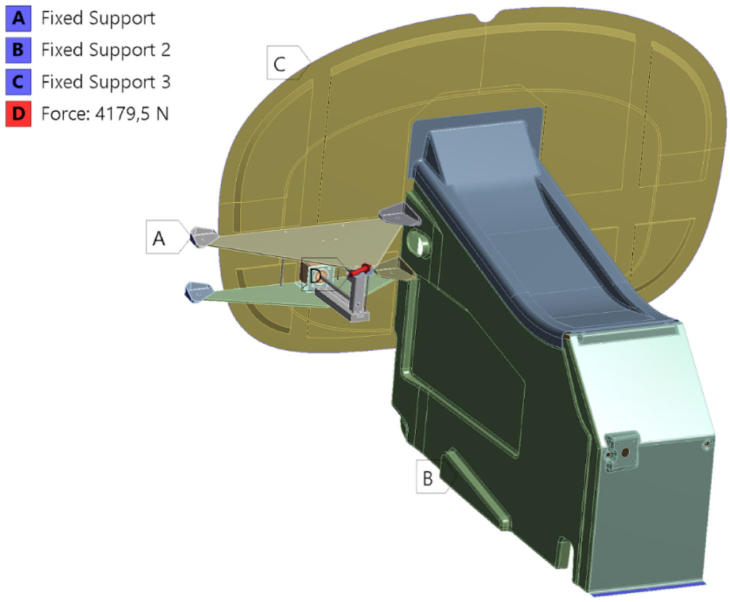

Figure 37: Boundary conditions for initial Dove analysis

**Additional connections**

- The sliding motion of the leadnut is simulated with the No Separation condition which only enables the rectilinear motion along the dovetail track.

- The leadscrew that causes the sliding motion of the leadnut is simulated with a deformable circular beam in stainless steel.

**Meshing**

- The overall element size was set to 5 mm with no further refinements, see Figure 38.

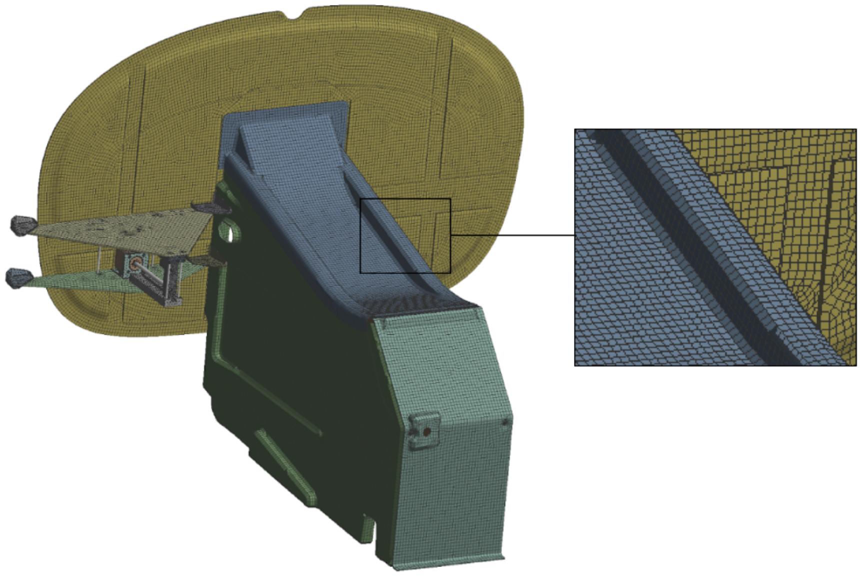

Figure 38: Meshing for initial Dove analysis.

### 4.2.4.2 Results

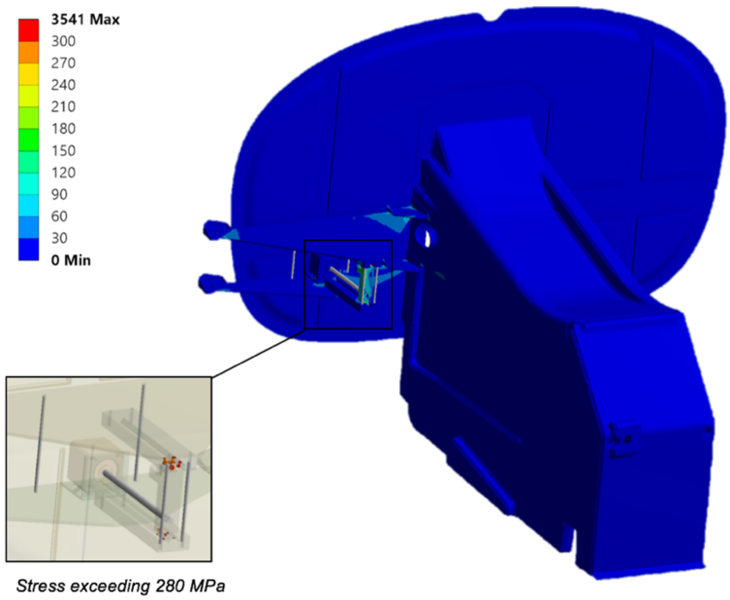


Figure 39: Equivalent stress (von Mises) given in [MPa]. Critical stress concentrations evolving at the contact region between the leadnut and the dovetail track

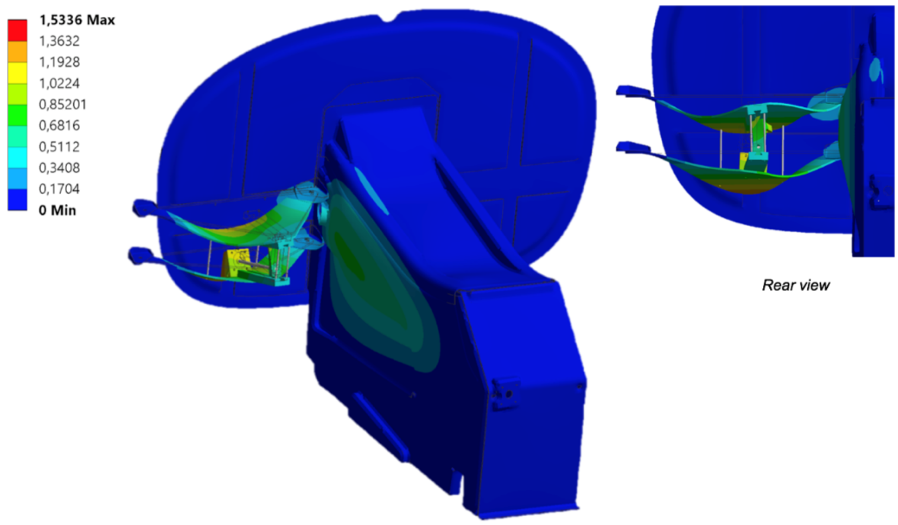


Figure 40: Total deformation given in [mm] (Magnification 48x)

The axial reaction force on the lead screw was acquired with a Probe Reaction and resulted in 671 N.

*4.2.4.3 Evaluation*

From Figure 39, one can deduce that stress areas evolving around the dovetail joint exceeds the yield stress ($\sigma_{aluminum}$ = 280 MPa), which suggests the necessity of further reinforcement. The deformation behavior is a concern (see Figure 40) when considering the stepping motor. The lead screw deviates from its linear axis which mustn't occur in linear precision systems, hence why, additional support to counteract deviation is required. The axial load of 671 N does not exceed the critical compressive load from equation (1), thus, the selected motor is approved.

## 4.2.5 The initial Pivot

*4.2.5.1 Boundary conditions, additional connections and meshing*

**Boundary conditions**

- Fixed Support is applied at the edge around the firewall and under the NW (see Figure 41), in order to simulate the attachment to the fuselage and the aircraft floor.

- The forces extracted from the segmentation are applied on the upper and lower plate, where pedal yoke is intended to be attached. The resultant force is 4179,5 N.

- The linear actuator is simulated by using the Remote Displacement Condition which prevents motion in the direction of travel.

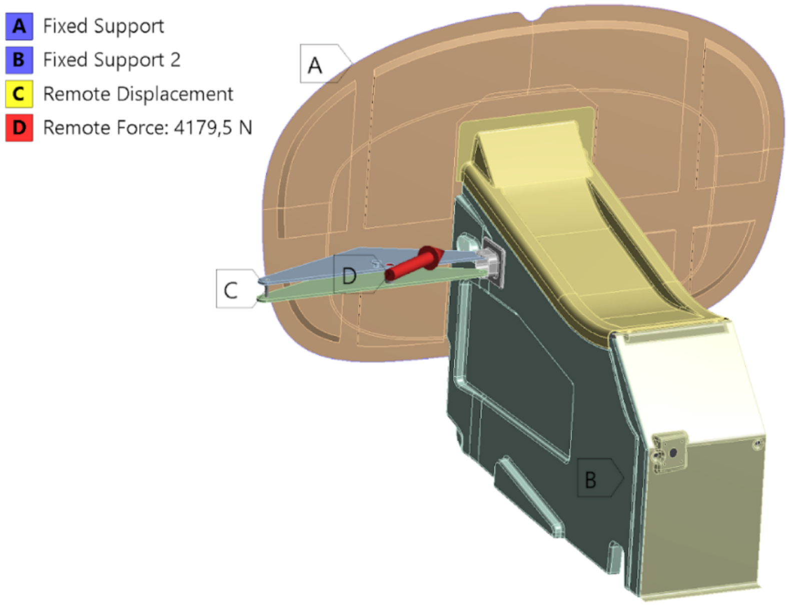


Figure 41: Boundary conditions for initial Pivot analysis

**Meshing**

- The overall element size is set to 4 mm with no further refinements, see Figure 42.

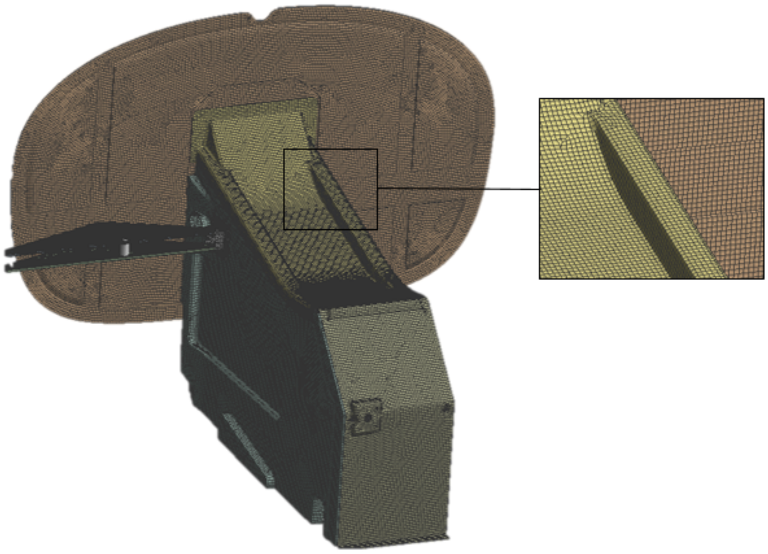

Figure 42: Meshing for initial Pivot analysis

#### 4.2.5.2 Results

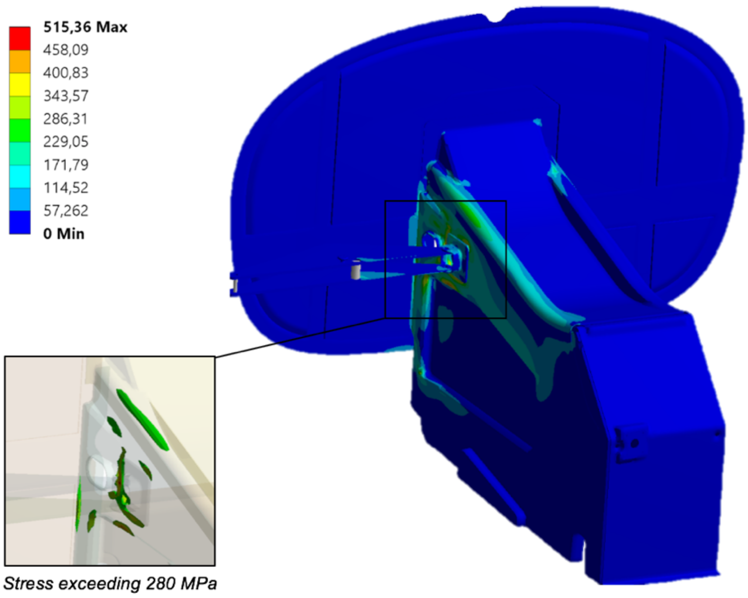


Figure 43: Equivalent stress (von Mises) given in [MPa]. Critical stress concentrations evolves on the bracket and on the contact region between the bracket and the NW.

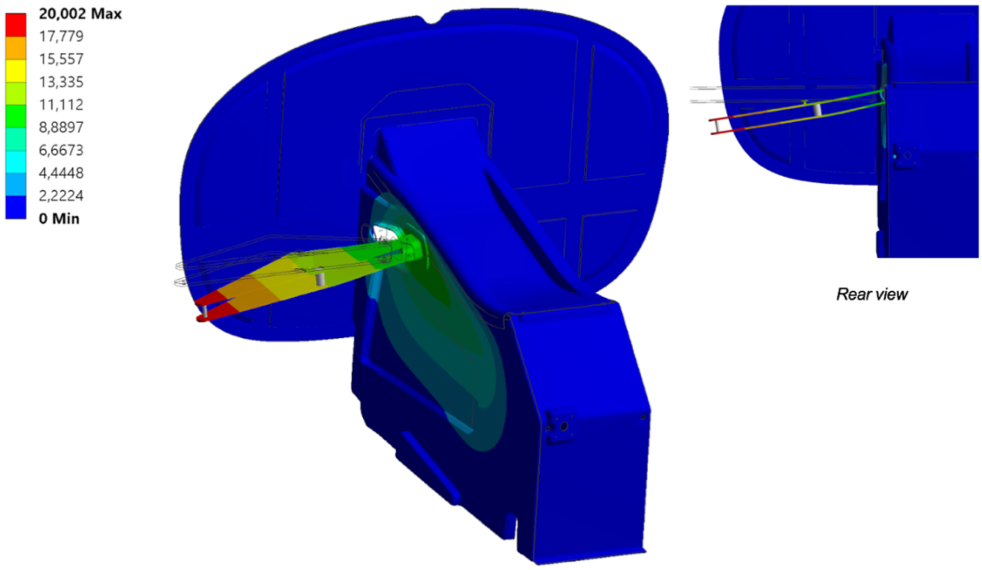

Figure 44: Total deformation given in [mm] (Magnification 3.9x)

*4.2.5.3 Evaluation*

From Figure 43, one can deduce that the stress concentrations occurring on the bracket and on the NW exceed the yield stress of aluminum. In the initial state of the analysis, the aluminum yield stress is used as a threshold for carbon fiber composites as well at the request of Blackwing. Thus, the stress concentrations suggest that the NW will benefit from further support in order to withstand the transverse load. In addition, support is required along the vertical axis in order to prevent deformation in that direction (see Figure 44), especially considering the linear actuator which mustn't be exposed to exceeding radial forces.

## 4.3 Secondary analysis

The secondary analysis does not introduce new aspects in terms of material data, geometry preparation, connections or boundary conditions and will thus utilize same prerequisites as the primary analysis.

### 4.3.1 The developed Dove

Structural improvements have been performed on the initial Dove. The center structure is brought to use in the concept design in order to counteract the deformation by attaching it onto the upper plate with screws. The center structure will thereby answer for the load endurance in the vertical direction and is somewhat redesigned in order to provide a suitable attachment area. Furthermore, the stability of the lower plate is increased by attaching an L-profile beam in aluminum below the plate as well as on the firewall with screws. The L-profile will answer for decreased deviation of the stepping motor, see Figure 45.

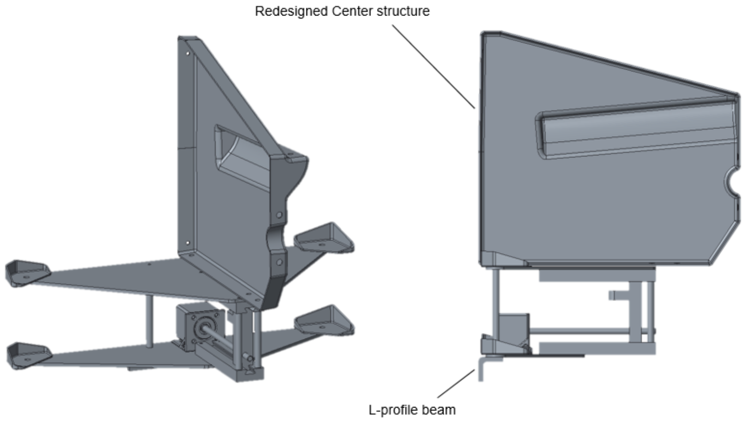

Figure 45: The developed Dove concept

*4.3.1.1 Boundary Conditions, additional connections and meshing*

No additional boundary conditions nor connections have been brought to use. The overall mesh is unmodified.

*4.3.1.2 Result*

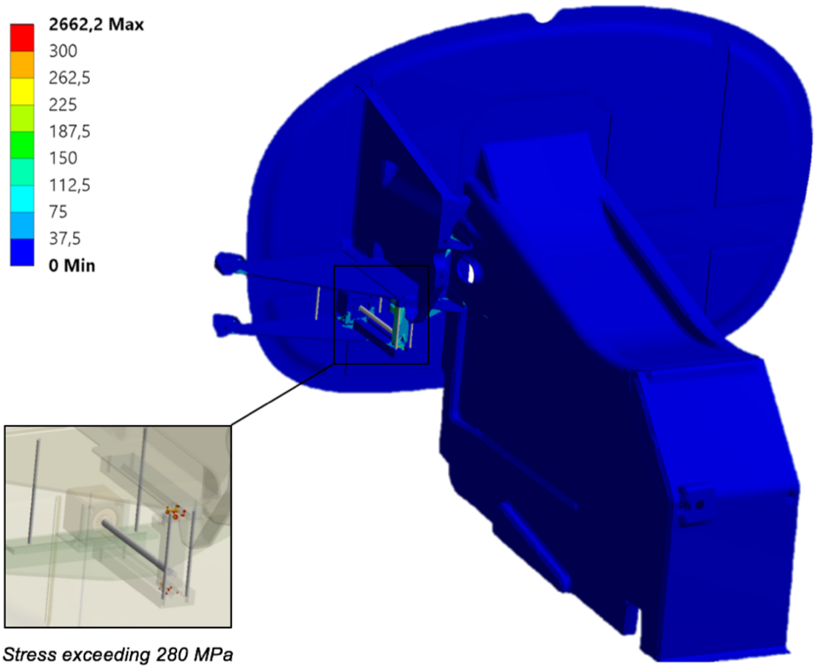


Figure 46: Equivalent stress (von Mises) given in [MPa]. Critical stress concentrations evolving at the contact region between the leadnut and the dovetail track.

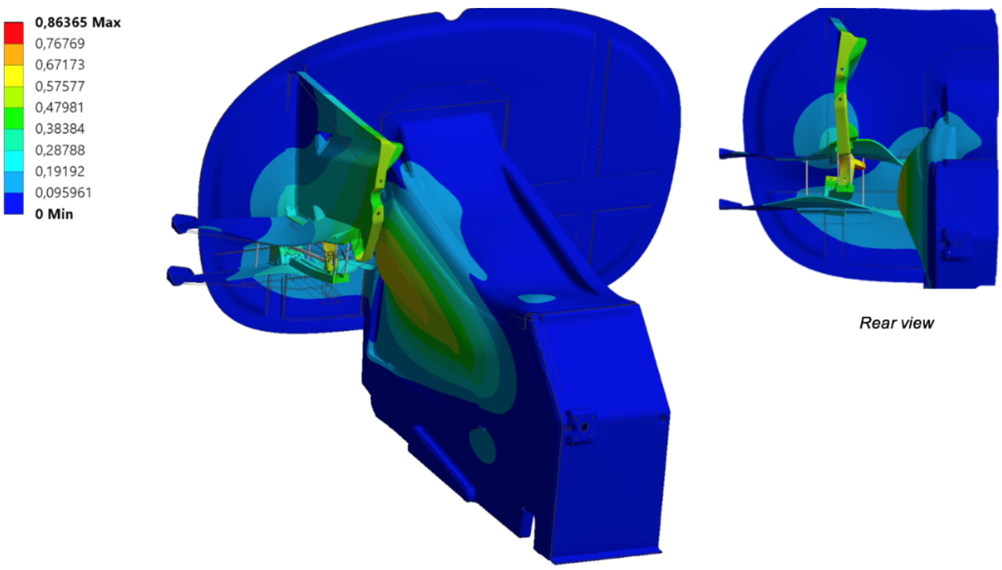


Figure 47: Total Deformation given in [mm] (Magnification 92x)

The axial reaction force on the lead screw was acquired with a Probe Reaction and resulted in 999 N.

*4.3.1.3 Evaluation*

The comparison of Figure 40 and 47 demonstrates that the structural improvements are beneficial for reduced deformation behavior. The stress concentration is, however, still exceeding the yield stress of aluminum (280 MPa), see Figure 46. Increased stability of the stepping motor is achieved, but uncertainty regarding fatal effects on the performance remains since it's difficult to evaluate whether the reduced deviation is enough or not. At last, the increased axial load of 999 N does not exceed the critical compressive load from equation (1), thus, the selected motor is still approved.

## 4.3.2 The developed Pivot

The center structure is brought to use once again in order to improve the vertical load endurance. The upper plate is provided with a bushing which is equipped with an end cap, see Figure 48. In addition, an aluminum sheet detail with a grooved track is fastened onto the bottom of the Center structure with aluminum brackets. The grooved track is the connective feature between the Center structure and the upper plate, as the end cap bushing will move along the track when the pedals are adjusted.

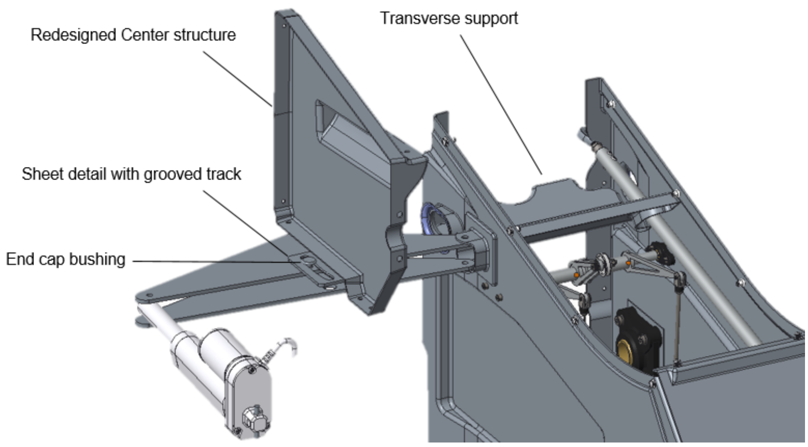


Figure 48: Additional components in the developed Pivot concept.

Due to the design of the center structure, it is of importance to solely expose it to vertical loads since remaining load cases will work transverse to the fiber direction which is a risk for failure. In order to achieve unidirectional load exposure, the grooved track is widened so that contact between the bushing and the track contours cannot occur, see Figure 49. The sheet detail will, however, provide support in the vertical direction as it prevents the end cap from moving downwards which reduces the deformation behavior. The Center structure is somewhat redesigned in order to provide a suitable attachment area for the sheet detail.

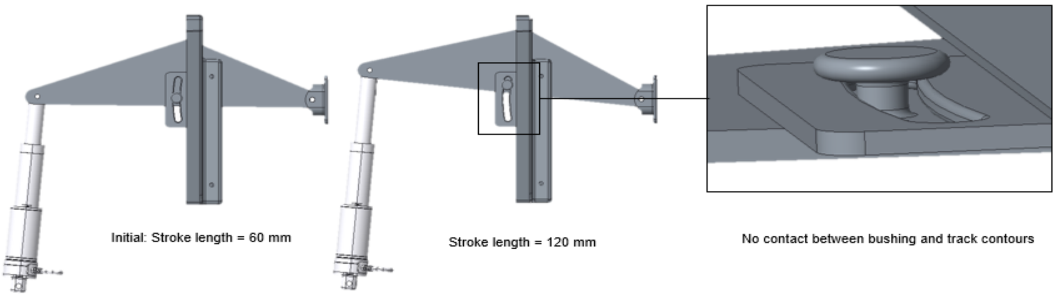


Figure 49: The only contact region occurs between the endcap and the upper surface of the sheet detail.

A carbon fiber detail, The Transverse Support, is applied inside of the NW as a last act of improvement, i.e. to provide additional support for the transverse load (see Figure 50). The design is carried out with respect to the internal architecture of the NW which mostly consists of parts in motion. This results in a detail of pliant character. It is glued onto the NW sideplates, the hatch and the front which requires the flanges to be at least 20 mm in order for the glue to fasten the detail properly. Furthermore, maximum rigidity is achieved when the angle between the flange and the web is kept at 90° throughout the geometry. Moreover, the web is positioned in the center of forces acting on the bracket. The preferable design would imply for the web to be vertical and coincide with the axes of the fastening holes in the bracket, see Figure 51. This would, however, result in varying angles preventing the component from being manufactured in one piece which significantly weakens the detail.

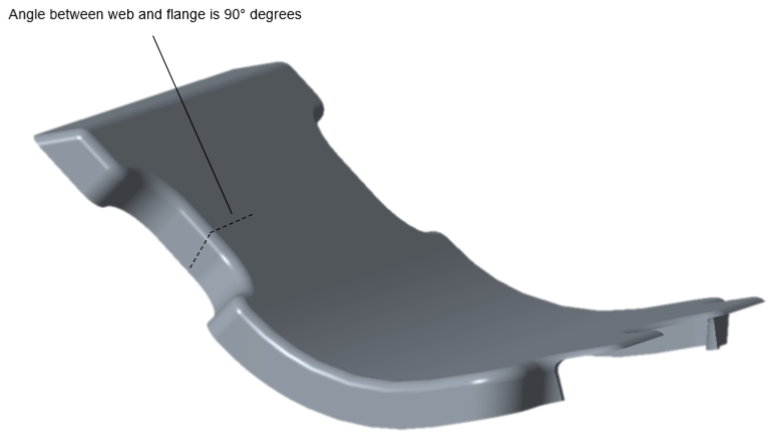


Figure 50: The NW Transverse support with a constant angle relationship between web and flange.

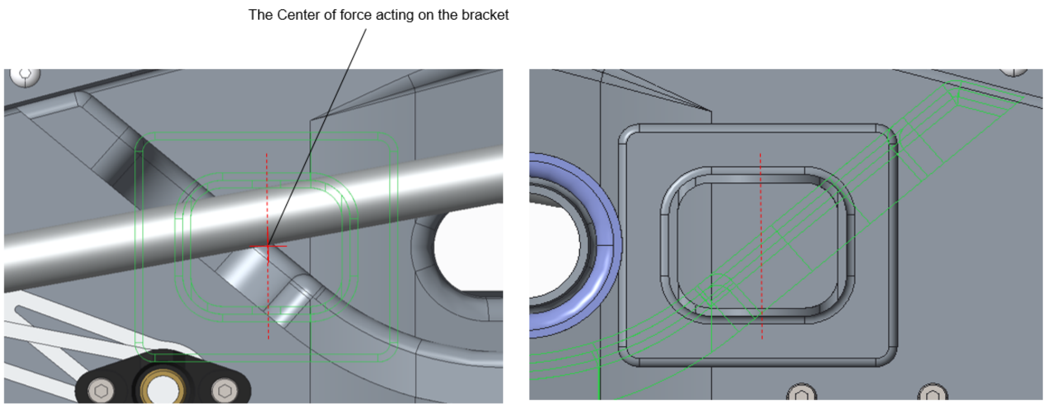


Figure 51: The web coincides with the center of force acting on the bracket.

*4.3.2.1 Boundary Conditions and meshing*

**Boundary Conditions**

- Fixed Support is applied at the front edge on the Transverse Support (see Figure 52), in order to simulate the attachment to the fuselage.

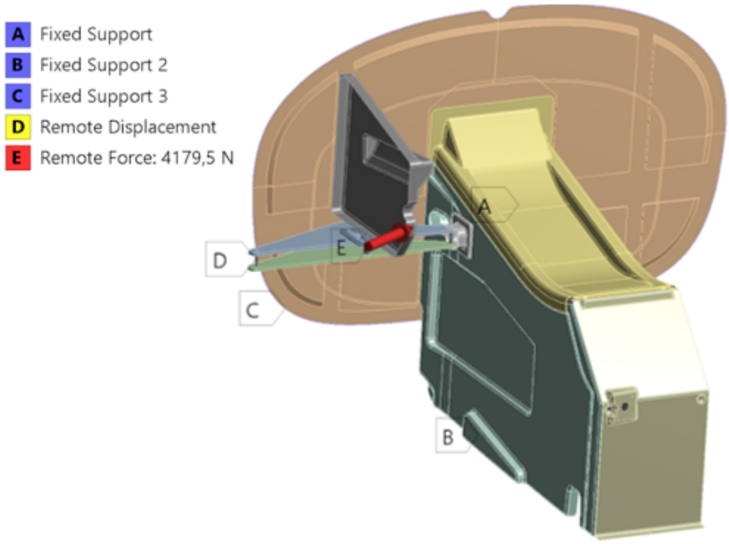

Figure 52: Boundary conditions for the developed Pivot concept.

**Additional Connections**

- The sliding motion of the bushing end cap along the grooved track is simulated with the No Separation condition which only provides contact in the vertical direction between the end cap and the sheet detail, but enables movement in the horizontal plane.

**Meshing**

- Further refinements are carried out in areas which are rich in detail, i.e. around the sheet detail and the end cap bushing. The element size is set to 1 mm in order to prevent convergent issues, see Figure 53.

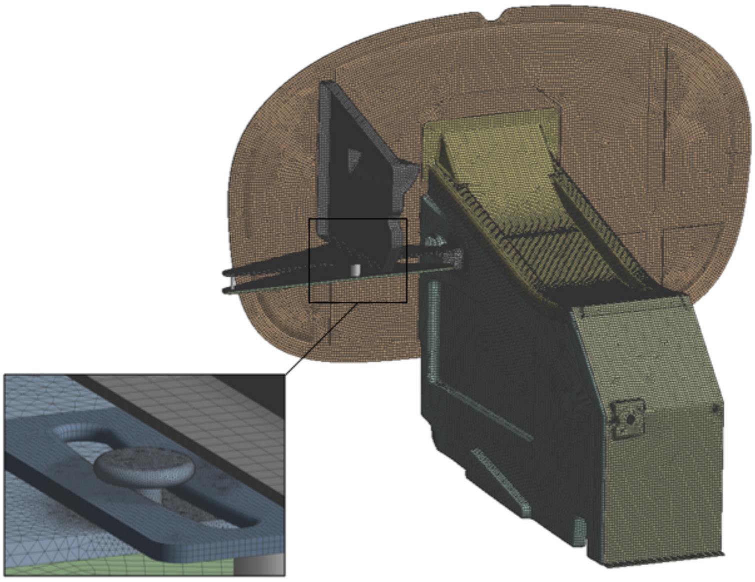

Figure 53: Meshing refinement around areas which are rich in detail.

### 4.3.2.2 Result

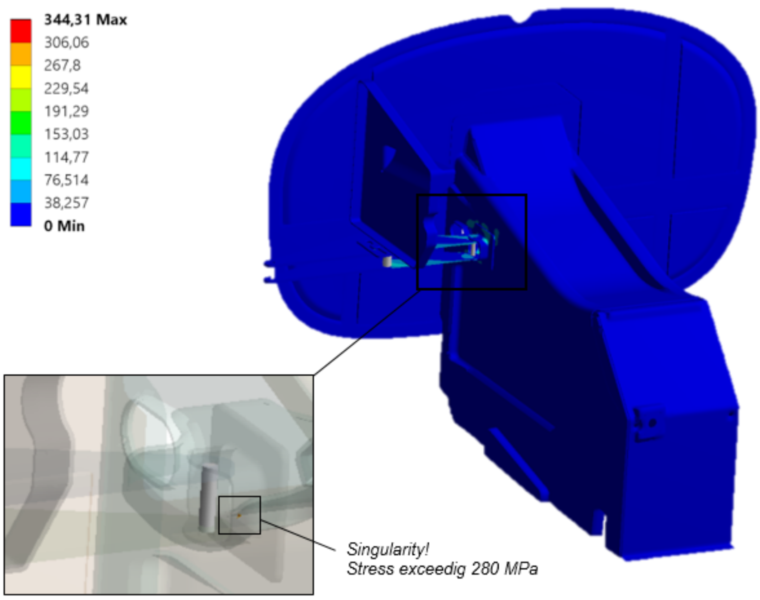


Figure 54: Equivalent stress (von Mises) given in [MPa]. Singularity appears on the Transverse support.

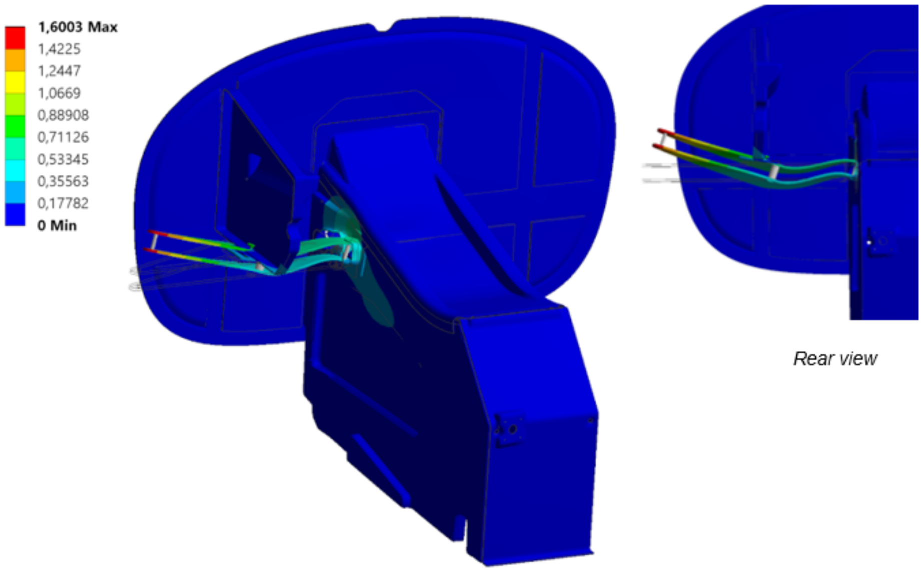


Figure 55: Total deformation given in [mm]. (Magnification 45x)

*4.3.3.3 Evaluation*

Significant improvements have been made on the developed Pivot in terms of deformation behavior (compare Figure 44 and 55). The stress concentrations have also been reduced noticeably, since stresses exceeding 280 MPa have been eliminated, see Figure 54. A few, small areas with critical stress concentrations are still existent, but can be considered as singularities due to their insignificant size.

## 4.4 Concept Scoring

Concept Scoring is a method carried out in order to choose the most suitable idea. The resulting concepts from the Concept Screening (2.4.4) are to be compared with respect to selection criteria acquired from the primary and secondary analyses. In addition, the selection criteria are accompanied with valuable framing of questions by Blackwing. The selection criteria are provided with a weight of importance which adds up to 100 % when summarized. Both concepts will be rated by their ability to meet the criteria on a scale from zero to three where zero doesn't meet the criteria at all and three is the "perfect" match. The rate is subsequently multiplied with the weight of importance whereas the resulting product constitutes the Weighted Score used for comparison, see Table 5. Presented below is the justification as to how the ratings are chosen.

**Stress distribution**
The change in stress distribution is similar for both concepts. The initial stress decreases by the acts of improvement performed with additional supports. However, the scope exceeding the yield stress for aluminum remains for the Dove whereas it has decreased to an insignificant amount for the Pivot.

**Deformation behavior**
The deformation behavior for the Dove wasn't much of an issue to begin with since a maximum deformation of 1.53 mm goes unnoticed. However, when put in relation to the stepping motor, even the smallest deviation from its original position will contribute to risk of failure in the lead screw. The same argument goes for the Pivot, as the largest deformation occurs in the radial direction relative to the linear actuator. Nevertheless, the actuator runs with a clearance fit which differs (slightly) from absolute axial precision.

**Risk for failure**
The biggest risk for failure is assumed to be in the precision systems, i.e. the linear actuator and the stepping motor. The latter is implemented in order to endure loads in the direction of travel in compression, which may contribute to buckling. Buckling is not an equally significant problem in the case of the actuator as it endures axial loads in tension.

**Weight deviation**
The Dove has a total weight of approximately 1180 g, whereas the Pivot has a total weight of approximately 1560 g.

**Ease of manufacture**
No aspects of the manufacture seem to be alarming for neither of the concepts. No components of high detailed precision such as cogs or fastenings have been custom made nor does the carbon fiber components differ from silhouettes in the current design.

**Ease of implementation**
Ease of implementation is in strict relation to number of components, their sizing and how they interact. The Dove consists of far more precision details

such as the bushings and the dovetail joint, which can become somewhat cumbersome to mount when considering the lack of space in the cockpit. The only concern regarding the Pivot is the grooved track which must be positioned with fine tolerance in order to not endure transverse loads.

**Perception of intuitive safety**

In conclusion, the Pivot concept is perceived as being the "best and safest". The developer behind a clean and straightforward design with less or no number of redundant details appears to carry knowledge and understanding about the necessities and how they are met with thought.

Table 5: Concept Scoring

| | | CONCEPTS | | | |
|---|---|---|---|---|---|
| | | Dove | | Pivot | |
| Selection criteria | Weight | Rating | Weighted score | Rating | Weighted score |
| Stress distribution | 15 % | 2 | 0,3 | 3 | 0,45 |
| Deformation behaviour | 15 % | 1 | 0,15 | 2 | 0,3 |
| Risk for failure | 25 % | 1 | 0,25 | 2 | 0,5 |
| Weight deviation | 25 % | 2 | 0,5 | 1 | 0,25 |
| Ease of manufacture | 5 % | 3 | 0,15 | 3 | 0,15 |
| Ease of implementation | 5 % | 1 | 0,05 | 2 | 0,1 |
| Perception of intuitive safety | 10 % | 2 | 0,2 | 3 | 0,3 |
| Total score | | 1,6 | | 2,05 | |
| Rank | | 2nd | | 1st | |
| CONTINUE? | | no | | YES | |

# 4.5 Nonlinear analysis

A nonlinear analysis implies a nonlinear relationship between applied forces and displacements. In contrast, the previous analyses hold a linear relation. Nonlinear effects can originate from several phenomena such as:

- Geometrical nonlinearities, i.e., large deformations.
- Material nonlinearities, i.e., elasto-plastic material model.
- Kinematic contacts, i.e., frictional contact between surfaces.

Blackwing have previous experiences with issues regarding flexural composite components causing nonlinear behavior, hence why, nonlinear effects originating from large deformations will be investigated in order to confirm that they don't have an impact on the result. The analysis is carried out as a final validation of the solution in progress, which will confirm if significant changes or additional supports are required for the performance. The nonlinear analysis utilizes an identical setup as in the Secondary analysis and in addition, Large Deflection is enabled. By enabling Large Deflection, the stiffness varies due to changes in shape of geometry in the simulation, i.e., geometrical nonlinearities. The behavior is illustrated in Figure 56. The force P impacts the beam in the initial state and continues to affect the beam in multiple iterations as it deflects due to the impact. This may result in significant changes in the deformation result compared to a linear analysis, for which the force impact is evaluated solely at the initial contact with the object.

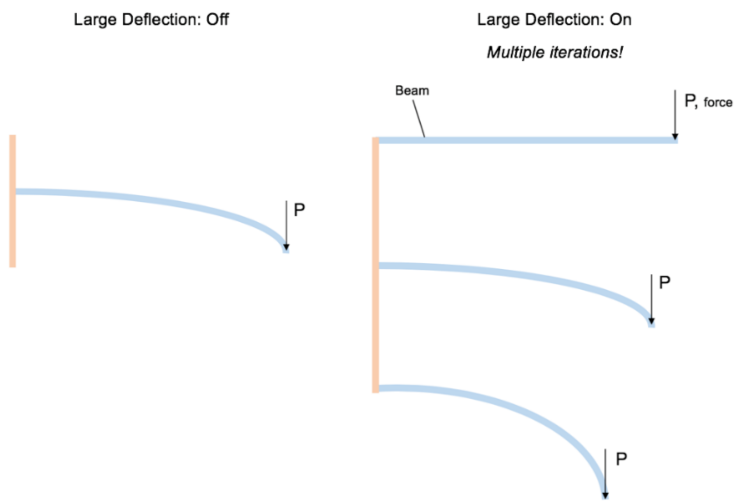


Figure 56: Force impact and deflection of beam enabled by "Large Deflection" setting.

## 4.5.1. Result

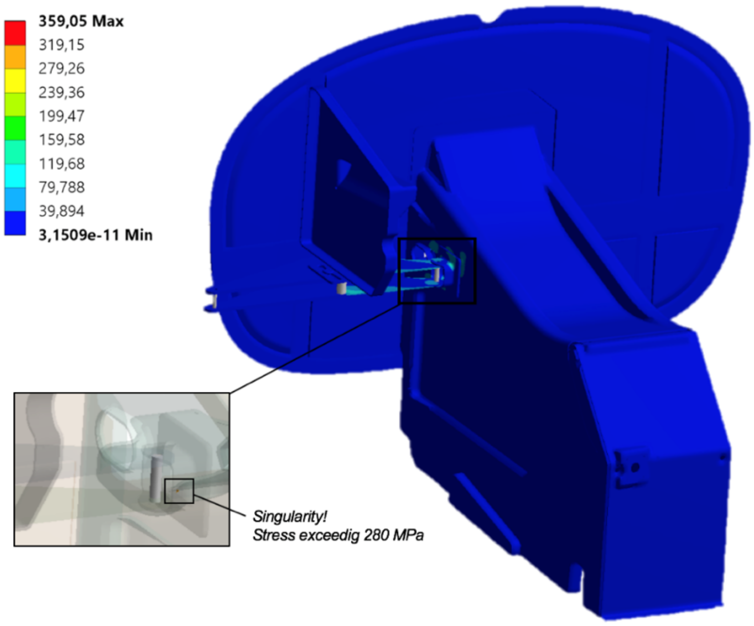


Figure 57: Equivalent stress (von Mises) given in [MPa]. Singularity appears on the Transverse support.

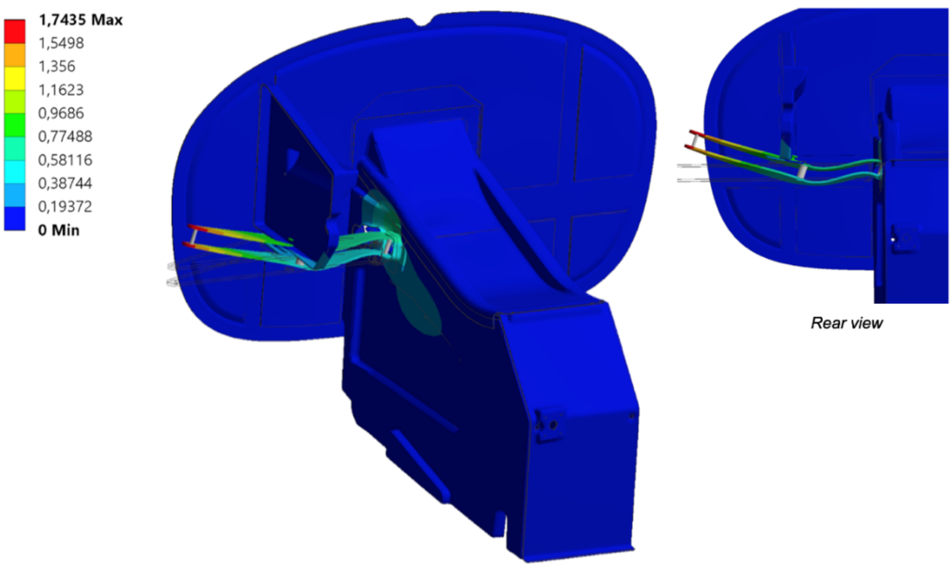


Figure 58: Total deformation given in [mm]. (Magnification 45x)

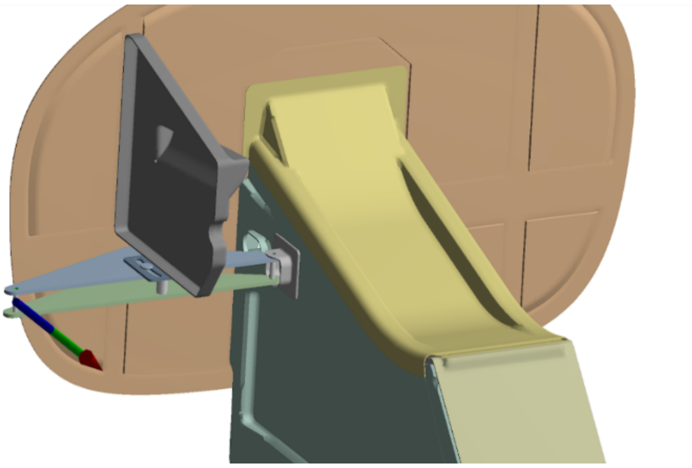

Figure 59: A Force Reaction probe acquired at the attachment point of the linear actuator. The resulting force is 905.6 N contrary to the direction of travel.

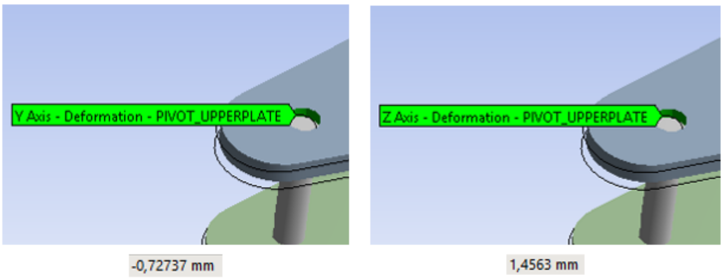


Figure 60: Deformation probes acquired at the attachment point of the linear actuator on the upper plate.

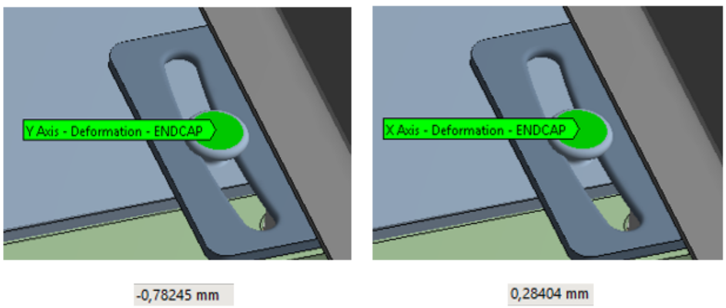


Figure 61: Deformation probes acquired at the end cap on the upper plate

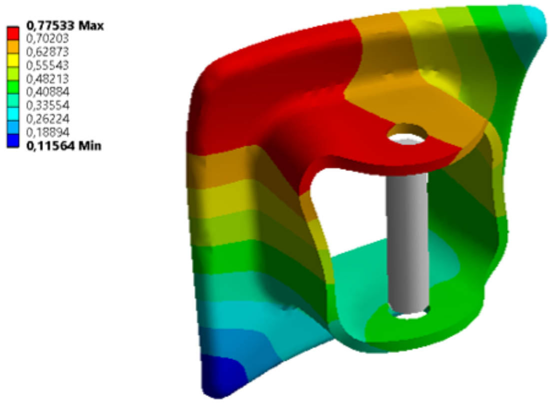


Figure 62: Deformation of bracket given in [mm] (Magnification 27x)

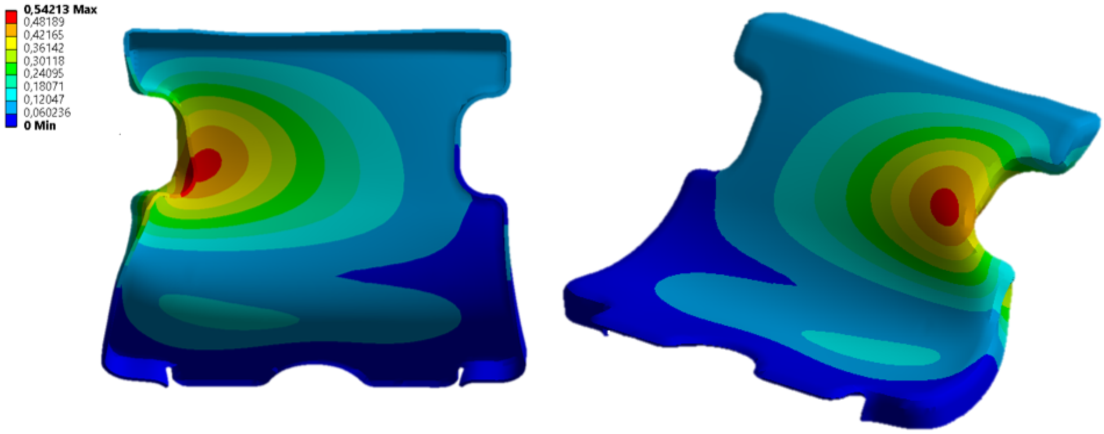


Figure 63: Deformation of Transverse Support given in [mm] (Magnification 43x)

Potential energy = 18 mJ

Stabilization energy = 0,00026 mJ

### 4.5.2. Evaluation

By comparing the results from the nonlinear analysis with the secondary (linear) analysis of the Pivot, one cannot deduce any significant differences. A minor increase in both deformation behavior and stress distribution occurs, where the latter is still a singularity (see Figure 57 and 58). The imperceptible changes can be explained either by humbly stating that the construction is rigid enough to not be affected by nonlinear effects, but also by the impact of Nonlinear Stabilization. Nonlinear analyses are generally time consuming and require a lot of error search if the geometries are complicated which is why it isn't suitable at initial state of projects. It was no difference this time; due to long calculation times in combination with convergence issues, a Nonlinear Stabilization was introduced. The Nonlinear Stabilization setting introduces an artificial damper which helps achieving convergence at the expense of *possibly* affecting accuracy of the result. If the outcome of the error search isn't successful, Nonlinear Stabilizations are a reasonable alternative to overcome the problems. In order to evaluate the accuracy of the result, the Stabilization energy can be compared to the Potential energy. The stabilization energy, i.e. the work done by stabilization forces, should not exceed 1 % of the potential energy in the system. The ratio between these energies is far less, which strengthens the accuracy of the result.

Figure 59 demonstrates a force of 906 N in the attachment point of the linear actuator, which validates that the chosen linear precision system is overdimensioned in terms of force endurance. Downsizing may, however, be an issue since it's carried out at the expense of the stroke length. Linear actuators generally have a stroke length related to increased load endurance (and thus increased weight), i.e. a trade-off situation arises. The radially directed deformations, see Figure 60, do not exceed 1,5 mm and are therefore not perceived as adverse, especially when considering the clearance fit. Deformation in the y-direction (the horizontal plane) would simply result in slight rotation of the actuator, whereas deformations in remaining radial directions can be crucial if they evolve. Nevertheless, impact of any kind deviating from the axial direction should always be counteracted in linear precision systems since the main purpose isn't performance in any other direction.

In order to evaluate the transverse impact on the Center Structure, a deformation probe was acquired at the end cap bushing, see Figure 61. A probe acquired at the Center Structure itself would yield misleading results since the deformations would originate from the behavior of the deformed firewall. This is caused by the choice of contact "No Separation" in the analysis settings, which doesn't consider any contact in the horizontal plane between the parts in question. The displacement of the endcap in Figure 61 validates that the grooved track is dimensioned to only endure loads in z-direction and thus it satisfies its purpose.

Figure 62 and 63 depict an unalarming result in similarity with all deformations in the nonlinear analysis. Moreover, it is evident from Figure 58 that the transverse support fulfills its purpose by decreasing the total deformation of the system.

## 4.6 Topology analysis

In order for the Pivot concept to reduce weight while maintaining the stiffness, a default Compliance Topology Optimization is carried out on the two structural plates. The Topology Optimization removes material from the original design with respect to settings identical to the setup in the Secondary analysis. The nonlinear analysis demonstrated no indication of nonlinear behavior, hence why, the topology optimization will be done without large deflection for time management.

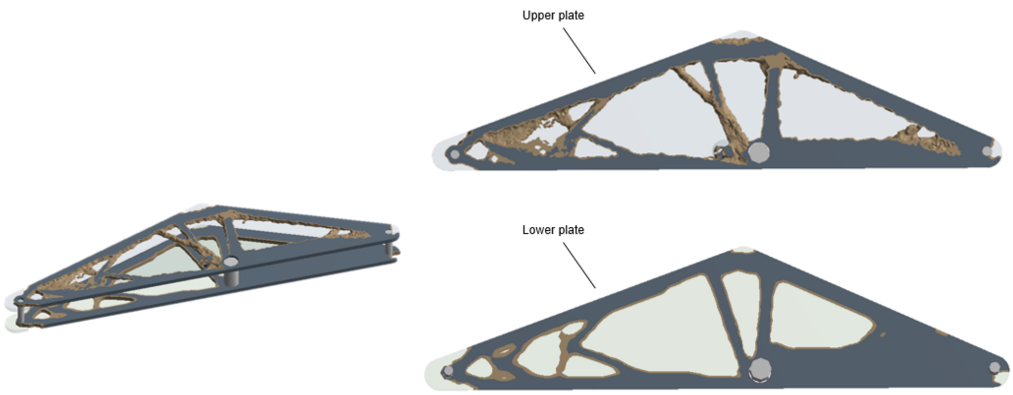


Figure 64: Material layout suggested by the Topology Optimization.

The original mass of the structural plates was estimated to 0.445 kg. With the suggested material layout from the Topology optimization, a total mass of 0.242 kg was achieved, opting for a mass reduction of 46 percent while retaining the structural stiffness.

As seen in Figure 64, the geometry is more robust on the right hand side by the virtue of the transverse load direction. The necessity of investigating both load directions in order to obtain an understanding of the material layout is emphasized. However, the overall material layout will be designed by mirroring the right hand side of the upper plate which is considered being the most robust area. In addition, this design is applied at the lower plate in order to obtain two identical details, see Figure 65.

Figure 65: Redesigned structural plate.

A final validation of the optimized plates is carried out with the same settings as in the Secondary analysis. In these analyses, the plates are impacted by both left and right pedal interaction, respectively. The results are depicted in Figure 66-67.

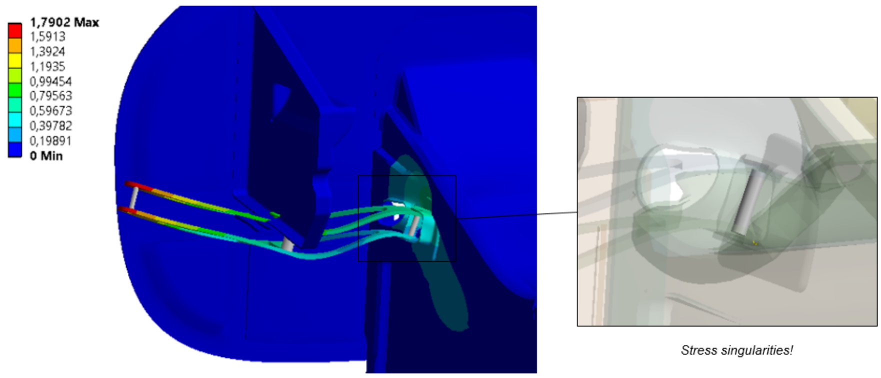


Figure 66: Deformation and stress exceeding 280 MPa due to load directed to the NW, i.e. left pedal interaction.

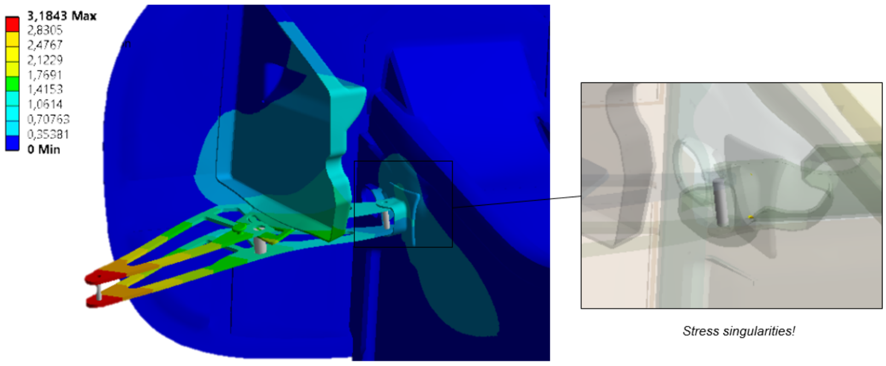


Figure 67: Deformation and stress exceeding 280 MPa due to load directed to the fuselage, i.e. right pedal interaction.

The stress distribution is not of critical character for any case of pedal interaction as the stress magnitude above 280 MPa occur solely as singularities. Moreover, the deformation due to left pedal interaction doesn’t deviate significantly from Figure 55. The deformation due to right pedal interaction is slightly higher, but is still considered acceptable since it goes unnoticed by the user, which according to Blackwing occurs when 3 mm is exceeded (see specification 11). However, the center structure will be exposed to transverse loads, which requires a modification of the dimensions in the grooved track in order for the bushing to not collide with it.

# 5 Discussion

*In this section, a final discussion regarding the whole working process will be held. The process is comprised of two main headlines, namely the "Concept development" and the "Concept testing and refinement". As a final statement, the overall result from the testing will be commented accompanied with recommendations for further development, that is, what is believed to be necessary before a Production Ramp-up can be initiated. Lastly, a conclusion is given as a summary of the whole thesis project.*

Utilizing the U&E design process proved to be beneficial particularly for this project. The method enabled for the workflow to stay open-minded which was necessary since the project required an innovative solution. The open-minded workflow generated a generous number of concepts which was crucial in the early stage of the project due to the product specifications being difficult to appreciate.

A Concept Screening was performed in order to proceed from the concept generation. The concepts were evaluated through supportive statements from Tomas and Niklas which were essential at this stage of the project considering the time management. Proceeding from there, it proved to be advantageous being two people working with the project since the resulting concepts required full-time attention for further elaboration. Although working in pair, the modelling and analysis stage required more time than initially planned for, see Figure 68. As a direct consequence, the chosen concept still requires refinement. There are several factors explaining why the stage of modelling and carrying out the analyses were time consuming, one of them being the dynamics (1.2.5.2). Continuous changes in the environment caused a larger delay than expected. Moreover, slow and unstable workstations postponed the project further due to long calculations and crashes. Nevertheless, reaching a final concept was an ambitious goal to begin with. A *systematic* concept for a fully automated rudder pedal assembly was achieved, thereof, the U&E is evaluated as a successful choice of approach for this project.

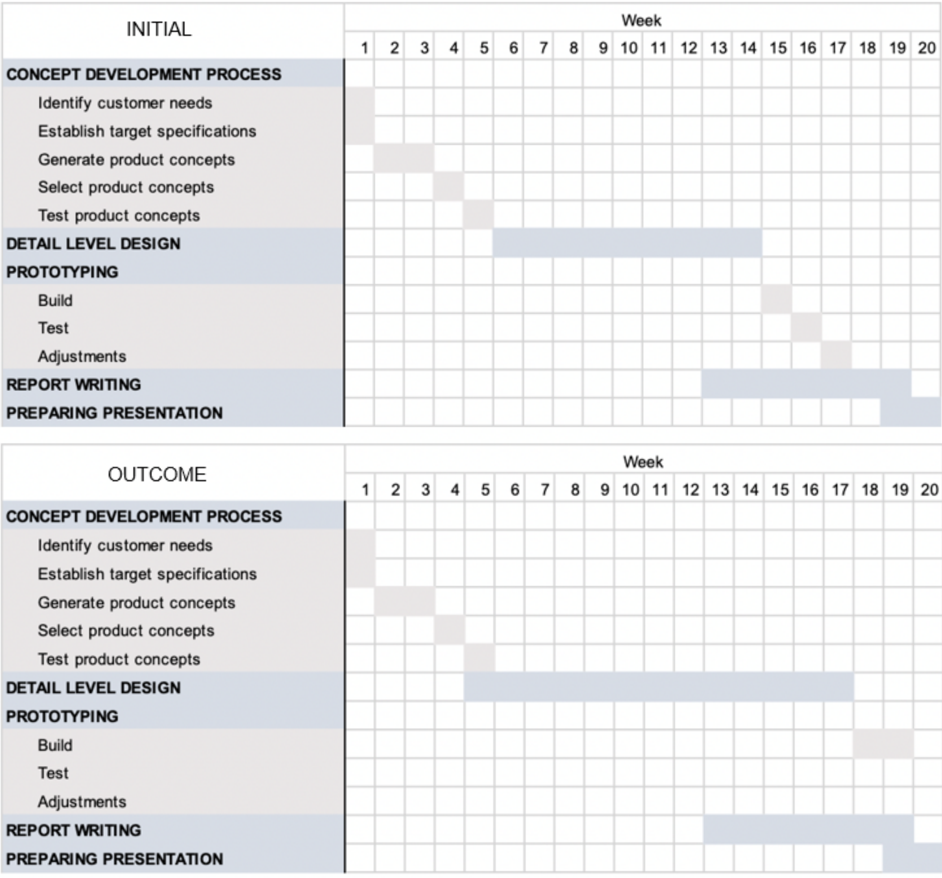

Figure 68: Initial time schedule and the Outcome of the time schedule for the project.

The analyses in the Concept testing have been dependent of many simplifications and assumptions which *may affect* the accuracy of the result, if not evaluated properly.

One simplification applies for the CFRP material. Throughout the analyses, a standard woven CFRP available in Ansys Workbench was utilized. The behavior of the material was evaluated with respect to properties of aluminum at the request of Blackwing. This is justified by the initial state of the project at which the analyses were performed. In order to proceed, it was assumed that “the CFRP will definitely stay intact if the aluminum will”, given that the components were designed with thought and that they satisfy their purpose of being included. Thereof, the components were designed with continuous support from the supervisors. In order to continue the project from this stage, the CFRP must be evaluated with respect to their anisotropic behavior when possible (even if the material is weaved to work in multiple directions in the horizontal plane) in order to reach full accuracy. That is, when load directions are known, it would be advantageous to make use of unidirectional properties. Additionally, it would be beneficial to perform a composite analysis. A composite analysis helps determine the right laminate stacking sequence of weaved components, which would prevent under as well as over-dimensioning.

Another simplification was performed for bolted joints, which were simulated with the Bonded condition. This is reasonable under the assumption that the ideal bolt is selected along with bolt pre-tension. Nevertheless, it can be considered as an acceptable assumption at this stage of the analysis since the conditions are equal for each concept. However, for a final prototype, a kinematic contact analysis is recommended for selection of appropriate fasteners.

When comparing the two final concepts in the Concept Scoring, the orthodox approach would be to include the current lock-pin mechanism as a reference concept in order to properly evaluate whether we accomplished any improvements or not. However, the problem statement clearly specifies the main importance which is to achieve a fully automated system. Any concept meeting this goal is assumed to be preferred over the old solution. Thus, a comparison of the automated concepts was considered enough.

As a final evaluation of the chosen concept, the linear actuator still remains undetermined. The final analysis provided the remaining data required for choosing among available designs, which can become a trade-off situation between the size (and thus the weight) and the stroke length. In addition, the linear actuator must be properly fastened in the fuselage. We approve of the chosen linear precision system, especially considering the benchmark process which resulted in multiple models to choose among.

The carbon fiber details are designed in a way which enables for easy actions of reinforcement. If the deformation behavior isn't approved of in the future by some means, it can be fixed by applying additional laminate layers rather than reconsidering the design as a whole. This may, however, lead to a trade-off situation with the cost if the alternative is overused. Moreover, further simplifications can be carried out when considering the sheet detail with the grooved track. The track can, for example, be applied on an extruded flange at the bottom part of the Center Structure with an aluminum reinforcement underneath. This is an action towards saving both space and weight, which can be modified in multiple ways with specific *pro's* and *con's* depending on the opinion of the designer. As a final statement regarding the chosen Pivot concept, we find it very advantageous due to the fact that every detail is chosen and/or designed so that it can be brought to use on the passenger side as well.

Several simplifications and assumptions were performed mainly for time management. Nevertheless, the conditions provide a reasonable estimation of the reality and thus is the result considered sufficient enough to determine that the concept is functional.

## 5.1 Conclusion

The thesis project has granted us a better understanding of the designing methods used in the micro-aircraft industry and its complexity. The starting point of Product Specifications which were somewhat hard to interpret, to the final stage of evaluating the chosen solution has been an educational journey for us. In the process of mastering this challenge, we experienced true-to-life scenarios with setbacks, preparing us for obstacles which may appear in our future work. Overcoming these obstacles resulted in satisfactory in the sense of a functional concept requiring a few additional refinements. With that being said, we believe the goal of the thesis project is fulfilled, i.e. we have presented a systematic solution for a fully automated rudder pedal system by gradually achieving the partial goals mentioned in 1.2.3. Moreover, we believe that our recommendations enable for a prototype to be produced, which can be strength-tested for certification and thereupon be implemented in the BW600RG aircraft. This is due to the grateful opportunity of working close to Tomas and Niklas.

Thank you for reading.

Figure 69: Simon de-mounting the current rudder pedal system.

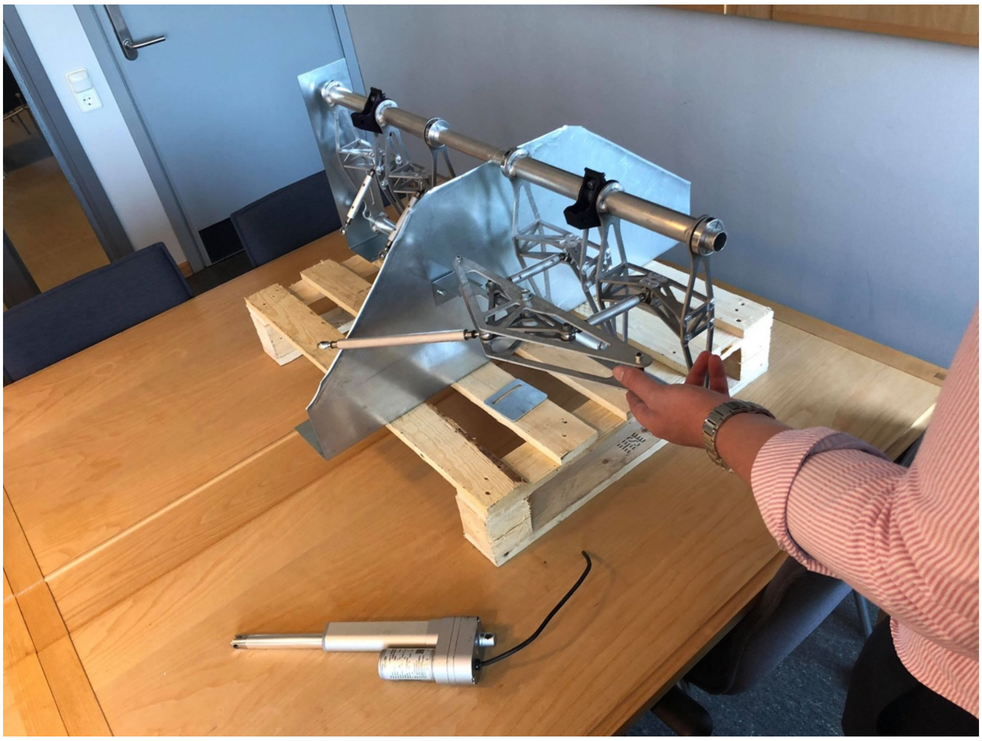
Figure 70: A prototype built for demonstration during the presentation of the thesis work.

# References


[1] Business Sweden. Retrieved May 10, 2019, from https://www.business-sweden.se/en/Invest/news-and-downloads/investment-news/blackwing-sweden-unlocks-next-horizon-in-ultralight-aviation/

[2] Motte, D. (2018). Product Development and Design Methodology [PowerPoint slides]. Department of Design Sciences LTH, Lund University, Lund, Sweden.

[3] RS Online. Retrieved May 11, 2019, from https://se.rs-online.com/web/p/products/7319402/?grossPrice=Y&cm_mmc=SE-PLA-DS3A-_-google-_-CSS_SE_SE_Tools-_-Spanners_And_Sockets%7CPipe_Wrenches-_-PRODUCT_GROUP&matchtype=&pla-393922589233&gclid=EAIaIQobChMI0dGTp7v_4QIVQ6qaCh2l_gATEAQYASABEgJzmPD_BwE&gclsrc=aw.ds

[4] Wikipedia. Retrieved April 25, 2019, from https://en.wikipedia.org/wiki/Scotch_yoke

[5] Thomson Linear. Retrieved March 23, 2019, from https://www.thomsonlinear.com/en/product/MLS17A10-310083P12000N-A000-RS3?fbclid=IwAR3lsjEMYULB0LuTT3XwV1nELCXHsmpcf1yS_KOydvp7ED2e7ZWrfIzsAfw

[6] Linear Mech. Retrieved March 23, 2019, from http://www.linearmech.com/linearmech/Viewer?foo=1&cmd=product_detail&id=1&type=1&pageId=101&fbclid=IwAR0qoq6HAG54l8R2qgkmjg9q6d-8o1UHoPpc6dsv77Y7KZjYmDzNWFONmQw&LANG=lang2

[7] Wikipedia. Retrieved March 18, 2019, from https://en.wikipedia.org/wiki/Dovetail_joint

[8] Collins, D. (2015). How to avoid ball screw buckling. Linear motion tips. Retrieved 4 March, 2019, from https://www.linearmotiontips.com/how-to-avoid-ball-screw-buckling/

[9] Thomson Linear. Retrieved March 24, 2019, from https://www.thomsonlinear.com/en/product/MLS17A10-M06010P20300N-A000-RS2

[10] TR Fastenings. Retrieved March 24, 2019, from https://trfastenings.com/products/knowledgebase/thread-geometry/metric-coarse-standard

[11] Haukka, B., Thomson Linear. Personal conversation (2019, 25 March)

[12] Transmotec. Retrieved March 25, 2019, from https://transmotec.com/product-category/linear-actuators/?AttributeVoltage=12&AttributeStroke=100.0

[13] Wikipedia. Retrieved March 26, 2019, from https://en.wikipedia.org/wiki/Similarity_(geometry)

[14] Alfredsson, B. (2014). Handbok och formelsamling i hållfasthetslära. Stockholm, Sweden: Institutionen för hållfasthetslära, Kungliga Tekniska högskolan.