MASTER THESIS

DESIGN OF A STABLE STEERING MECHANISM FOR TRIKES

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DOCUMENT NUMBER
BE - 837

UNIVERSITY OF TWENTE.

12-07-2022

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Prevent the trike from tilting and keep your feet from the floor

Preface

With elderly everywhere around us getting less mobile, my desire to give these people certainty of movement and the ability to move around outside is great. As I have experienced around me, people of a certain age tend to stay more inside and limit their daily movements because they become insecure about their movements and are afraid to fall, i.e. they get problems keeping their balance. One of the situations in which losing your balance is rather unfortunate is when riding a bicycle. Being active myself, I know the importance of having the freedom which comes with riding a bicycle, and I would wish people of all ages to have this freedom. Working on this ideal, while developing a bicycle was an assignment which attracted me a lot because this would really give an impact to physically insecure people. People in general, because the design which was presented to me by Beixo had the important difference to other trikes of looking fashionable and not stigmatizing unbalanced people who cannot use a normal bicycle, thus not limiting its target group to elderly with balancing problems, but also to younger people who would like the support in not falling over.

Beixo also is the first I would like to thank, because of the opportunity they gave me and the flexibility to work from home and have the prototype at my own availability to test at any time. Special thanks to Ad Trummers, who gave me the freedom to design in my own way, but also helped me find electronic components through their supplier in Asia. Also a big thanks to Edsko Hekman and Bart Verkerke for your endless support and patience when I was stuck and could not find my rest and focus to work on this project, but also for your continuous feedback and help while working to a final design. Though you did not have to do that much, I also enjoyed the chats with Hans Rietman as you were very enthusiastic about this project as my external supervisor. At last, I also want to thank my family and friends for keeping up with me, hearing over and over again that it was “getting to the end”, providing me with distractions and giving me the time and space to work on this project.

Abstract

On average, every person in the Netherlands own 1.3 bicycle. This means that cycling is an important element in the life of most Dutch people. However, with increasing age, people tend to get more problems with balancing, resulting in insecureness to go out with a bicycle. As a solution, people can use a trike, which gives more stability but often is less comfortable to ride with. Therefore, a trike with a regular tilting mechanism can be adjusted. This design assignment is about realising a dynamic stabilizing mechanism for such a trike. The mechanism will enable the trike to lean in the turns, like a normal bicycle, but will prevent falling at low speeds and even keep the trike in an upright position, such that users can stay on the trike at traffic lights.
Based on the requirements and existing devices, concepts are formed on how the trike could be stabilized. The design of the final concept is described in detail and calculations are performed on the feasibility of required forces. Also, the electronics and regulations of the system are developed. This resulted in a trike of 17/33kg, depending on the materials to be used, with a dynamic stabilizing mechanism which automatically detects when to be activated and which keeps the trike upright (maximum deviation 2°) when at low speed or at stand-still.

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List of abbreviations

BoS	Base of Support
CoM	Centre of Mass
PWM	Pulse Width Modulation
TR	Trapezoidal thread

List of symbols

r	(m)	Radius
v	(m/s)	Speed
a	(m/s^2)	Acceleration
(Δ)t	(s)	Time (difference)
Θ	(°)	Angle
m	(kg)	Mass
g	(m/s^2)	Gravitational acceleration
W	(Nm/J)	Work
P	(W)	Power
D_r	(mm)	Minor diameter of a spindle
l	(mm)	Length between bearing supports of a spindle
C_s	(-)	Type of end connection of a spindle
rpm	(min^{-1})	Rotational speed
N_c	(min^{-1})	Critical speed
D_p	(m)	Pitch diameter
L	(m)	Lead distance of screw
F	(N)	Force to be moved
M	(Nm)^	Moment
f	(-)	Coefficient of friction (depends on material and lubricating manner, 0.15 for steel screw and nut)
T_u	(Nm)	Torque required to move a load up the thread

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1. Problem Analysis

1.1. Introduction

Driving on a bicycle is a common, but physically complex task, for which every person has to practise before being successful. In the Netherlands only, there are over 22.8 million bicycles, coming down to an average of 1.3 bicycle per person.[1] A regular bicycle, with two wheels, only gives tilting restrictions in the sagittal directions. However, there is no restriction in lateral movements, which means that cyclists need to balance the bicycle to keep an upright stability. By novel cyclists, this is being experienced as one of the most complex tasks. This is amplified as balancing at a low speed is more difficult than balancing at a higher speed, which is rather contradictory for novel or uncertain cyclists.

With increasing age, people get more difficulties with keeping balance. In cycling, this is mostly expressed during the accelerating and decelerating phases, where the speed reaches 0 km/h, whereas people have less difficulties when up to speed, because of the steering mechanism behind a bicycle. Therefore, it would be useful for elderly, or other people with a reduced balance, if there would be a bicycle which helps balancing at low speed but does not need to alter the cycling dynamics when up to speed.

In the first part, the problems of and principles behind balancing and turning a bicycle are explained, and the importance of a balancing bicycle is elaborated. Also, parties which influence the course of the project are evaluated and the problems which lead to the requirement of a balancing bicycle are visualised. After this, the design assignment is explained, requirements are defined, and functions are elaborated upon, resulting in a set of concepts and a final design.

1.2. Problem definition

The main problem of this project, as defined by the client Beixo, is to keep upright stability at a low speed with a trike (three wheeled bicycle) while allowing tilting at higher speeds. A trike is stable by nature and is a solution to the balancing problem. To allow for tilting in turns as a normal bicycle, the trike can be provided with a tilting front axle. The objective of this assignment is to regulate the movements of the front axle at low speed without limiting the freedom at normal speed. By doing so, the trike will be unable to fall over, even if the user has an insufficient balance control. However, the trike should give complete freedom of tilt when up to speed, as tilting is required in order to remain balanced in turns.

This bicycle will mainly be designed for elderly people with a reduced balance. With increasing age, mobility decreases. This makes it more difficult to get and stay on a bicycle, as cycling is a complex movement which consists of a set of independent tasks. Different tasks, which can be defined, are stepping on and off a bicycle, accelerating from and decelerating to stand-still, pedalling around and turning the trike around different corners. During all this, the surroundings have to be watched, and people have to react to unexpected situations. In the pressure of this, safety can be preserved by keeping the trike upright when out of turns.

1.2.1. Balancing a bicycle

There have been many experiments investigating how a bicycle can balance on its own or how a cyclist can balance a bicycle while riding in a straight line.[2]–[9] One element that can give stability but also helps steering is the trail of the bicycle, which is the distance between the intersection of the steering axis and the vertical line through the axis of the front wheel. If the distance between the contact point with the ground and the point where the virtual steering axis reaches the ground increases, the bicycle becomes more stable, but it is also more difficult to steer around turns. A small trail is very easy to turn, but because of this, it is rather tiring and not desired that much for recreative cycling. [2], [4], [5], [9]

When riding in a straight line or while accelerating/decelerating, cyclists try to keep balance in an upright position. This means that the desired lean angle of the bicycle is 0°, as there are no horizontal forces acting on the combination of cyclist and bicycle, assuming there is no strong sidewind. However, it is very common to have a certain amount of tilting while riding in a straight line. This could be seen as small perturbations to the balance of the cyclist.
There have been multiple experiments investigating the roll or lean angle of a bicycle while riding in a straight line, including research of Cain and Moore. Cain showed a lean angle between [-1.5 1.5°] while driving straight at a speed of 9 km/h.[6] The results of Moore showed the same average lean angle, but at a speed of 10 km/h.[7]
Moore also shows that the lean angle has an interquartile range of [-0.51 0.64°] and 1.5*interquartile range of [-1.95° 2.12°] for speeds between 10 and 25 km/h, as can be seen in Figure 1. For speeds as low as 2 km/h, the maxima increase to 1 and 3° respectively. This shows that it is normal to have some lean at all speeds, but that this increases with low speed, because the bicycle becomes less stable.

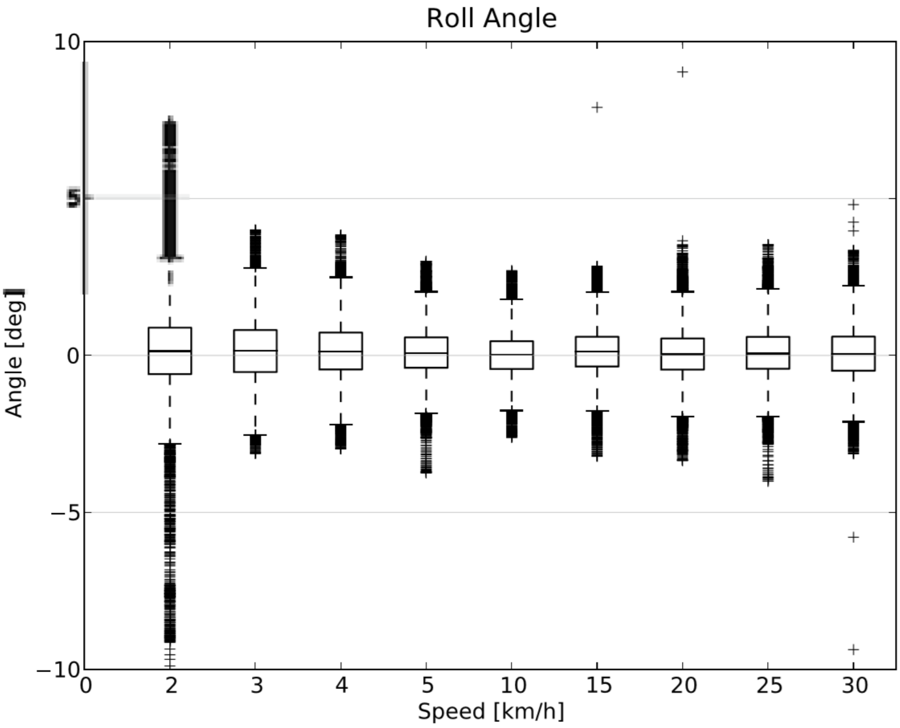


Figure 1 Boxplot of lean angle versus speed for 3 subjects with 4 measurements per speed.[7]

1.2.2. Turning a bicycle

A turn is made by making use of centripetal forces acting on the combination of bicycle and cyclist, which keep it in a curved path. This centripetal force is directed inward towards the centre of rotation.[10] To compensate for the centripetal force and prevent tilting outside of the turn, the cyclist has to tilt the bicycle, such that a moment equilibrium is maintained.[9] The amount of tilting required to maintain balance depends on the radius of the turn (r [m]) and the speed (v [m/s]) at which it is taken. The degree at which the bicycle has to be tilted, depends on gravity (F_g), acting on the combination of bicycle and cyclist, and the reaction force of the ground ($F_{reaction}$) and centripetal forces (F_c), both acting on the wheels, such that equation (11 and 2 are balanced. F_g and $F_{reaction}$ give the resultant force F_{res}, which acts under a distinct angle Θ. Dividing (1) by (2) results in equation 3, which gives the lean angle (Θ) at which the bicycle should be tilted for a given speed and turning radius. If the actual lean angle is smaller than the lean angle required by the centripetal force, the cyclist will lose the curved path and change into a straight line. Figure 2 shows the forces acting on the body.

$$\Sigma F_x = 0 = F_{res}\sin(\theta) - \frac{mv^2}{r} = F_c - \frac{mv^2}{r} \rightarrow F_{res}\sin(\theta) = \frac{mv^2}{r} \quad (1)$$

$$\Sigma F_y = 0 = F_{reaction} - F_{res}\cos(\theta) = mg - F_{reaction} \rightarrow F_{res}\cos(\theta) = mg \quad (2)$$

$$\tan(\theta) = \frac{v^2}{gr} \quad (3)$$

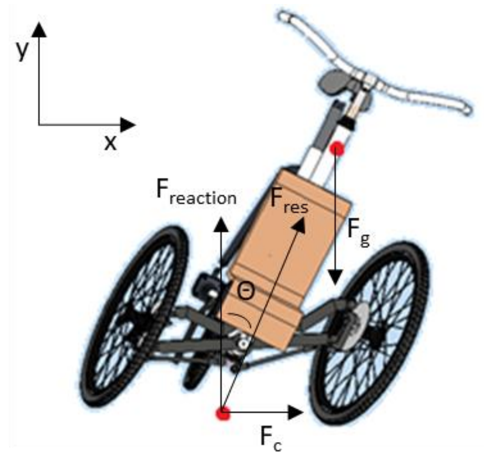


Figure 2 Free body diagram of the bicycle with forces acting on the bicycle in a left turn.

Road design

Based on the mechanics that are behind turning a bicycle, governments and other authorized organisations have set up guidelines on the development of roads or specific cycling tracks. These guidelines are based on safety measurements which arise through tire friction, road conditions and the mechanics of a bicycle, as explained above. As cyclists are part of a traffic system, precautions are also taken in relation to association with other vehicles and common traffic situations.
Guidelines of three different countries are evaluated to get a wider insight in the design of roads and what the bicycle should be able to do. It must be taken into account that this are their results and that in some cases, safety margins were increased.

In the Netherlands, the CROW (knowledge platform for traffic and transport, established by governmental instances in 1987) has a range of guidelines, which are further amplified by the "Fietsersbond", the interest group of cycling in the Netherlands. The following guidelines stand out the most. However, the previously established relation (3) is adjusted by CROW before their results were obtained.[11]–[13]

- 23° is the maximum lean angle at which tilting is safe in all weather conditions.
- In general, cyclists can keep stable with a speed above 12 km/h. This means that cycling tracks should be designed with a minimum inner radius of 4m.
- Main cycling routes are designed for a speed of 30 km/h, resulting in a minimum turning radius of 17.5m with a regular city bicycle.
- Other cycling routes should be designed for a speed of 20 km/h, requiring a minimum turning radius of 10m.

In Belgium, specific guidelines have been established for turns and evasive manoeuvres.[14]

- Sideward movement on a straight road (evasive manoeuvre): minimum radius is 10m.
- For turns, a minimum radius of 4m is advised, but the norm is only 3m.

In England, multiply institutes have set up guidelines for road design. In principle, these are the same. However, the Department for Transport and the Cycling Embassy England have significantly different explanations of the guidelines.

- Cyclists can ride in a straight line with a speed above 11km/h. In this case, the sideward deviation is only 0.2m, whereas this increases to 0.8m at a speed of 5 km/h.[15]
- The minimum inner radius of a turn should be 4m, unless a deliberately smaller radius is used to control speed (e.g. in a park).[15]
- The minimum radius of the followed path should be 6m. Only at sharp turns, e.g. when leaving the carriageway, the radius may be reduced to 4m.[16]
- Roads should be designed in such a way that cyclists can manage corners at a speed of 30km/h. Junctions and safety precautions are exempted, where a minimum speed of 10 km/h can be required.[16]

Values which return in different guidelines are minimum radii of 4m and a minimum cycling speed of 11 or 12 km/h. The design of 30km/h roads also is a convenience of which multiple countries realize the importance. Therefore, Figure 3 and Table 1 will give an overview of different speeds (including typical speeds as the minimum, average and maximum) and what lean angle and radius combine with this.

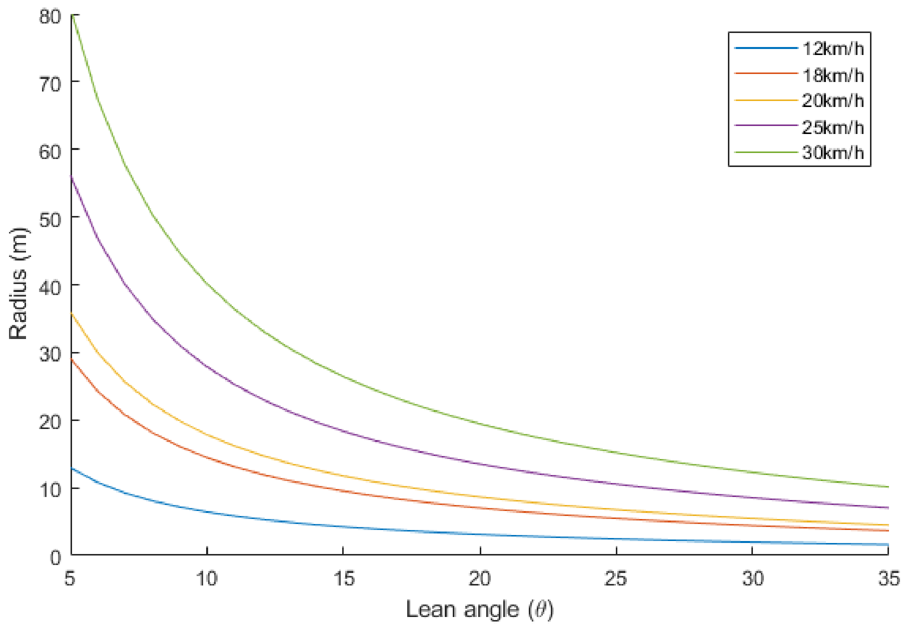


Figure 3 Turning radius as a function of lean angle for different speeds with a bicycle.

Table 1 Overview of critical cycling speeds, lean angles and turning radii with a bicycle.

Speed (km/h)	Lean angle Θ (°)	Radius (m)
10	5	9
12	23	2.7
12	10.7	6
12	5	12.9
14.7	23	4
18	23	6
18	10	14.5
20	23	7.4
20	10	17.8
25	23	11.6

1.2.3. Accelerations

While cycling, the speed changes naturally depending on external factors like wind and road quality, but acceleration is larger when braking. During undisturbed cycling, accelerations between 0.8 and 1.2 m/s^2 were found to be normal. With braking, accelerations are assumed to be between 1.5 m/s^2 for comfortable breaking and 2.6 m/s^2 when making an emergency brake.[17], [18] When approaching a traffic light, it can be assumed that a cyclist is aware of it and will have a more comfortable braking acceleration, but at a crossing where a vehicle appears in the last moment, an emergency brake will be needed. At a speed of 20 km/h, this results in a braking distance of 10.3 and 5.9m respectively, before the cyclist is standing still.

1.2.4. Balance disorder

Balance disorders can vary in a wide range between dizziness and result after a stroke. However, this does not make the first less dangerous, as this results in an increased number of falls, especially in elderly. In all ages, about 15% of Adults in the USA has problems with balance.[19] In the Netherlands, general dizziness has an incidence of 1.6% over all age ranges, which increases above 8% for people above 85 years. This results in a prevalence around 12%.[20] These problems may not seem very severe but cause a lot of falls and consecutive problems with elder persons. Therefore, it is important to help them keep balance in situations which are more extreme, such as cycling, as a bicycle can tilt easily. This is also a reason why many elderly people stop cycling, because they are afraid of falling.[21]

People with a balance disorder or a lack of balance are less able to keep the bicycle upright. Therefore, the experienced certainty would be highest if the bicycle maintains upright in all circumstances, except in those where tilting is necessary to maintain balanced forces. As described before, this is the case in turns. If the bicycle does not tilt in a turn, the lack of centripetal force will pull the bicycle out of the turn, which can cause dangerous situations. Thus, there has to be a tilting of the bicycle in turns, with an increasing allowed degree of tilting at higher speeds or smaller radii. In this way, the bicycle would be able to remain stable in all positions but allow a natural balance in turns.

1.3. Existing device

In the last 2 years, two students from the TU Delft and Hogeschool Utrecht have been working on this project. First, Isabelle Lugert has worked on the design of a non-stigmatizing bicycle for elderly, which gives stability but also has a good design. Figure 4 shows this design. This carrier bicycle style design has a modern look instead of the stable trike with two wheels and a basket at the back, which model is rather reluctant for most people. The two front wheels make use of the Ackermann principle, a trail of 12°, which results in 4.65cm with 20’ wheels, and a Centrepoint steering. For the latter, a kingpin inclination of 10° was chosen.

The Ackermann principle is used to make turning easier, as the outer wheel will have a smaller turning angle than the inner wheel. As a result, both wheels will have the same center point. This allows for a small turning radius and prevents slipping tyres.[21]

Figure 4 Design by Lugert [21]

As this project was finished, the bicycle has a good-looking design, but the steering mechanism was very unstable. Therefore, Coen Oosterlaken of the Hogeschool Utrecht continued this project. His main focus was on making the steering fluent. Therefore, he added another mechanism, which enabled the bicycle to lean in turns. To do so, he used a Feetz bicycle (see the left picture in Figure 5), which makes use of the same tilting principle. After this, he designed the steering mechanism in the right picture. The complete design is shown in Figure 6. However, this design has not been produced.

Figure 5 Left: Feetz bicyle which was used as a prototype to analyse the steering mechanism. right: The steering mechanism which Oosterlaken developed. [22]

Next to the steering mechanism, Oosterlaken also developed a stabilising mechanism based on 2 springs, which have to be controlled by a stepper motor (see Figure 6 – right). The principle behind this would be that a control algorithm behind the step motor locks or unlocks the springs, providing resistance when tilting the bicycle. The range of motion of the springs is thought to reduce with reducing speed, forcing the bicycle in an upright position as in Figure 6 – right when standing still. The disadvantage of this model however, is that it requires a large battery capacity to power the step motor.

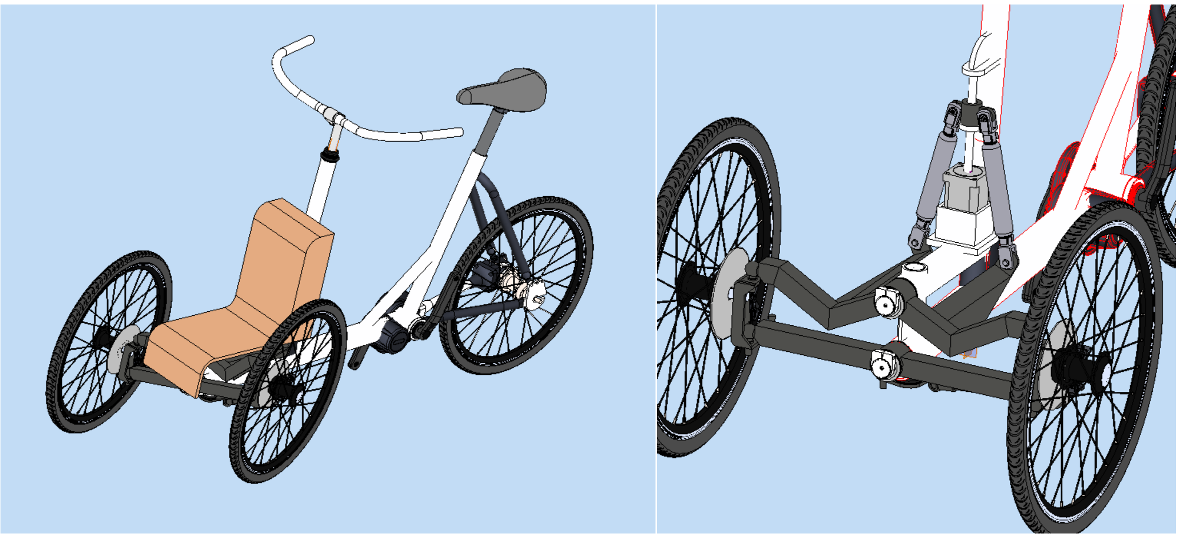


Figure 6 Design by Oosterlaken with spring stabilisation [22]

Coen Oosterlaken also did extensive research on the centre of mass of the combination of the bicycle (31.6kg) and a cyclist of 76kg. This resulted in the findings that the centre of mass (CoM) was at a height of 839mm and 689.4mm behind the front wheel axis (see Figure 7.2).
The length between the front and rear wheel axis is 1130mm and the width between the two front wheels is 682mm (see Figure 7.1). This means that when the bike is tilted 12°, the CoM is at the tilting line AC or BC (Figure 7.1). This means that, if the lean angle of the bicycle and cyclist is more than 12°, an unstable situation will arise because the CoM is outside the base of support (BoS).

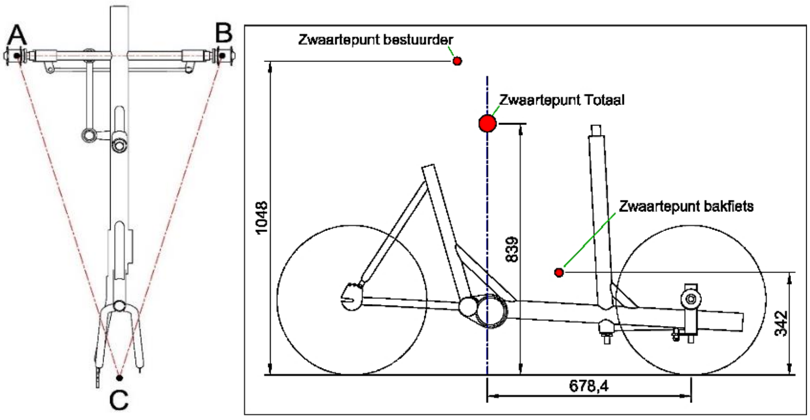


Figure 7 (1) Base of support and (2) centre of mass. [22]

1.4. Stakeholder analysis

Because of the high number of parties concerned in the development and future production of this product, it is important to have a clear view on their interests, capabilities and deficiencies and to know how much influence they have on the development of the product.

The target group of this product are elderly or other persons with a reduced balance, for example due to a balance disorder. From now, this group will be referred to as "elderly cyclists". The product should be interesting enough to them to buy, which places their interests at a high level of importance.
A subgroup, which may use the product as well, are novice adult cyclists. This can be persons who have never learned to ride a bicycle and do not want to make use of sidewheels, which are widely used by children to support balancing a bike when learning to ride a bicycle. For this group, the product might be interesting as well, but only for a shorter period, until they have learned how to balance the bicycle

on themselves. They have slightly different expectations than the elderly cyclists, including a higher importance for a non-stigmatizing bicycle.

The client for this assignment, Beixo, is a company whose main goal is to develop and produce (electric) folding bikes. However, they also have city bikes. Bikes developed by Beixo stand out because they make use of a cardan shaft drive instead of a chain drive. Advantages of the Cardan shaft are that it is cleaner, silent and needs less maintenance compared to a chain drive. As client, Beixo has the highest interest and influence in the development of the product. As their goal is to sell the product, they will represent the interests of the target group. If they are not convinced of a concept, or do not believe in the demand of a certain feature, they can change the trajectory of the design project.

Beixo is a brand of Urban Bike Concepts BV, which focusses on innovative cycling concepts. As long as Beixo's interests are fulfilled, it is expected that Urban Bike Concepts BV will set as well.

Beixo works in collaboration with 2 companies, Jee Ann Bicycle CO. and Distri-net. Jee Ann is a bicycle manufacturer located in Taiwan, which finalizes the designs and produces the bicycles of Beixo.[23] Their interests lie in the producibility of the product. Jee Ann will not have an influence in the project, except for the situation in which they see easier or better ways to produce the product. In that case, they will for example make a suggestion on the design of the frame. Distri-net is the assembling and distributing company, situated in the Netherlands. After most parts of the product are assembled by Jee Ann, the product is transported to the Netherlands, and Distri-net will do the remaining assembling and distribution of the complete product, depending on what exactly Beixo requests.

As the product will make use of public roads, there are certain requirements which it has to fulfil, such as light and reflection. However, other cyclists and general traffic have more expectations, as they do not want to be bothered by the product and its' user. Therefore, it is important that the dimensions of the product are limited and that it is safe to use.

Lastly, the engineer and supporting team of the University of Twente have a large influence on the product as well. They must come up with concepts, think through what is required and possible, and deliver a safe product. If they experience any physical limitations, they will not adapt these into the product.

To get an overview of the different stakeholders, their characteristics, experiences and influences, Table 2 shows a stakeholder analysis concerning all parties that are interested.

Table 2 Stakeholder analysis

Stakeholder	Characteristics	Expectations	Potentials and deficiencies	Implications and conclusions on the project
Beixo	Company which produces and sells the product	A good working product which fulfils the requirements of non-stigmatizing and stable	Marketing of the bicycle, has less technical insight in the development process.	Will give the final decision on the product and chosen concept, depending on their preferences
Urban Bike Concepts	Coordinative organisation of innovative cycling concepts, of which Beixo is a trademark	Innovative and solid product	Will allow/disallow Beixo to take the bicycle in production	Will support Beixo if the bicycle has a high enough innovative factor and market relevance
Distri-net	Assembling and distributing company	A bicycle which can be assembled relatively easily	Sees possibilities in "adjustable packages" where the bicycle is adjusted to sub-target groups	Will assemble and distribute the product
Jee Ann Bicycle CO.	Producing company: Produces the frame and does part of the assembling	Individual elements of the product are available or possible to produce	Needs to be able to produce the product and sees possible difficulties when special parts are used	Will produce the product once delivered
Elderly cyclists	Main target group. Reduced balance, unsure of movements	A bicycle which is easy to use and gives a save and balanced cycling experience	Needs the bicycle to keep balance in unsure situations	Will only buy and use the bicycle if they feel it balances for them and has a big enough advantage against stigmatizing balancing bicycles
Novice cyclists	Lack of knowledge on how to balance a bicycle	A bicycle which helps them keep balance but looks good and non-stigmatizing	Needs the bicycle to stabilize	Will only use the bicycle if it is easy to use and helps with balancing
General cyclists	Use roads and cycling paths in collaboration with the target group	A product that does not obstruct with normal cycling traffic	Can hinder the cyclist and can be hindered, will have prejudices based on the design of the bicycle	The bicycle should be non-stigmatizing and may not (largely) exceed sizes of normal bicycles, such that it fits within traffic
General traffic	Uses the roads at different speed ranges	A product that does not interfere with normal traffic	Can stigmatize users and cause dangerous situations if the bicycle is developed incorrectly	Bicycle will not be allowed if it is unsafe for other traffic
Engineer	Design and engineering skills	Want to develop a solid and useful bicycle which gives users a safe cycling experience	Sees potential how the bicycle can be improved and has the most knowledge within the design process	Will design the bicycle and make decisions in accordance with Beixo
University of Twente	Coordination of the master assignment	Wants to see a clear project with results of the engineer	Can support the engineer in the decision and design process	Assures that the design project is of a certain level, will support the engineer in making decisions

1.5. Cause-effect diagram of the problems

To get a clear overview of the problems and their effect, Figure 8 shows a cause-effect diagram of problems elderly are faced with and their effects on cycling and health. With this overview, it can be defined where problems arise, and which can be solved within the field of bicycle design. This helps with formulating a correct assignment description.

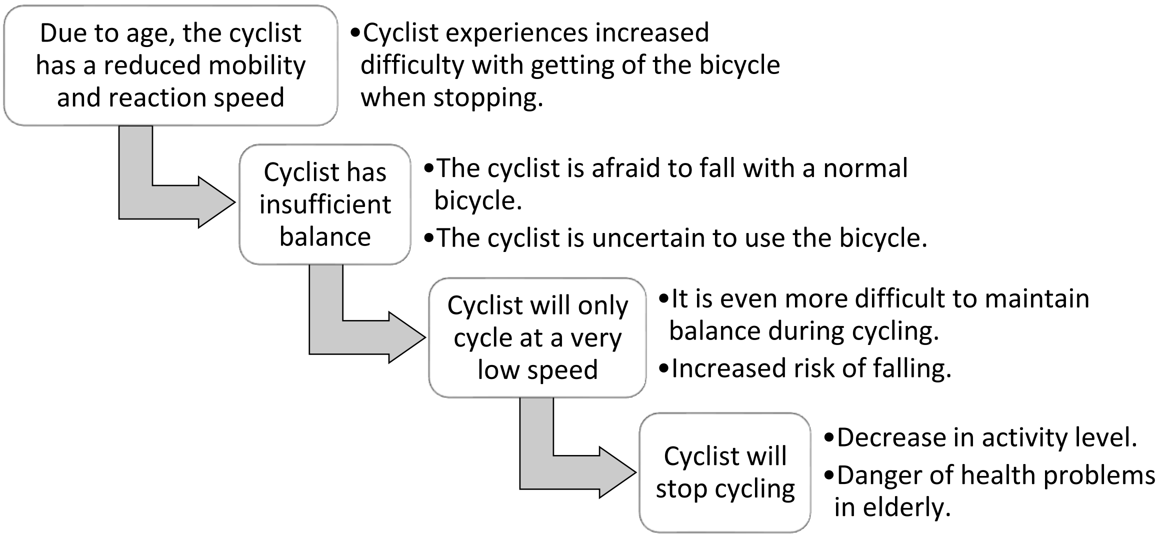


Figure 8 Cause-Effect diagram of problems

2. Design assignment

The design assignment is to realise the stabilizing mechanism of the trike which should lean in the turns but should not fall over at low speed. The design will be based on the models as have been developed by Lugert and Oosterlaken, which have a functioning steering mechanism, and the focus of this assignment will only be on the stabilizing mechanism, which operates with both an electric and a non-electric bicycle. This stabilizing mechanism will be designed for elderly people, who have a reduced balance and are apprehensive to fall. Thus, it is important that the trike is intuitive to use and gives the cyclist a safe experience.

In the problem analysis, it is described why the bicycle should have freedom of tilt in the turns, as unstable situations would arise elsewise. Also, it is explained why balancing is less difficult with higher speed and hence balancing support is mostly required at low speed.

Based on this information, a list of requirements can be set up, which should be fulfilled during the design of the new or adjusted dynamic stabilizing mechanism of the trike.

3. Requirements

Based on the problem analysis and wishes of the different stakeholders, requirements have been defined. Requirements are defined for the stability of the system and what it must be able to hold, for the model and what the property limitations are and for cycling, as this is a main function of the trike which must be fulfilled.

Stability

1. Maintain stability of the combination of bicycle and cyclist at all times.
   - The centre of mass should preferably be positioned to the front and as low as possible. This should be accounted for in the weight distribution of the bicycle.
2. Keep the bicycle upright when at low speed (below 10 km/h).
   - While kept upright, the bicycle may have a deviation of 2° from the vertical position. This is based on the lean angles as discussed in section 1.2.1. In this case, the centre of mass of a regular bicycle stays within the base of support, and the bicycle will not fall over if steering is locked. By keeping this tilting angle as the limit, the experience of riding on this trike will be as close as possible to riding on a normal bicycle.
3. Keep the bicycle upright when braking to stop.
   - When a braking acceleration is measured above 1.5 m/s^2, the bicycle should be kept upright as is the case for requirement #2.
4. The system which keeps the bicycle upright has to activate itself as fast as possible, as soon as it is switched on. This should at least be within 0.2s. After this time has gone by, the bicycle should be fixed in its' vertical position.
5. The system should require only little energy, if any, to be activated. No large battery should have to be carried on the bicycle to power the system.
6. The system has to be strong enough to, once fixated, absorb movements in the frontal plane and around the sagittal axis, which can result in large moments. These movements need to be absorbed, to keep the bicycle fixated upright, even when a person is unbalanced and moving sideways with his upper body.
7. The bicycle should stay upright (i.e. balanced) when standing still. The system should have as little play as possible, but it may not result in a deviation above 1° from the vertical axis.
   - The system should not tilt unintendedly.
8. It must be confirmed that both wheels are in exactly the same position when the system is fixated.
9. The bicycle should remain stable in turns, also at higher speed. Therefore, it should be able to account for centripetal forces.
10. The bike should be able to tilt in turns.
    - In order to tilt freely, an angle of 30° from the vertical position is required. As such, the physical dimensions of the bicycle cannot cause an instable situation in turns.
11. All three wheels should maintain contact with the ground in turns, both at low and high speed and with and without additional load in the front.

Model properties

12. It should be possible to fixate luggage up to 50kg on the front of bicycle (e.g. in a basket).
13. The bicycle should have a bike rack at the back to take along additional luggage.
14. The maximally allowed dimensions of the bicycle are 165 by 75 cm (length by width).
15. The bicycle should make use of an easy and intuitive steering method.
16. The bicycle should have a step-in between 25 and 30 cm of height.
17. The bicycle should be usable for people of different length. This is between 1.60 and 1.80m.
18. The bicycle should be usable for people with a weight up to 100kg.
19. The bicycle has to be usable with and without motorized cycling support.

20. With motorized support, the bicycle may cost around €3500,-.
21. The used materials may not wear out within 3 years with frequent use (above 3 hours per week).
22. The system should use durable materials which are easy to obtain on the market.
23. If there are any parts that wear out, these should be easily replaceable.

Cycling requirements

24. The bicycle should transport the cyclist in a safe and comfortable matter.

4. Concepts and selection

4.1. Function analysis

To allow for an extensive concept phase, general functions have been determined, which describe the actions that are needed to fulfil the design assignment and corresponding requirements.

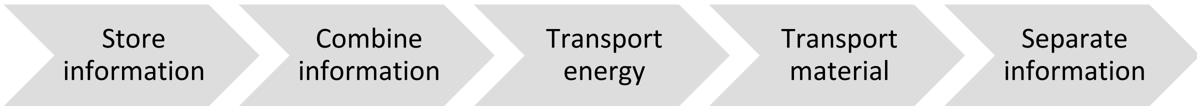


Figure 9 Function analysis

Store information: Receive information on the bicycle behaviour, which encompasses the cycling speed. Acceleration, lean angle, lean angle velocity, steer angle and other variables can be accounted here as well, in case this is required for transforming the material.
Combine information: Combine the obtained information determine whether and if any action has to be taken, and if so, how much stabilisation of the bicycle is needed. If the cycling speed has reduced below 10 km/h, stabilisation has to be activated. Also, when the brakes are pressed and the deceleration is above 1.5 m/s^2, stabilisation should be activated as well.
Transport energy: Transport energy to get a change of position, such that the required stabilisation can be created. In a practical matter is this the preparation for or activation of the stabilisation mechanism of the bicycle, such that stabilisation can take place.
Transport material: Adjust the construction to realize the required stabilisation of the bicycle. Here, the stabilising mechanism is actually activated and functioning. This means that the bicycle is kept upright and the lean angle is limited to 2° (see requirement #2).
Separate information: Separate information from the system to analyse when the stabilising mechanism is not required anymore, which is when the bicycle's speed is above 10 km/h. If this is the case, the processes of energy transport and material transformation are reversed and the stabilizing mechanism is switched off.

After a more detailed explanation of all six functions, isolated solutions can be found and combined to multiple concepts, where it is convenient to change parts with the same function. The established concepts will then be evaluated for the requirements.

4.1.1. Function 1: Store information

First, information must be gathered and stored. Cycling speed and deceleration-recognition are required to run the system. Both can be measured with the rotation frequency of the wheel, which is the standard method to measure speed with a cycling computer.
Rotation can be measured with a small generator such as a bottle dynamo, in the wheel axis, or with a magnetic sensor. To measure the rotation in the wheel axis, specific hubs need to be used. Using a dynamo will result in reduced reliability in wet conditions, because of variations in the friction.[24] By using a magnetic sensor with magnets in the spokes, there are no problems with changing weather conditions. As with a measurement in the wheel, the position is measured every rotation, but the accuracy can be improved by adding magnets in an even distribution around the spokes. This method is easy to apply to any bicycle and does not require specific wheel axis with build-in sensors.
Different types of magnetic sensors can be used. An agreement between all the sensors is that they react to a magnet which passes the sensor. As a benefit, accuracy can be improved by adding more magnets, which are fixed to spokes in the wheel. The Reed sensor is the most common type of magnetic sensor, as it is small and has a fast response. Also, the sensor has a protection over the reed switch to protect it from temperature changes and other environmental influences.[25] A Hall effect

sensor can also be used but requires an active circuitry.[26] For this reason, the Reed sensor is preferred for measuring cycling speed.

Solutions:

- Generator
- Wheel axis
- Magnetic sensor in the wheel
    - Reed sensor
    - Hall effect sensor

4.1.2. Function 2: Combine information

Information gathered in function 1 will fulfil the requirements to activate or de-activate the stabilisation mechanism. This will result in a switch which activates the transportation of energy. This function is decisive for the activation of energy transport.
To activate the mechanism and continue to the third function, one of two requirements must be met:

1. Cycling speed is below 10 km/h. This is based on lean angle variations, as have been described in section 1.2.1. A cycling speed of 10 km/h corresponds to 0.60s per rotation for 20” wheels. This means that every 0.6s, the cycling speed can be recalculated. To increase the accuracy of the measurements, multiple magnets can be used to decrease the time between two pulses (Δt). For example, if 6 magnets were to be used, the system is activated if $\Delta t > 0.1s$.
2. Deceleration is above 1.5 m/s². This means that the acceleration (a) is below -1.5m/s², which, translated to time between pulses, can be calculated with equation 4, where t_1 and t_2 are the second-last and last Δt respectively and L is the circumference of the wheel, corrected for the number of magnets.

$$a = \frac{v_2 - v_1}{t_2} = \frac{(t_1 - t_2)L}{t_1 {t_2}^2} \quad (4)$$

The bike computer will measure if one of both requirements is fulfilled. If this is the case, the switch will turn on and function 3 will be activated, directly followed by function 4 and 5.

4.1.3. Function 3: Transport energy

The way in which energy is transported to create the power for transforming the material depends on the transforming material. Therefore, different solutions are gathered, of which is known that the compatibility with certain solutions of function 4 is limited. Blocks have to be moved from one place to another, to switch between a locked low-speed state and an unlocked high-speed state. To do this there are two options: active locking and active unlocking. Active locking means the system is unlocked in its relaxed (high-speed) state, but energy is supplied to lock it during slow driving and standing. Active unlocking means energy is supplied to unlock the system during high speed. This means that energy supply must remain active as long as the system is in its high-speed state. For safety reasons, the second method can be preferred, as the bicycle will stay locked upright in all situations, up to the moment where it is up to speed. However, this is of high influence on the solutions which are possible and when the higher transporting energy is required.

Solutions:

- **Clamping a disk brake**
  A disk brake can fixate an element which is elsewise free to slide through. It can open and close based on a force which is transmitted through a cable or hydraulically.[27], [28]
- **Spring & locking mechanism**
  Tightening or fixating a spring (coil or air spring) can put one ending at a desired position. However, the locking mechanism needs a manual activation or push-release.
- **Spindle**

Rotating a spindle can change the position of a nut, which can hold the position or range of motion of movable parts.

- **Lock damper**
  A normally damped but free movement can be blocked by using a lock on the damper, as is used in bicycles with lock-out suspension forks. Although this is a solid solution which can handle varying forces, the damper can only be fixated in 1 position, when the damper is expanded, and it needs regular maintenance.
- **Tighten a cable**
  Tightening a cable which is loose when at rest can decrease the range of motion. A cable can be tightened by a pulley block.
- **Fixate a ball-and-socket joint with a thumb screw**
  Ball-and-socket joints, which are already available on the connections between the wheel axis and the wheels can be fixated with a thumb screw. By fixating ball-and-socket joints, no rotation is possible, and a rigid system arises.
- **Pin pull through**
  As with the thumb screw in the previous solution, a pin can be pulled through any point of interest to prevent movement between two parts. A requirement to enable this would be that the points of interest are lined out when the pin in pulled through, as it will not be able to fixate elements which are not aligned.
- **Hydraulic cartridge**
- **Air pressure**
  Translation of a blockade could be realised by air pressure. While cycling, front wheel rotation could be transformed into air pressure, which could possibly push a blockade apart. There are two elements which should be considered. First, only limited forces can be realised by this system and second, the system can only function with sufficient cycling speed, meaning the stabilising mechanism will always be active (i.e. a blockade is not pushed apart) when no or limited front wheel rotation is available.
- **Pulley**
  With a pulley, elements can be brought together.

4.1.4. Function 4: Transform material - transport

After energy is transmitted, the first function of the activated system is to bring the bicycle in a vertical position. If this would not be done, the bicycle could be fixated in a tilted position, resulting in an unbalanced system, which does not provide the reliability which is required by the target group and results in a high probability of cyclists tipping over and/or putting a foot on the ground. i.e., exactly the actions which this system should prevent.

Considering the steering mechanism, there are three possible connections which can prevent tilting of the bicycle when blocked, as can be seen in Figure 10. The first connection is between the upper wheel axis (green) and one of the steering axis (blue), the second is between the upper and lower wheel axis (green) and the third connection is between the wheel axis (green) and the stub axles (red), i.e. the ball-and-socket joint. To bring the bicycle in a vertical position, at least one of these connections should be fixated in its neutral position. Therefore, solutions will be presented for each of these connections. As no solutions were found to obtain a vertical position with the ball-and-socket joint, this connection is left out.

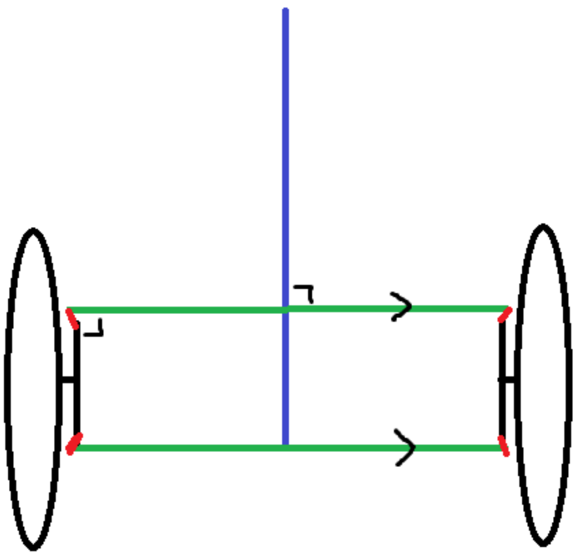


Figure 10 Connections which change when tilting the bicycle in their neutral positions.

Connection between the steering axis and one of the wheel axes

In a neutral position, the steering axis and upper wheel axis are in a perpendicular position. Therefore, this principle should put two beams in a perpendicular position. Solutions 1 and 2 are based on this principle.

1. In this solution, there is a triangular connection between the edges of the upper wheel axis and the steering axis. The diagonal connections are springs, which elongate or shorten while tilting. To put the axis in a perpendicular position, the connection to the steering axis is a ring, which can be moved upwards. If this ring is at its highest position, both springs are fully stretched. As a consequence, the distances AB and BC will be the same. Because springs are used, there might be other solutions with a higher accuracy. The ring can be moved upwards with an external blockade.

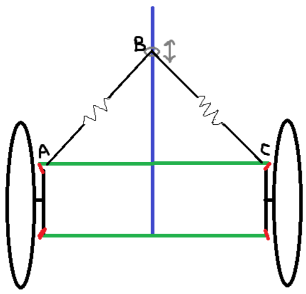


Figure 11 Solution 1

2. In this solution, the steering axis is splitted into two beams. On each beam is a ring connected to the edges of the upper wheel axis. When inactive, these rings can move free on the bars. In function 4, the rings are pulled up- or downwards to the same height. If both rings are at the same height, the bars are perpendicular. This can be realised by pulling both rings together with tightening a connection between them, or by direct control of the rings' position, thus pushing them up/down to the same level with a blockade. To block this system the rings must be fixated at the same height. This can be done by
    i. Clamping or fixating the rings to the bars.
    ii. Keeping up an external blockade, which prevents both rings to move up (or down).
    iii. Keeping a tight connection between both rings.

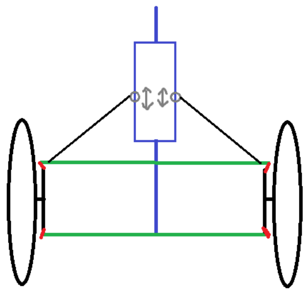


Figure 12 Solution 2

Connection between the two wheel axes

The wheel axes together with the hub function as a parallelogram. The neutral position is obtained by enforcing this parallelogram into a rectangular shape. Solution 3 and 4 are based on this principle.

3. In this solution, two additional connections between both wheel axes are made. The connection is fixed on the upper wheel axis but has freedom of movement in the sideways direction around the lower wheel axis. By moving an external blockade on the lower wheel axis, this freedom can be limited until the bicycle is fixated in the neutral position.
   As a disclaimer it should be stated that the blockades can be positioned outside of the connections as well as between the connections. Also, one connection could be used with two blockades around it, which would theoretically give the same result.

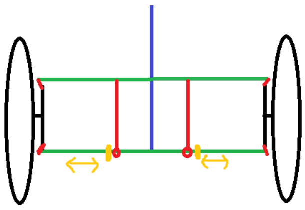


Figure 13 Solution 3

4. In this solution, two additional connections between both wheel axis are made as well. The connection is fixed on both wheel axis but can stretch because it is made of a damper. By pressurizing both dampers evenly, the bicycle will be fixated in a vertical position, as this solution uses a w-shaped upper wheel axis. Because a w-shaped upper wheel axis is used, the connection itself does not function as a parallelogram, however the wheel axis and hub are.

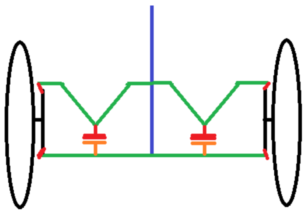


Figure 14 Solution 4

4.1.5. Function 5: Transform material - fixation

As soon as the bicycle is in a vertical position, it is important to fixate the bicycle as such and prevent a change in tilting angle. As such, it is presumable that function 4 and 5 are fulfilled by one and the same solution. However, as this does not necessarily have to be the case and the functionalities of both functions are different, they are treated separately as well. Function 5 can be solved with the same three connections as function 4. All solutions of function 4 are solutions for function 5 as well. These will not be explained again but are completed with other solutions, again presented per connection.

Connection between the steering axis and one of the wheel axes

5. In this solution, a rigid cable is connected to both sides of the upper wheel axis and is lead through a ring at the steering axis, where it can slide when then bicycle is tilted. By closing this ring, the cable is fixated, and so is the relative position of both axes. Fixating the cable can be done by
   i. Clamping the ring to the bar.
   ii. Fixating the cable by screwing it on.

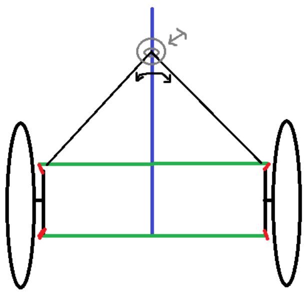


Figure 15 Solution 5

Connection between the two wheel axes

6. In this solution, based on solution 3, a wide ring is used as a connection to the lower wheel axis (see … in red). This is done to prevent friction on the moving parts. By decreasing the diameter of the circle (red to orange), sideward movement of the lower wheel axis can be prevented. However, it must be guaranteed that the steering axis is vertical before the parallelogram is fixated. The diameter of the ring can be changed by
   i. Pressurizing it with air as is done with tires.
   ii. Clamping the ring to the bar.

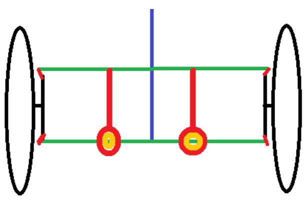


Figure 16 Solution 6

Connection between one of the wheel axis and wheel hub

7. The wheel axes are connected to the hubs by a ball-and-socket joint. In normal situations this ball-and-socket joint has limited friction and can rotate in any direction. However, if the joint would be fixated, a rigid body is obtained, and the system is fixated. A simple but efficient method to fixate a ball-and-socket joint is to use a thumbscrew.

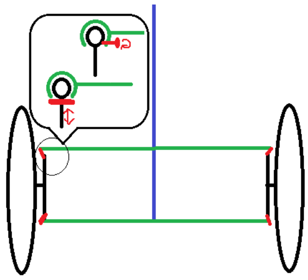


Figure 17 Solution 7

4.1.6. Function 6: Separate information

This function is based on the solution of function 1 and 2. However, as the system has to be de-activated here, the requirements are different. Also, both requirements must be fulfilled to switch off the system automatically.
Requirements:

1. Cycling speed is above 10 km/h
2. No deceleration

For safety and manoeuvrability, a manual off-switch can be added as well on the steering bar. This could be done with an ordinary switch, which you have to switch off by hand and overrules the requirements. To maintain high enough safety standards, the switch must have a certain complexity or resistance, to prevent accidental switch-offs. Also, by shutting down the electric systems of the trike, the switch should be reset, such that the system is active the next time the trike is used.

4.1.7. Function 7: Transport energy back

Function 7 is the reverse action of function 3 and follows function 6 in the same way in which function 2 is followed by function 3. This means that by principle, function 7 should be the reverse of function 3 and choosing another solution would be a waste of resources and addition of unnecessary weight to the system. The list of solutions for function 6 therefore is the same as for function 3, but by defining function 3 in the morphologic scheme, function 6 is defined as well and thus no separate column needs to be added.

- Spring / damper has to be put back into its' original position.
- Pull spring with cable, "connected" to the turning frequency of the wheels.
- Unlock damper and let tilting forces push it in again. This would only require an unlock and does not need additional forces/energy supply.
- Get energy out of the wheel, e.g. with a dynamo.
- Relax the disk brake.
- Relax the pulley.

4.2. Concept generation

From section 4.1 it can be concluded that the most variability exists in function 3, 4, 5 and 7. Function 1 has 4 solutions of which one can be chosen independent from the other funtions. Including function 1 in the concept overview would increase the complexibility unnecessarily and solely give more or the same options. Therefore, the preferred solution of function 1 will be chosen in section 4.5. Function 2 and 6 concern the computation and analysis of data, which is done through software which will be developed at a later point. Function 7 is the reverse action of function 3, thus requiring the same method to be used. Therefore, function 2, 6 and 7 do not need to be included in the concept overview. If function 4 and 5 are fulfilled with the same solution, only one actuation mechanism is required. Based on the solution of function 4, a solution follows for function 3. If function 4 and 5 are solved with a different method, two actuation methods will be given for function 3 as well. Therefore, a list of concepts with possible combinations for function 3, 4 and 5 has been set up, which can be found in Appendix I.

4.3. Testing of the requirements

Each concept, as defined in section 4.2, is tested for the requirements which were set up in Chapter 0. These requirements are weighted according to their relevance on a scale of 1 – 5, where 5 represents the most imporant requirements. Each concept is then evaluated for the relevant requirements. Requirement 12, 13, 15, 16, 17 and 24 have been left out of this analysis, as these represent characteristics which have already been assessed and defined during previous phases of the trike development by I. Lugert and C. Oosterlaken [21], [22]. The assessment of the requirements can be found in Appendix II and will be discussed in section 4.4.

Regarding requirement 5, "The system should require only little energy, if any, to be activated. No large battery should have to be carried on the bicycle to power the system", it was soon discovered that it would be difficult if not impossible to develop a completely unmotorized system. Therefore, the evaluation of this requirement is somewhat more delicate than might have been expected beforehand.

4.4. Results and evaluation

Based on the results of the requirement assessment, it can be concluded that none of the concepts completely failed the requirements. However, there are a couple of requirements which imply to be more critical, and have a poor assessment. This is the case for requirement 5, 21 and 23, which all have a score of "1" in multiple concepts. This concerns 1) the energy consumption of the system because of the motorized solutions 2) the wear out of materials within 3 years due to moving elements and repetitive movements and 3) the ease to replace worn materials, as for some moving elements, it will be required to disassemble the entire front part of the trike before it can be replaced.

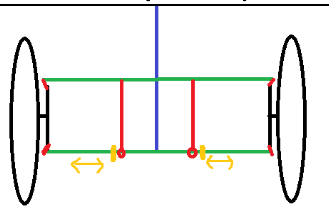
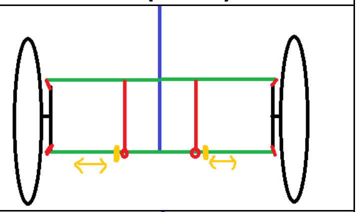
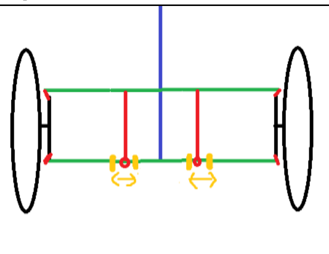
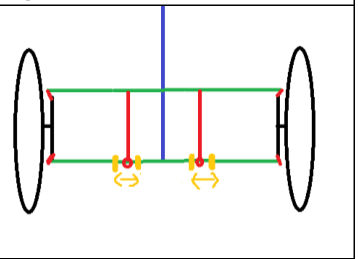
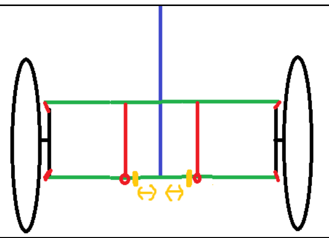
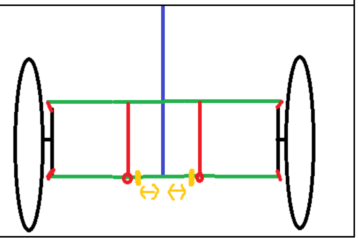
The five best results from the requirement testing are presented in Table 3. In descending order, they scored a total of 225, 224, 221, 219 and 216 points. Comparing to the other results, it is pressing that in general a connection between the two wheel axes is better evaluated than a connection between the upper wheel axis and the steering axis or wheel-fuse. A blockade which can be moved is expected to give the best results. It should be noted that this blockade can be placed both medial and lateral from the connection between both wheel axes.

Concept 17, 18 and 19 contain one method to fulfill function 3, whereas concept 24 and 25 require two different methods. This will increase the complexity and might increase the chance of failure as well, as there are more components which can decline. Although concept 17 and 24 do not differ that much in score, this makes concept 17 preferred over concept 24 logistically.

As stated before, there are 3 main requirements with low scores. It is remarkable that concept 25, which is ranked third, still has a score of 1 on requirement 5. Concept 24 did not score much higher, but is expected to be a bit less energy consuming and more efficient. This shows that a lack of energy efficiency theoretically does not directly disqualify a concept.

Concept 17, 18 and 19 are developed on a similar basis, with main differences in the energy transport of function 3. Opposite to concept 18 and 19, concept 17 will have a very high accuracy and because of this minimal margin, the stabilization can be adjusted very accurately. This makes concept 17 the preferred option of all concepts, even though the scores within the top five do not differ that much.

Table 3 Top 5 weighted concepts.

Rank	Concept	Function 3	Function 4 (vertical)	Function 5 (fixate)
1	17	Spindle moves blocks to the inside		
2	24	Medial blocks: lock damper Lateral blocks: spring & locking mechanism		
3	25	Medial blocks: lock damper Lateral blocks: pulley		
4	18	Lock hydraulic damper between both blocks		
5	19	Spring & locking mechanism in between		

4.5. Concept selection

As described in the previous section, concept 17 is chosen to be the best concept and the expected highest accuracy for controlling the system. For the final concept, a solution should be chosen for each individual function.

Function 1

The Reed sensor is chosen as the preferred solution because it is well protected for external influences, is small, has a short operating and release time and does not require an active circuitry.[25], [29] Reed sensors vary in cycle durations, based on the operating time and release time. Typical operating times are in between 0.2 and 1 ms, and release times are in between 0.05 and 0.3 ms. For example, the MK31 of Standex Electronics has operating and release times of 0.2 and 0.15 ms respectively, with a cycle duration of 0.35 ms. The MK17, also from Standex Electronics, takes 0.6 and 0.05 ms respectively, with a total cycle duration of 0.65 ms.[29], [30] Although the release time is much shorter, this does not define the cycle time definitely.

Function 2

Information will be combined with a control system, which will be explained in section 5.4. Boundary conditions are presented in the requirements and in the function description.

Function 3

Energy transport will be done with a rotating spindle, which moves blocks to the inside. Two spindles should be used, which are driven by a motor in the center. The mechanism can be mirrored in the middle using a bevel gearbox with 90° angles, therefore the left and right spindle should have opposite threads, such that both blocks will move in the medial direction with a rotating motor and spindles.

Function 4

Material transformation for transport will be done with sub-solution 3 as was presented above (see Figure 18), a connection between the two wheel axes together with external blockades on both wheel sides. The blockades are fixated to the spindle, and therefore provide high rigidity and can withstand high counterforces to fixate the trike in the neutral or upright position. The "red" part will be refferred to as the connector, the "yellow" part as the blockade (see Figure 18). Thus, the spindles and blockades will be the moving parts, whereas the connectors are rigid to the wheel axes and the wheels.

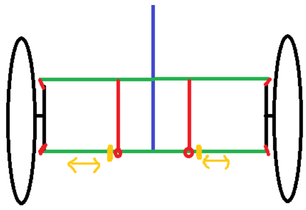


Figure 18 Sub-solution 3

Function 5

Material transformation for fixation will be fulfilled with the same solution as function 4, as this solution appears to be solid and adding another system is foremost an increase in cost and complexity, and does not improve the functionality of the system.

Function 6

Information will be separated with a control system, using the boundary conditions as presented in the function description.

Function 7

Energy will be transported back by activation of the motor and rotation of the spindles until they are in their original position. The system presented in function 3 will be used to do so, such that the blockades are non-restricting once the cycle is completed.

5. Prototype description

5.1. Design of the prototype

Based on the concept choices made in Chapter 4, a prototype is designed with the solutions as are described before. The design of the physical prototype focuses on functions 3, 4 and 5 and is based on the trike frame as developed by C. Oosterlaken, which included the two wheel axes. Three things must be considered when designing the prototype; positioning of the spindles with blockades, connectors between the wheel axes and the motorized support.

First, positioning of the spindles should be evaluated. Based on the function, i.e. move blocks in a horizontal direction, it can be stated that the spindle must be parallel to both wheel axes.

Second, the blockades need to be connected to the spindle (see Function description in Section 4.5) and one of the wheel axes. To get a wide range of movement, the spindle and wheel axis to which the connectors are fixated should be separated as far as possible. Thus, fixate the connector to the upper wheel axis and the spindle around the lower wheel axis or vice versa. The spindle could thus be positioned within the lower wheel axis, which would also be beneficial for protection of external (weather) influences. However, this means that the motorized support has limited space and must fit within the wheel axis as well, resulting in either a limited set of optional and complex motors or a very large wheel axis.

To prevent both of these problems, the choice is made to place the spindle below the lower wheel axis, which makes it possible for both wheel axes to have the same dimensions, i.e. simplify the production, reduce their weight and have have a better chance at finding the right motor which fits within the construction. Covering the spindles for stain should be discussed afterwards.

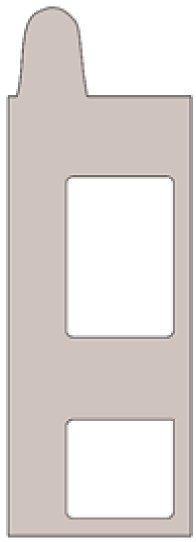


Figure 19 Connector with fixation to upper wheel axis and holes for the lower wheel axis and spindle.

Knowing the position of the spindles, the connectors can be placed second. Because these now must be fixated to the upper wheel axis and at the spindle below the lower wheel axis, the connectors have to get around the lower wheel axis. To do so, a construction has been developed with a rectangular shape with a smaller fitting at the top. As can be seen in 19, space is left out for the lower wheel axis and the spindle, and the top side can be brazed or welded inside the upper wheel axis.

Third, the positioning of the motor is assessed. There are two spindles at the left and right side, which drive blockades in opposite direction, i.e. mirrored in the middle (see Figure 18). This can be realised by either using two motors, or threading the spindles differently. With the latter, both spindles can be connected to one motor, which would remove the possibility of synchronization errors between the motors. Using only one motor, it can be placed either at the end of a spindle or in between both. Placing the motor in the middle is the most stable method, as the weight is centered, both spindles have the same momentum to the outside and shear forces will be the same on both spindles. Although the center is the most stable position for the motor, this brings a challenge in where to position the motor, as there is a connection between the wheel axes and from the wheel axes to the back of the trike, and because there is only limited space between the lower wheel axis and the ground, which can easily damage the motor with regular contact. Because of both reasons together with the position of the spindles, it is chosen to place the motor below the lower wheel axis in longitudinal direction, i.e. perpendicular to the spindles and as close as possible to the lower wheel axis. Using a gearbox, the motor can be connected to both spindles.

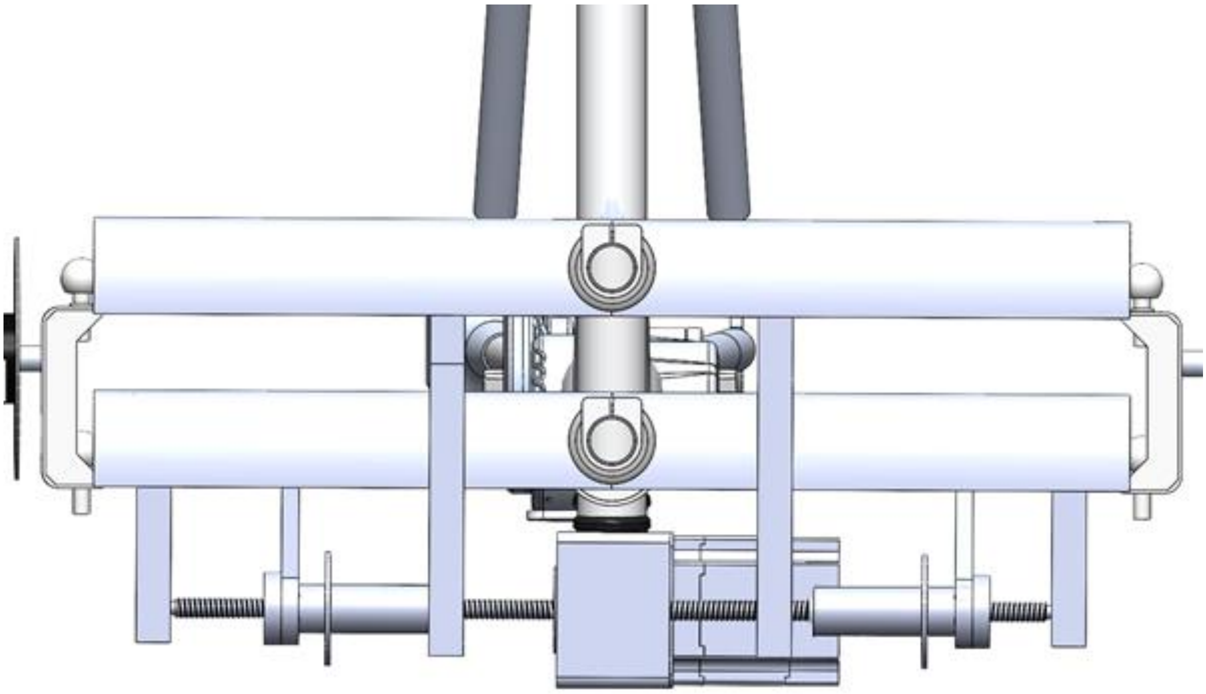
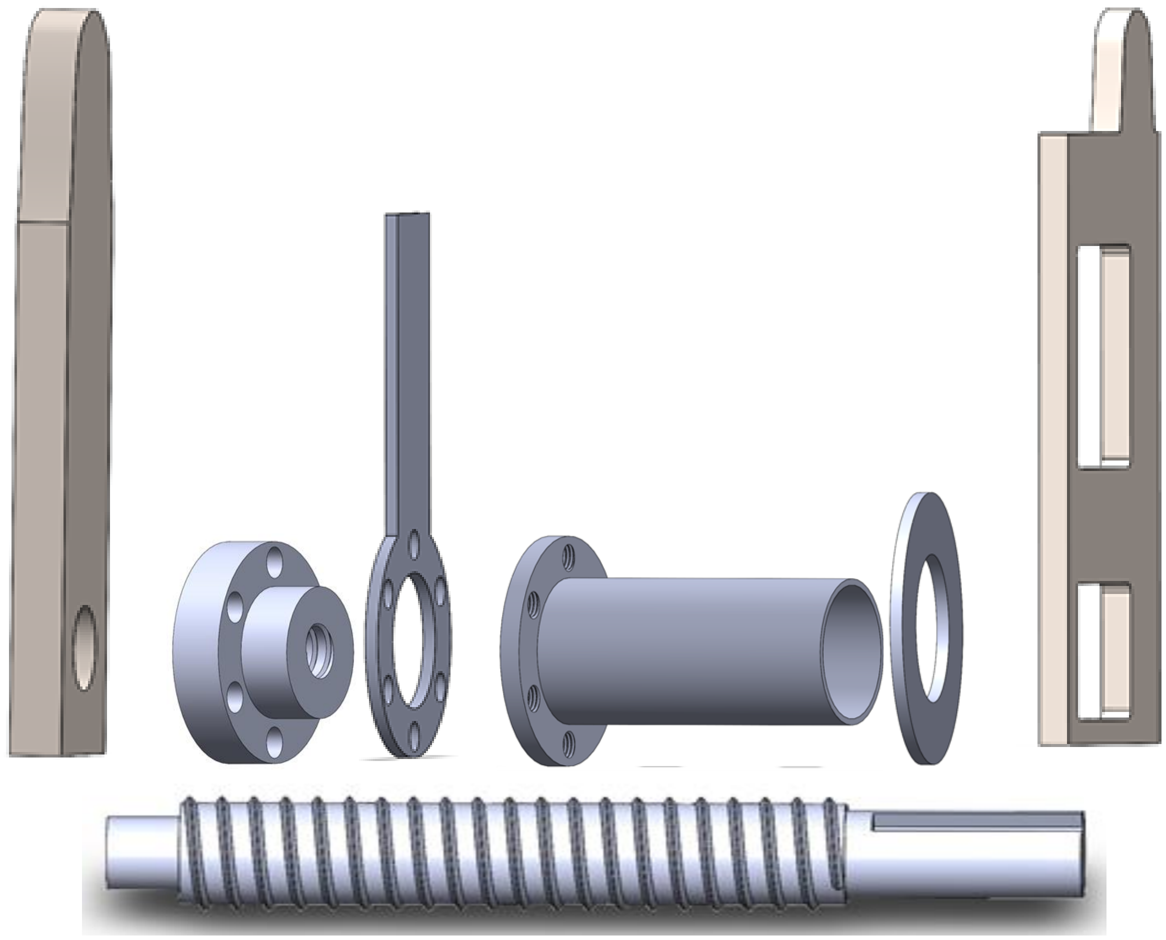


Figure 20 Lay-out of the stabilizing mechanism including all elements as explained in Figure 21.

With the position of these three elements defined, the basic design of the stabilisation mechanism is known and will be as is shown in Figure 20. The elements below the lower wheel axis form the stabilizing mechanism and are named and shown in more detail in Figure 21. Exact dimensions are given in Appendix IV. By moving the motor (block in the middle of Figure 20, the spindles will rotate, causing the nut, position fixator and blockade to move. The position fixator nut is connected to the nut by screws. The blockade can move freely around position fixator nut part 2, but will most likely be closest to the outside as possible. The system is active when the blockade is pressed against the connector.

It can be seen that the position fixator nut part 1 is fixated in a vertical position by the lower wheel axis. This is done to prevent rotations and ascertain an effective translation of the blockade when rotating the spindle. The translation can be performed with a flange nut or a hex nut, which both have the ability to connect to a non-rotating external element such as the blockade to the spindle. Both types of nut fixate to the blockade in a different way. The flange nut is connected to the blockade by screws which completely fixate the connection and do not allow any form of rotation or axial translation between the nut and the blockade. The hex nut can fixate the blockade if the inner circle of the blockade is a negative of the hex nut, such that these hexagonal forms fit exactly and no rotation is possible. Because they need to slide over each other to connect, translation can only be limited at one side, which will most likely cause problems if the spindle is rotated backwards to give back tilting freedom to the trike. This is the main reason why the flange nut is preferred over the hex nut, even though the hex nut is smaller than a flange nut and thus adds less weight.



Description of the elements

Spindle positioner	Flange nut	Position fixator nut part 1	Position fixator nut part 2	Blockade	Connector
Spindle with at the left place for the spindle positioner, at the right a fitting for the motor / gearbox and a 22x5 lead screw.					

Figure 21 Detailed design of the working parts of the stabilizing mechanism in order. The spindle is shown enlarged.

Having defined how everythinig will be fixated, there is a rather rigid system. It is evaluated that with this method, the transfer of forces to the steer is very direct and might be experienced as incomfortable by the cyclist, because the trike will react quickly and not give the user time to adapt to the changes in tilting freedom or the pushback into a vertical position. To prevent this from happening, a spring can be placed between the connection on the spindle and the actual block on the blockades. This spring should be rather stiff and have little expansion, just such that the zero tolerance is removed. To resolve this problem, different kind of springs can be used. The first option is a standard helical compression spring (Figure 22a), which has a relatively high free length and low maximum load which can range between 0 and 7350N. However, as the spring will be placed around the “position fixator nut”, which has an outside diameter of 28mm, the inside diamter of the spring must be bigger than this. This results in a load range between 4 and 3738N. The second option is a die spring or heavy duty spring (Figure 22b), whose free length is approximately the same as for the helical compression spring, but which has a higher maximum deflection load. The deflection load of die springs ranges between 60 and 11400N in general and between 2912 and 5928N for the specified diameters. The third option would be a disk spring (Figure 22c), which can reach even higher loads but has a much smaller free length, because of the design of the spring. In general, the force a disk spring can handle ranges between 20 and 383000N, and with the given minimum diameter this reduces to a force between 136 and 33653N, which is still more than 5.5 times as strong as the die springs, but with a free length between 1.5 and 8.2mm, which is less than 10% of the length a compression spring or die spring would have.[31]–[33]

Figure 22 Spring types: a) helical compression spring, b) die spring, c) disk spring.[31]–[33]

Because of the limited range of motion which is available on the spindles and wheel axes, the disk spring would be the best option to use. In this way, limited elasticity can be provided without highly increasing the inaccuracy of the system (by forcing the spring to maximally compress), but still give some delay to the user of the trike.
Disk springs can be stocked to increase the unloaded length and the nominal load. Adding two springs in the same direction adds the force, adding them in opposite direction increases the length but does not change the force required for compression.[34]

The chosen solution requires multiple holes within the connectors, which present a challenge for the strength of these connectors. Therefore, it is important that these connectors are made of a material which can give the connectors a high stiffness. To develop the entire stabilizing mechanism, different materials can be used, but for the realisation of a prototype, the choice is made to not use multiple materials, but to simplify and stick to one single material. For calculations, steel will be used, with a density of 7800kg/m^3. However, the trike frame itself (excluding the stabilizing mechanism) could be made out of 6061 aluminum alloy with a density of 2700 kg/m^3. [35] This is the material traditionally used for producing bicycle frames. [36]
Having defined the final design of the trike (see Figure 23), it's volume (excluding wheels but including the motor) sums up to 4.350 dm^3. If everything was to be made out of steel, this would result in a total weight of 33.930kg, whereas the total weight would reduce to 16.700kg if only the stabilizing mechanism including the two wheel axes was to be made out of steel (7.577kg) and everything else from aluminum (9.122kg). More detail on the design of the trike can be found in Appendix III.

Figure 23 Final design of the trike with stabilizing mechanism.

5.2. Forces and moments

In this section, the forces and moments acting on the setup as a whole are discussed. The setup consists of both the trike and the cyclist.

In section 1.3, the Base of Support was defined for the existing device. With the changes that have been made, the BoS on the ground has changed as well. Using the width and length of the trike as shown in Figure 24 and the same CoM as was used in section 1.3 (although the CoM including the cyclist will have shifted forward slightly because of a different weight distribution in the trike), the tilting angle Θ at which the CoM is within the BoS is 14.3° (see equations 5 and 6). Up to this angle, the system will be able to stabilise the trike. In other cases, the trike will tip over if the system would try to pull it up.

$$width_{CoM} = \frac{402.5*580}{1181} = 197.671mm \quad (5)$$

$$\theta = \sin^{-1}\frac{width_{CoM}}{height_{CoM}} = \sin^{-1}\frac{197.671}{800} = 14.305° \quad (6)$$

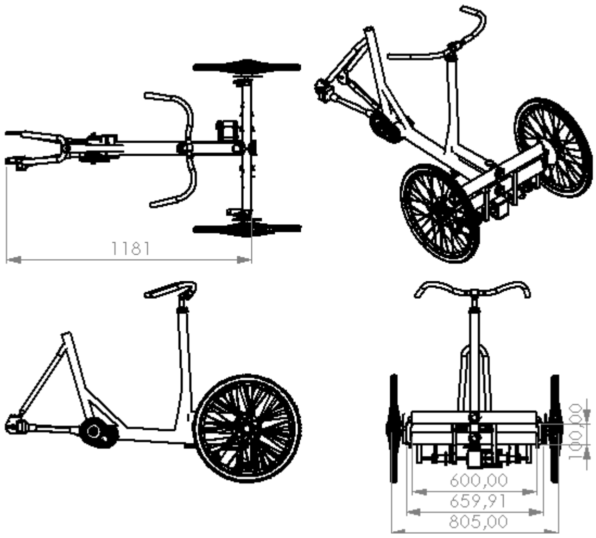


Figure 24 Sketches of the final design in front, up and sideview with dimensions given in mm.

Knowing the critical tilting angle, the required system force F_s to uphold this critical position can be calculated using equations 7 – 12, as the systems moment must equate the physical moment to remain in any given position with the CoM within the BoS. Distances between the forces' actuation points and the centre of rotation are known as 500 and 100mm for F_g and F_s respectively. A clarification is shown in Figure 25. A total weight of 150kg will be used (100kg maximum user weight, 30kg trike weight and 20kg luggage).

$$M_g = M_s \quad (7)$$

$$M_g = F_g * r_g = F_g * 0.5 * \sin\theta \quad (8)$$

$$M_s = F_s * r_s = F_s * 0.1 * \cos\theta \quad (9)$$

$$F_s = F_g * 5 * \tan\theta \quad (10)$$

$$W_s = F_s * r_s = F_g * 0.5 * \sin\theta \quad (11)$$

$$P = \frac{W}{\Delta t} \quad (12)$$

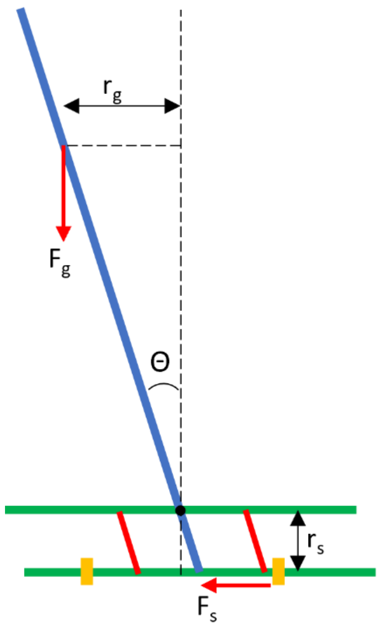


Figure 25 Forces acting on the trike to remain a tilted position, front view.

Evaluating the system with the above equations gives the forces as presented in Table 4. The critical angle of 14.3° is highlighted in the middle with a force of 1876.134N acting on the system (blockade). As the maximum possible tilting angle is set to 30° (see requirement 10), this would result in an acting force on the system of 4247.855N. Although the CoM is outside the BoS at this point, this would be the maximum force which could act on the system if it is faulty activated in the maximally tilted position. The work required by the system to apply this force is given as well, as is the power to do this work in 2 time stamps, which correspond to the reaction time which will be discussed later and is set at 0.2s in requirement 4. These values are based on the assumption that the force F is applied directly on the connector.

Table 4 Evalution of forces, work and power acting on the stabilizing mechanism.

Tilting angle Θ (°)	**5**	**10**	**14.3**	**20**	**30**
Force F_s (N)	643.698	1297.326	**1876.134**	2677.911	**4247.855**
Work (Nm / J)	64.125	127.762	**181.796**	251.641	367.875
Power at Δt = 0.2s (W)	128.250	255.523	**363.592**	503.283	735.75
Power at Δt = 0.5s (W)	320.624	638.808	**908.980**	1258.207	1839.375

5.2.1. Physical limitations

As the system is integrated in a trike frame, there are some physical limitations to the rotations that can be realized, originating from the user, motor and trike. Limitations by the trike are of a constructive nature, the motor limits the reaction speed and moments which can be compensated for, and user limitations concern comfortability and confidence in the trike and system as a whole.

Most meaningful for determining the drive is the limitation in spindle displacement. As the trike tilts, the connectors will translate along the spindles. An ultimate tilting angle of 30° means a displacement of 50mm on both spindles, given the distance between the two wheel axes. Thus, limitation in the spindle-nut displacement must be beyond 50mm in horizontal direction. Although this is the ultimate angle which must be reached, the tilting angle for which the stabilizing mechanism must be activated within restricted time is smaller and known to be 14.3°. At this angle, the horizontal displacement is limited to 24.7mm, which will be used in subsequent design steps for the choice of spindle and motor. This can be stated as such because the stabilizing mechanism is wanted to be activated when the CoM is within the BoS. Other cases will cause the trike to lean over.

5.3. Drive

Based on the known strengths and forces acting on the system, the driving system can be developed, which consists of the spindles and a motor. A very effective method of transmitting linear motion is using a ball screw or power/lead screw, which can have a square, acme or buttress thread.[37] The main difference between both is the free flow of a ball screw, where the lead screw is self-locking, thus does not require a braking system. Another advantage of the lead screw is the greater torque and higher motor drive which it can tackle. Advantages of a ball screw however are a higher efficiency (90% vs. 30%), lower friction and temperature and longer lifespan.[38] Disadvantages of the ball screw are that it is relatively noisy and needs grease to maintain the design life.[37]

Although the ball screw seems more interesting with higher smoothness, efficiency, accuracy and precision and high-speed movement, the lead screw is chosen because of its' self-locking mechanism and the ability to connect the drive directly onto the spindle.

As stated, there are three kinds of thread which are used in a lead screw. First, the square thread, which is the oldest, has maximum efficiency compared to the other threads, has a uniform motion and has an increased lifespan because it has no radial bursting pressure on the nut. However, this type of screw is very expensive because it is difficult to manufacture and has to be completely replaced once worn out.[39] Second, the acme thread, which is developed for power transmission, has a high load carrying capacity due to a large root thickness and is inexpensive to cut. The main disadvantage of a acme thread is the lower efficiency. Third and comparable to the acme thread is the trapezoidal thread, which is basically the same but has a thread angle of 30° where acme is threaded at 29°.[39], [40] An acme or trapezoidal thread is chosen for this system as this is the most standard type of thread which is widely available and comes in a wide variety of sizes and materials.

To realise the required dislocation of the blockades within the available time as has been defined in the requirements (0.5 seconds), the lead distance and maximum torque should be considered. Lead distance is the translation realised by one revolution. Thus, a larger lead distance makes it easier to get more horizontal shifting. Assessing the spaces available between wheels and wheel axes, the reaction time (0.2s or 0.5s) and a required displacement of 24.7mm of the nut on the spindle, a couple of combinations can be made between lead distance and rotational speed (rpm) of the spindle (see Table 5) following equation 13. This shows the significance of the lead distance for the rpm, which will be of high influence for the motor choice.

$$rpm = \frac{\Delta x * 60}{L * t_{reaction}} \quad (13)$$

Table 5 Lead distances with reaction times and corresponding rotations per minute.

L (mm)	**$t_{reaction}$ (s)**	**rpm (min^{-1})**
1.5	0.5	1976
3	0.2	2470
3	0.5	988
5	0.2	1482
5	0.5	593

For the efficiency of the motor, a higher rpm is preffered, but the critical speed (N_c) of the spindle should be taken into account as well. This depends on the minor diameter of the spindle (D_r), the length between the bearing supports (l) and the type of end connections (C_s), see equation 14. For two-sided support with a bearing, C_s = 1.00, for two-sided fixed support, C_s = 2.24 and for one-sided fixed support and one-sided simple support with a bearing, C_s = 1.55. The maximum speed should then be below 80% of the critical speed.[37], [41]

$$N_c = (C_s * 187.6 * 10^3 * D_r)/l^2 \quad (14)$$

The system can be defined as fixed at one end to prevent rotation (the side connected to the motor) and simply supported by the spindle positioner at the other end, thus C_s = 1.55. The critical speed is added in Table 6 and states that the smaller lead distance (range from 1.5 to 6mm) and diameter (range from 10 to 36mm) has a lower critical speed, although the required rpm is 3.3 times as high as for a 5mm lead spindle, which makes it almost impossible to realise.

Table 6 Torque required to move the load up the thread of a spindle of different sizes.

Spindle thread (mmxmm)	TR 10x1.5	TR 14x3	TR 18x3	TR 22x3	TR 22x5	TR 24x5	TR 36x6
T_u at 4248N (Nm)	3.971	6.053	7.322	8.592	9.678	10.311	14.658
T_u at 1876N (Nm)	1.754	2.674	3.234	3.795	4.275	4.554	6.474
N_c (min^{-1})	59	76	405	134	120	134	211

Aside rotations per minute, the torque which is required to move the load up the thread of the spindle is the most important parameter. For acme or trapezoidal thread equation 15 can be used to calculate the torque based on the force to be moved, the lead distance, pitch diameter and a coefficient of friction. The coefficient depends on the material and lubricating manner. For well-lubricated steel-on-steel, f = 0.15 is a conservative value.[37] Knowing all other variables, the torque can be calculated for a certain number of spindle sizes.

$$T_u = \frac{FD_p}{2}\left[\frac{L+\pi f D_p}{\pi D_p - fL}\right] \quad (15)$$

To determine the size of suitable spindles, rpm, weight and stresses should be accounted for. Whereas weight is optimal for smaller spindles, rpm and stress are better included with larger spindles. Therefore, Table 6 gives the torques for a maximal acting force of 4247.855N and a maximal working force of 1876.134N, as discussed in section 5.2. At the hightest possible force to act on the system (if tilted up to 30°), torques vary between 4.0N and 16.7N. At the highest working force, this is limited to 1.8N and 6.5N respectively. This suggests a preference for the smaller spindle, but as stated before, this is impossible because of the extremely high rpm which is required. Concerning the critical speed, all spindles which are presented would give problems, but the spindles with a 5 or 6mm lead give the least problems. Therefore, and taking into account the required torques and availability of motors which come with these specifications, the TR 22x5 spindle is evaluated to be the best option. Thus, further calculations will be done with the TR 22x5 spindle.

This determines that a motor would be required with a motor torque of minimal 9.7Nm and 1482 rpm. Although the the reaction time is defined at 0.2s in the requirements, evaluation could allow for 0.5s as well, because it will actually take longer to brake and the system will otherwise be extremely abrupt. Consequently, a motor with T_u = 9.7Nm and rpm = 593 min^{-1} is sufficient as well. This would result in a motor power of 601.004W. Using a bigger spindle with TR 36x6 would have resulted in a required motor power of 758.268W, which results in an even lower possibility to find a suitable motor which can be attached to the trike and powered while portable. Thus, a motor with 10Nm torque would be sufficient.

A solid connection with minimal play must be realised between the motor and spindles. To increase the availabiliy of motors, it is most likely to use a gearbox with a ratio, such that the motor specifications fit the requirements. Because of the position of the motor and spindles, a 90° rotation is required between the motor axis and the spindles, and the motor has to be connected to two spindle shafts. To realise this, a bevel gearbox is the most likely to be used. Bevel gearboxes come in a variety of sizes, but as 2 spindles must be connected, a bevel gearbox with 2-way hollow shaft is the best option. Solid shafts could be used as well, but in most cases, this results in a decreased strength of the connection, whereas the end of a spindle can be tapped to fit perfectly within the hollow shaft of a gearbox.[42], [43]

Figure 26 Bevel gearbox with 2-way hollow shaft and connection to the motor.[43]

5.4. Electronics and control

As the motor is the main electronic component which should be controlled, a flow chart is drawn up, based on the requirements as have been defined in Chapter 3. This flow chart, see Figure 27, is the basis of the motor control system and represents all necessary in- and outputs. Speed, acceleration and blockade position will be measured continuously and can activate the control (set the pulse width modulation (PWM)) if boundary conditions are exceeded.

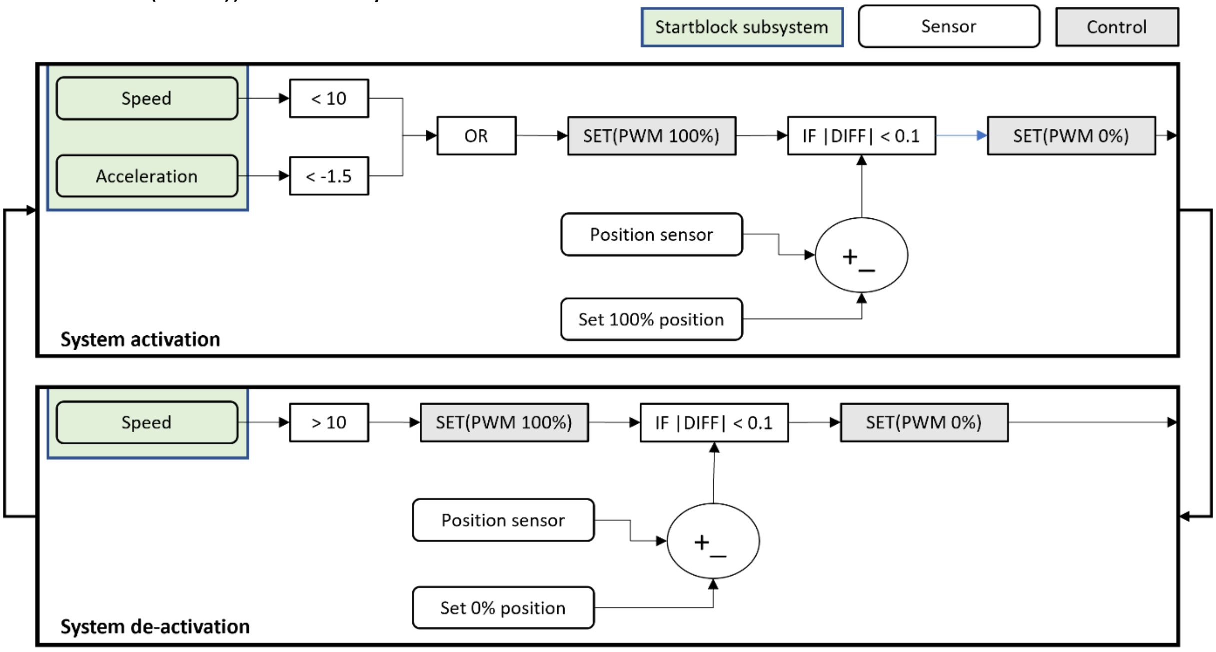


Figure 27 Flow chart of the control system. Subsystems start by measuring within the startblock, and PWM will be adjusted if boundary values are reached. Position in mm, speed in km/h, acceleration in m/s².

The main input of the control system is the sensor in the front wheel, which measures rotation time and which is used as a velocity sensor. As described in section 4.5 – Function 1, a reed sensor is chosen as the type of magnetic sensor to measure rotations. Reed sensors are widely available and are very effective in recognising magnets in a close distance. A reed sensor is a reed switch, the mechanism that reacts to a magnet once it is within the range of the switch, packed with protection to prevent damage to the switch. Reed sensors have short operating and release times, ranging from 0.2 to 0.6ms and 0.15 to 0.05ms respectively. [29] Based on the system requirements and reaction times, the Reed sensor MK31 of Spandex Electronics is chosen for this system, with an operating time of 0.2ms and a release time of 0.15ms, which results in a cycle duration of 0.35ms, within the reaction time of the motor and the time between impulses given to the sensor (0.1s).[30]

As the stabilising mechanism is build on an electronic trike, the powerbar of the trike can generate power for the motor as well. Thus, no additional power supply has to be added to the trike. As the stabilising mechanism will not be active most of the time while cycling, its overall energy consumption will be below that of the e-bike component. As the motor has a rather high energy consumption, the peak power supply will exceed that of the trikes' motorized cycling support, which should be accounted for when selecting the powerbar of the trike. This to guarantee that the powerbar can give the output power which is seeked by the motor of the stabilization mechanism.

5.5. List of components

A list of components is collected in Table 7, which are needed to build the stabilizing mechanism. This mechanism can be connected to a trike frame, which should be produced. For testing purposes, a Feetz trike frame can be used, which is available to this project. More details on the components and prices are provided in Appendix V.

Table 7 List of components

#	Description	Amount	Produce/buy	Price (€)
1	Upper wheel axis	1	Produce	-
2	Connector	2	Produce	-
3	Lower wheel axis	1	Produce	-
4	Spindle positioner	2	Produce	-
5	Spindle 22x5 (left and right)	2	Buy [44]	14.91
6	Flange nut 22x5 (left and right)	2	Buy [45]	78.80
7	Position fixator nut	2	Produce (in 2 parts)	-
8	Spring S4342 (2 for each side)	4	Buy [46]	3.08
9	Blockade	2	Produce	-
10	Motor	1	Buy [47]	57.17
11	Gearbox	1	Buy	Unknown
12	Reed switch MK31	1	Buy [30]	Unknown

The choice for a spindle is discussed in section 5.3, and a company has been found which produces both spindles and corresponding flange nuts, guaranteeing a good fit. [44], [45] For the spindles, a piece of 50cm spindle is bought in both threads.
The choice for a disk spring is based on the outside diameter of the position fixator nut and the force which acts on the stabilizing mechanism. This results in disk spring S4342, which is of the DIN2093 type. This type of disk spring has a tolerance of 1.270mm on the inside diameter. With an inside diameter of 29.50mm, the spring will not be limited in its movements. This spring has a nominal load of 2621N, unloaded length of 3.45mm and loaded length of 1.99mm.[46] To increase the movement of the blockade, it is chosen to place two springs with opposite orientation next to each other.
The motor and gearbox are provided though a supplier of our client, who has provided us with motor model 86BL130, with 1.542Nm output torque and 1500rpm.[47] Together with a provided bevel gearbox with a 1:5 ratio, this results in a motor-gearbox combination with 36V, 700W, 600rpm and 10Nm. This is within the requirements that are defined in section 5.3. A drawing of the gearbox is provided in Appendix VI.

5.6. Validation of the requirements

With the final design presented in the previous section of Chapter 5, the requirements can be evaluated and it can be verified to what extend the design fits the requirements. Recollecting the results of the evaluation of the requirements, all requirements had a moderate or better score. Only requirement #19 was scored 2/5, meaning this might not be the best solution to create a trike which can be used with and without a motorized support.
Looking at the results of the requirement validation (see Appendix VII), all requirements concerning the stability of the mechanism are fulfilled, except requirements #4 and #5. Requirement #4 demanded the system to be activated within 0.2s. During the developing process, it is evaluated that instead of providing a rigid system, this might actually give a feeling of discomfort to the user. Also, and more important, are the rotations per minute which have to be made by the motor and spindles to fulfill this requirement. Analysis showed that it is almost impossible to find suitable components which enable this. Therefore, it is chosen to change the reaction time from 0.2s to 0.5s, thus to fail this requirement.
Requirement #5 asked the system to require little energy to be activated. Early on in the developing process, the problem was found that it is required to provide energy either to enable or to disable activation of springs (as were used by Oosterlaken, C.) or tilting of the trike. In accordance with the client of this project, is was decided that an energy source is allowed. It was also discussed that this should be combined with the power supply of the electric bicycle component, to prevent having two power packs which have to be charged separately. This seems to be possible, but cannot be stated for sure without being tested in practice. Requirements #9 and #11 are expected to be fulfilled as well, as

this was the case with the original Feetz frame on which the prototype is based, but this again must be tested in practice.
For the model properties, there is somewhat more variation in the validation of requirements. Although most of them are (expected to be) fulfilled, there is one requirement which is partly fulfilled and there are two hard no's. Requirement #12 is partly fulfilled, as the thought of a basked was present, but this has not yet been implemented in the prototype, as can be seen in Appendix III. Requirement #13 is not fulfilled, as the width of the trike was limited to 75cm, but came out to be 80.5cm. 75cm was set as the maximum width, because this is the size of a smaller doorway. The 75cm is exceeded because of the required tilting freedom from requirement 10. Requirement #19 is not fulfilled either, because it was chosen to use a motor for activation of the stabilizing mechanism, as has been discussed for requirement #5. It is unsure if requirements #20 and #21 are fulfilled, because the exact price of the product highly depends on the price of the motor and the production costs of the frame and steel elements. This again depends on the number of products to be produced and the place of production. For a single prototype, this would be done in the Netherlands, whereas Beixo, the client for this project, is used to be in contact with China and Taiwan for developmental and productional purposes. This would mean a significant reduction in costs, and will be the case if the product finds its way to the market. Requirement #21 again depends on the choice of materials. Wheel tubes for example can wear out within three years, but the steel wheel axes are not expected to wear out at all.
There is one requirement left in the category cycling requirements. And with the knowledge of the Feetz trike, and after excessive testing of the prototype, the product is expected to transport the cyclist in a safe matter. Thus, this requirement is marked as fulfilled as well.

6. Discussion

During the project, the goal of the project has shifted from producing and testing a trike with stabilizing mechanism. This was caused by an increase in the extent of the stabilizing mechanism, but most of all because the delivery of components was largely delayed. Components had been ordered, but because orders were cancelled, the assignment was reduced to the design of a dynamic stabilizing mechanism. Therefore, building the prototype and testing the functionalities are postponed to future projects.
From the previous assignment on this project, a result was presented with hydraulic springs which kept the trike in an upward position, but which were not controlled and allowed for a tilt of up to 16.8°. However, as these springs were not controlled, there was no difference in user experience for different situations. A change in this control was the main request by the client and from the target group. For this assignment, two functions were added. 1) The springs had to be able to pull the trike into a vertical position, also while being tilted. 2) The springs should be transformed to give the trike freedom of tilt. To do this, energy is required in one of both directions. Either to give the trike freedom to tilt, or to pull the trike into its vertical position. During this project, a choice was made for the latter. However, there is no case in which a mechanic system is possible, which was initially preffered by the client. This changed the original assignment into "developing an electrical stabilizing mechanism for a trike".
During the process, material knowledge was sometimes limited and therefore, a more sophisticated material choice could be made according to the trike frame and elements of the stabilizing mechanism that have to be produced. This choice could lead to a significant weight reduction, less energy consumption and better manageability of the trike. For example, the weight could be reduced by a factor 0.5 if the trike frame was to be made out of aluminum instead of steel (see section 5.1).
For efficiency, the use of sliding bearings was discussed within the spindle positioners. This will reduce the friction between and increase the durability of both the spindle positioners and the spindles. However, at the end this was not included in the design, leaving a component which should be chosen and bought when actually producing the prototype. Apart from increasing the durability, adding sliding bearings to the design will also reduce the motor torque because of the reduced friction.
Another element which would increase the durability of the spindles is a coverage which can protect the stabilizing mechanism against stain. For a prototype, this has not yet been developed, although this should be added before producing and selling the final product.
A last component in the design section which deserves a discussion is the width of the trike. A width of 75cm was set as a requirement, as this would theoretically fit through any door. However, a trike of exactly 75cm will still not fit through a doorwy of 75cm. A general (modern) doorwidth is between 83 and 88cm, where modern houses even have 93cm as standard doorwidth.[48] This would mean that both a trike of 75cm as requested as a trike of 80.5cm as has been developed can fit through the door. Because the target group of the trike are people with reduced balance, it might well be possible that they use some kind of walking support or are of an older age. Senior housing for example is prepared for this, and will probably have wider doors because of this. Therefore, it is not expected that this will be a very big problem.

Next to the design part, some changes also have been made in the drive and control section, which should be discussed as well. The reaction time of the system was set relatively strict, because this seemend to be an essential component of functionality and thrustworthyness of the mechanism. However, research showed that with the chosen solution, this reaction time was almost impossible to reach. Not only because of the motor types which could be chosen from, but also concerning other components which are connected to the motor and how the user experience would be if the trike was to be pushed into a vertical position within 0.2s gave problems. Of course, the latter can only be guessed, but should be evaluated after building the prototype. Because of these reasons, the critical reaction time has been changed to 0.5s. This could possibly be further increased as well, because with a reaction time of 0.5s, the cyclist will most likely have to correct with his core muscles, which could lead to a disbalance.

Increasing the reaction time would also be better for the spindle, because the operational speed of the screw should be below the critical speed. For all spindle sizes which have been tested, the operational speed was above the critical speed. This means that maybe, some kind of transformation should be added, such that the operational speed could be decreased while the translation of the blockade would remain the same.
Although at this moment, it is chosen to only have an “on” or “off” state, clutches could also be opened slowly, e.g. reducing the tilting freedom to 15° below a cycling speed of 20km/h. This would further reduce the stress on the spindle and the forces required by the motor, and in addition reduce the muscular correction asked from the cyclist.
With all requirements, including 1) the combination of high torque and rpm, 2) the limited energy supply because this is limited to the power bar of an e-bike, 3) the weight of the motor which has to be carried on the trike while cycling and 4) the price of the motor, it was difficult to find a suitable motor. Finding a motor online (in Europe) was even more difficult. Therefore, it was appreciated that the client had good contact with its supplier in china, where there is a broader availability within a lower price range.
The control of the system is not yet written in programming language, as it is expected that, when someone continues testing the electronics, he would like to choose the type of board being used and the programming language himself.
Besides the functionality of the control, the event in which the battery is empty should be addressed as well. If the battery of the e-bike and stabilization mechanism is low, a warning should be given on the e-bike computer (presented on the steer). As the trike is of a significant weight, only low speeds are expected to be reached in case of an empty battery. Therefore, it is advised to lock the stabilizing mechanism at a 5° tilting angle in case of an empty battery. Also, a warning should be given to either an emergency contact or a road service, such that the cyclist can be picked up if necessary.
Besides locking the system, manually unlocking the system was mentioned in the requirements as well. To do so, a physical button could be used, but this gives unneccessary danger because a buttonn can always be pressed by accident and/or it can be shifted into the wrong direction. Therefore, it would be advised to add a function in the settings of the on-board e-bike computer, where you can disconnect the stabilizing mechanism. After the trike is turned off and on, the mechanism will automatically be activated to guarantee safe transportation.

Last, a basket at the front of the trike was requested by the target group and client, and therefore put up as a requirement. After the initial concept design phase, this has not been given any thought, also because of the change in assignment description. A basket can however easily be fixated to the upper wheel axis or to the steering axis, and can bear quite some weight. Nonetheless, adding weight to the steering axis is not desired, as this can be experienced very well while steering. Connecting the basket to the upper wheel axis on the other hand would barely be recognized, apart from giving more stability in the turns. Besides, placing the basket on the wheel axis would not influence tilting of the trike, because it will follow the wheel axes.

7. Conclusion

Based on previous research, designs and development of Isabelle Lugert and Coen Oosterlaken, the problem of a dynamically stabilizing mechanism for a trike was redefined. Through general research and an investigation of cycling habits and practise, an overview was created of what the solution must include. Together with stakeholder expectations, a design assignment was formed. With the requirements defined, this was the start of elaborate brainstorming and the concept phase. First, a function analysis was performed, splitting the problem into subsystems which need different kind of solutions. Although this started out very generic, it created the possibility to make combinations which were never thought of otherwise.

After a list of concepts was created, it became time to limit the selection to a more manageable set of options. At this point, the choice was made what kind of drive would be preffered. Although different options like linear actuators, a rack and pinion or a chain and chainwheel were available, a spindle was favorized with less limitations in the reaction time, range of motion and weight. To choose the final concept, the seven functions information storage, information combination, energy transport, material transformation for transport and fixation, information separation and back transport of energy were described in more detail, such that a design could be made.

The design started with a more general design of how the prototype should look, including all components which had to be manufactured manually. This focussed on the design of the stabilizing mechanism, using the trike frame as had been designed before. This made it possible to do force calculations, which were then required to set up the drive for the stabilizing mechanism. Rotations per minute and torque to move the load turned out to be the most difficult parameters to find a fitting solution. Although several adjustments had to be made, a more or less suitable solution has been found. Because it was not yet possible to connect the motor to an actual system, only a general control system is defined.

This resulted in a prototype, of which all components are either ready to produce or can be bought from stock. With these components, the design was again tested for all requirements. This resulted in two requirements which were failed completely, although this can be overcome or has been discussed with the client. From two requirements it is still unsure whether or not they are fulfilled, but this will not limit the functionality of the trike. Three more requirements are partly fulfulled, but as these are adressed in the discussion (or even during the design assignment), a suitable solution is presented. This means that there are no requirements which are rejected in such a degree that they make it unrealistic to let this design work. Therefore, the design can be described as succesfull.

Although the design seems to fulfill its purpose, some future work is still required. Because the building and testing phase of the prototype has been skipped, this will need to be done by someone else, before the trike can actually be produced and sold. Also, it is discussed that sliding bearings, a stain coverage and a front basket should be added, and it would be advised to investigate if the critical reaction time of the system can be increased or if intermediate steps can be added.

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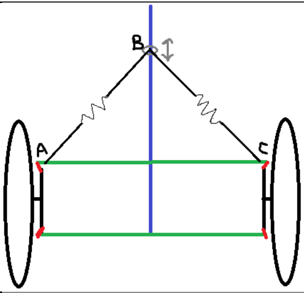
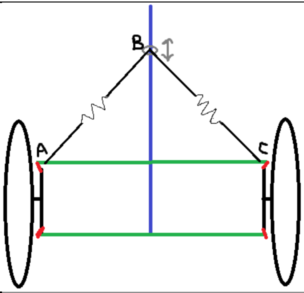
Appendices

I. Overview of concept generation

First, an expanded list of concepts is generated (see Table 8), which are tested for the most relevant requirements and general feasibility. From here, a first selection is presented, which is further evaluated in sections 4.3 and 4.4. Concepts are ordered based on the location of the stabilizing mechanism, i.e. between which elements a connection is made or fixated.

Table 8 List of concepts

<table>
<tr><th>Con-cept</th><th>Function 3</th><th>Function 4 (vertical)</th><th>Function 5 (fixate)</th></tr>
<tr><td></td><td colspan="3">Connection between steering axis and wheel axis</td></tr>
<tr><td>1</td><td>Clamping a disk brake combined with spring & locking mechanism</td><td>
</td><td>
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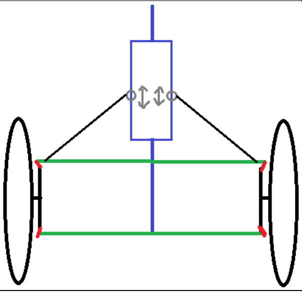
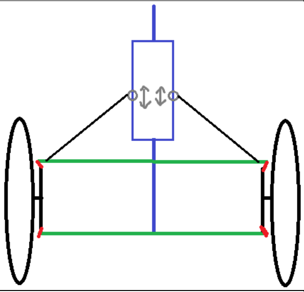
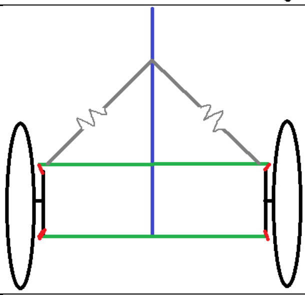
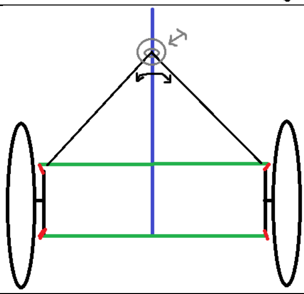
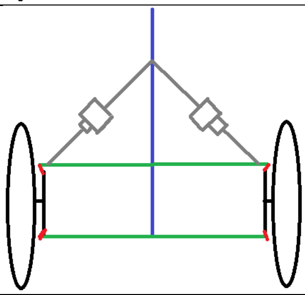
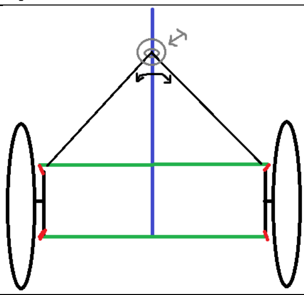
<tr><td>2</td><td>Spring & locking mechanism</td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>3</td><td>Lock (hydraulic) damper</td></tr>
<tr><td>4</td><td>Air pressure</td></tr>
<tr><td>5</td><td>4 Spring & locking mechanism
5 Clamping a disk brake</td><td></td><td></td></tr>
<tr><td>6</td><td>4 Lock damper
5 Clamping a disk brake</td><td></td><td></td></tr>
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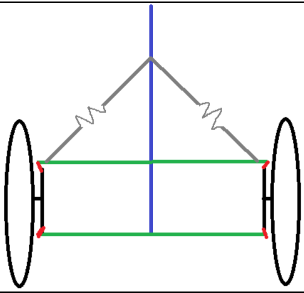
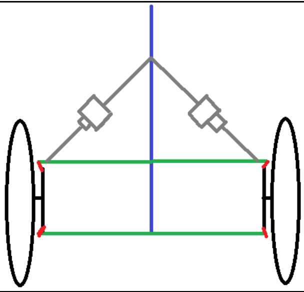
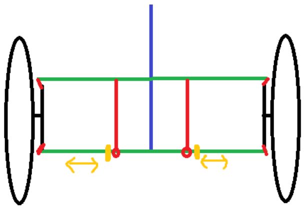
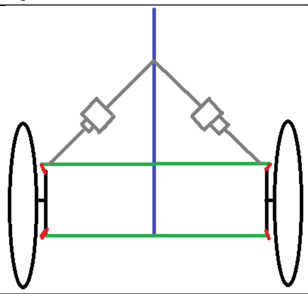
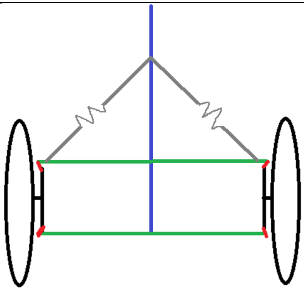
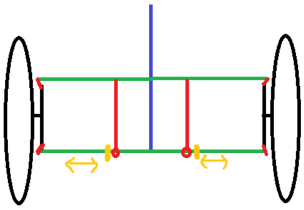
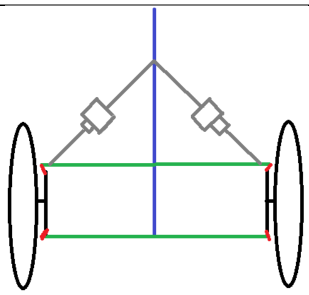
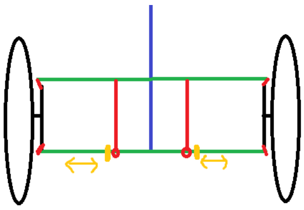
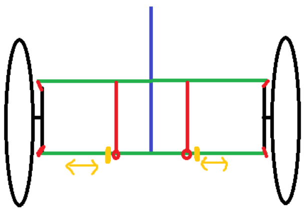
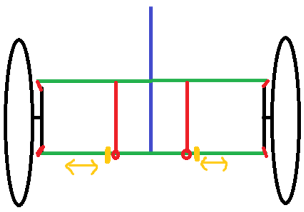
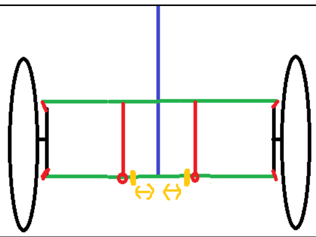
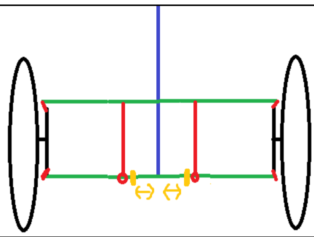
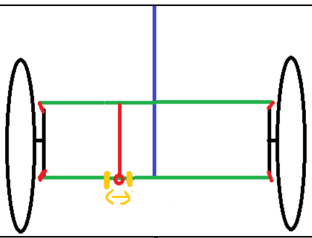
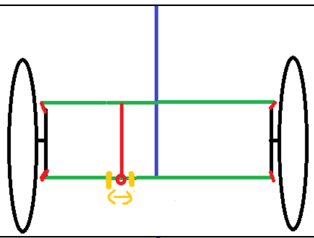
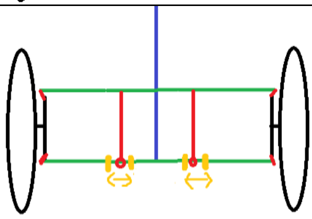
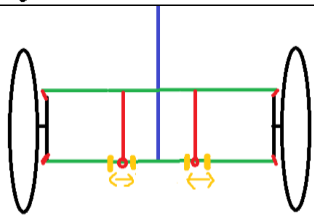
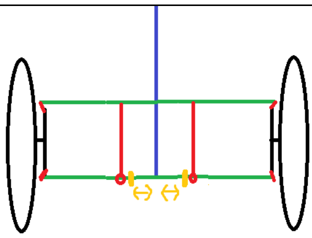
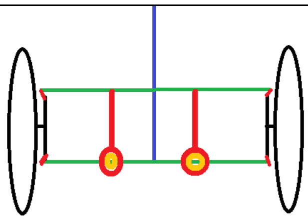
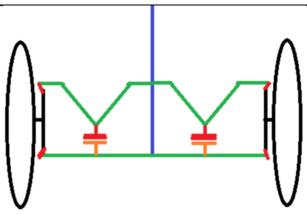
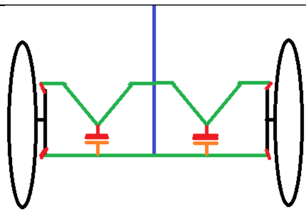
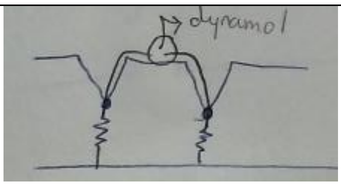
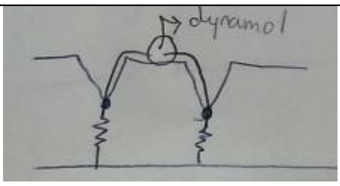
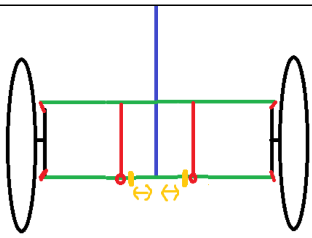
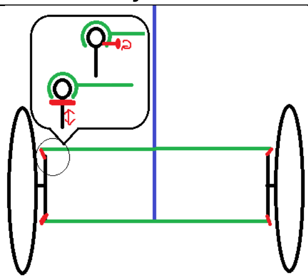
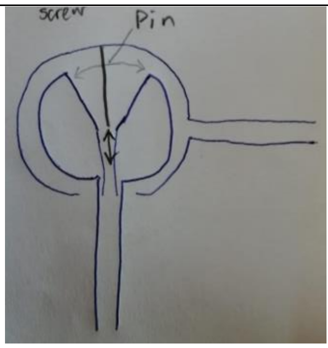
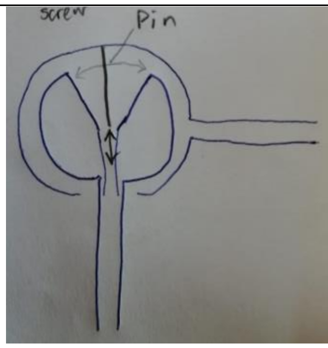
7	4 Spring & locking mechanism 5 Lock (hydraulic) damper		
8	4 Spring & locking mechanism 5 Lock (hydraulic) damper		
9	4 Spring & locking mechanism 5 Lock (hydraulic) damper on the outside		
10	4 Spring & locking mechanism 5 spring & locking mechanism		
11	4 Lock damper 5 Lock hydraulic damper on the outside		
12	4 Lock damper 5 Spring & locking mechanism		
	Connection between the upper and lower wheel axis		
13	Spring & locking mechanism on the outside	Move blocks to the inside 	
14	Lock hydraulic dampers on the outside		
15	Air pressure		
16	Pulley		
17	Spindle		
18	Lock hydraulic damper between both blocks		
19	Spring & locking mechanism in between		

20	Pulley		
21	Spring & locking mechanism		
22	Lock 2 dampers		
23	Pulley		
24	Medial blocks: lock damper Lateral blocks: spring & locking mechanism		
25	Medial blocks: lock damper Lateral blocks: pulley		
26	4 Lock hydraulic damper between both blocks 5 Clamping a disk brake		
27	4 Spring & locking mechanism between both blocks 5 Air pressure		
28	Lock (hydraulic) damper		
29	Lock damper combined with a parallel spring to pull axes together		
30	Tighten both springs	 Pull upper and lower bar together	
31	Pulley		
	Connection between the wheel axis and the wheel-fuse		
32	4 Lock (hydraulic) damper between both blocks 5 Thumb screw		
33	4 Spring & locking mechanism between both blocks 5 Thumb screw		

<table>
<tr><td>34</td><td>Release blocking under pin</td><td rowspan="2">

To sink the pin is forced into a vertical position</td><td rowspan="2">

Let the pin sink to fixate</td></tr>
<tr><td>35</td><td>Unlock spring/damper between pin & socket</td></tr>
</table>

II. Assessment of the requirements

All concepts which have been defined in section 4.2 and which are shown in Appendix I, are tested for the requirements which were defined in Chapter 3. The results of this analysis are shown in the table below.

Category	#	Requirement	Concept Weight factor	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Stability	1	Position center of mass	2	4	3	3	3	4	4	3	4	4	4	3	3	5	5	5	5	5	5
	2	Upright position <10km/h	5	2	4	4	4	4	4	2	4	4	3	3	3	4	4	3	4	5	5
	3	Upright position while braking	5	3	4	4	4	4	3	3	4	4	4	3	3	4	4	4	4	5	5
	4	Switch on Δt<0.2s	4	3	4	3	3	3	2	3	4	3	3	2	2	4	4	3	3	3	3
	5	Little energy required	2	4	2	2	1	3	4	3	2	3	3	3	3	3	3	3	2	3	2
	6	Absorb movements frontal plane	3	2	4	3	2	3	3	2	2	4	4	3	4	4	4	3	4	5	4
	7	Upright position at stance	5	2	4	4	4	3	4	3	3	4	4	4	4	3	4	3	2	5	5
	8	Identical wheel position	3	2	3	3	3	2	2	2	2	5	5	5	5	5	5	5	5	5	5
	9	Stability in turns	4	5	3	3	3	5	4	4	4	5	5	4	4	4	4	4	4	4	4
	10	Tilt in turns	3	4	3	3	3	4	4	4	5	4	4	4	4	4	5	5	4	5	5
	11	Ground contact wheels	3	4	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4
Model properties	14	Max. 75cm width	4	5	4	4	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	18	Max. user weight 100kg	2	3	4	4	4	2	2	2	4	3	3	3	3	4	4	4	3	4	4
	19	Usable with & without motorized support	2	5	3	3	3	5	5	5	2	2	2	2	2	3	3	2	2	2	3
	20	Cost approx. €3500,-	1	4	3	3	3	4	4	3	3	4	4	3	3	3	3	3	3	3	2
	21	No wear-out within 3 years	1	3	3	3	3	2	2	1	4	2	2	3	3	3	3	4	1	3	3
	22	Use durable materials	1	3	4	1	4	3	2	4	3	3	3	3	3	3	3	4	4	5	3
	23	Simple replacement worn materials	2	4	2	2	2	4	4	4	4	4	4	4	4	3	3	2	4	3	3
		Total Stability		119	137	130	125	137	134	116	138	157	152	134	137	154	162	145	143	176	171
		Total Model properties		54	44	41	44	51	50	50	50	47	47	47	47	49	49	47	46	49	48
		Total		173	181	171	169	188	184	166	188	204	199	181	184	203	211	192	189	225	219
		Rank										12				13	7			1	4

Category	#	Requirement	Concept Weight factor	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
Stability	1	Position center of mass	2	5	4	4	4	5	5	5	5	5	5	5	3	3	5	5	5	5
	2	Upright position <10km/h	5	5	3	5	5	3	5	5	5	5	4	4	4	5	5	5	3	3
	3	Upright position while braking	5	5	3	5	5	3	5	5	5	4	4	4	3	3	4	4	4	4
	4	Switch on Δt<0.2s	4	3	3	4	4	3	4	4	5	4	4	4	2	3	3	3	5	4
	5	Little energy required	2	2	2	3	3	2	2	1	1	2	4	2	3	2	3	3	5	4
	6	Absorb movements frontal plane	3	4	3	3	4	3	5	5	5	4	3	3	4	4	4	4	3	3
	7	Upright position at stance	5	5	2	3	3	4	5	5	3	4	3	4	3	3	4	4	2	2
	8	Identical wheel position	3	5	3	3	3	4	5	5	4	4	3	3	2	3	4	4	3	4
	9	Stability in turns	4	4	5	5	5	4	4	4	4	4	2	2	4	4	4	4	4	4
	10	Tilt in turns	3	4	5	5	5	4	4	4	4	4	2	2	3	3	4	4	4	4
	11	Ground contact wheels	3	4	4	4	4	4	4	4	4	4	3	3	4	4	4	4	2	2
Model properties	14	Max. 75cm width	4	5	5	5	5	5	5	5	5	5	4	4	5	5	5	5	5	5
	18	Max. user weight 100kg	2	4	2	4	4	2	4	4	2	4	4	5	2	2	3	3	2	2
	19	Usable with & without motorized support	2	3	2	3	3	2	3	3	4	3	4	4	4	4	2	2	5	5
	20	Cost approx. €3500,-	1	2	5	3	3	5	2	3	2	2	3	3	2	2	4	3	5	5
	21	No wear-out within 3 years	1	3	1	2	3	1	3	2	2	4	4	3	4	2	3	3	1	1
	22	Use durable materials	1	3	3	4	4	3	4	3	3	4	5	4	4	3	3	3	3	3
	23	Simple replacement worn materials	2	3	4	2	3	4	3	3	1	4	4	4	1	3	4	3	3	3
		Total Stability		168	129	160	163	137	175	173	164	159	130	131	125	135	157	157	137	134
		Total Model properties		48	45	47	50	45	49	48	41	52	52	52	44	45	48	45	49	49
		Total		216	174	207	213	182	224	221	205	211	182	183	169	180	205	202	186	183
		Rank		5		9	6		2	3	10	7					10	14		

III. Prototype details

Sketches of the prototype from different views are presented.

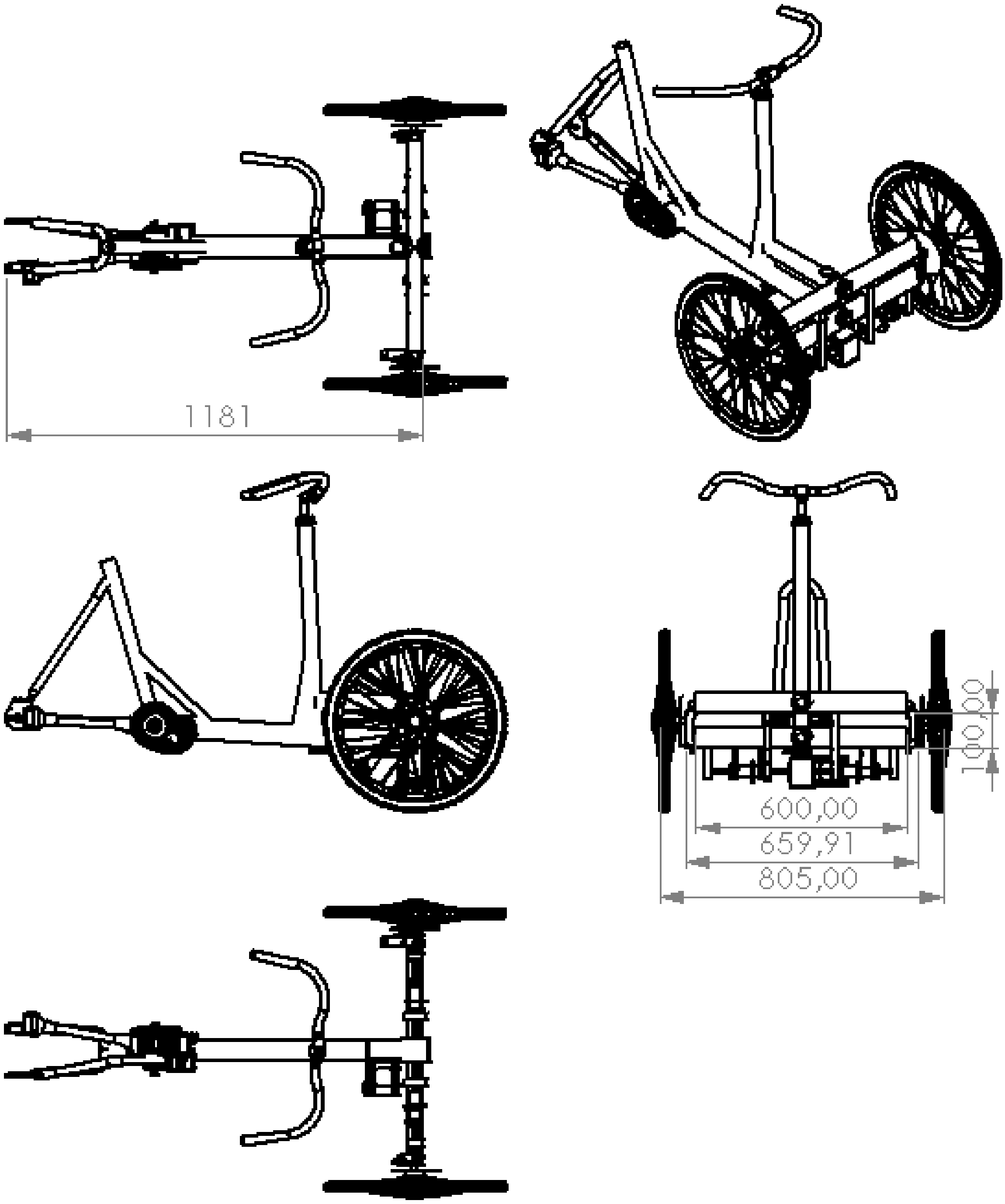
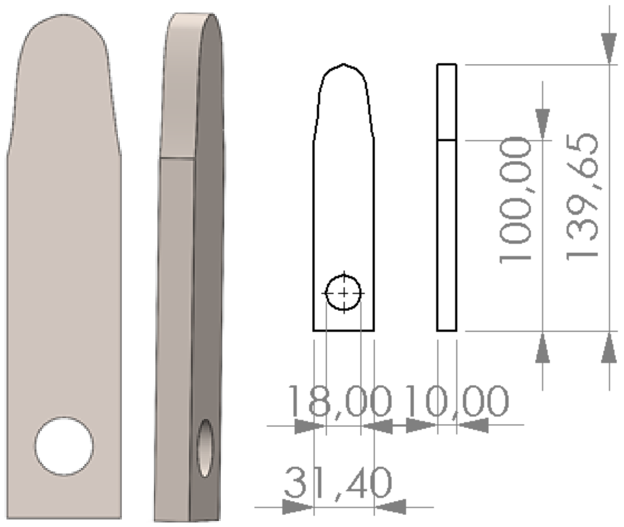


Figure 28 Sketches of the prototype.

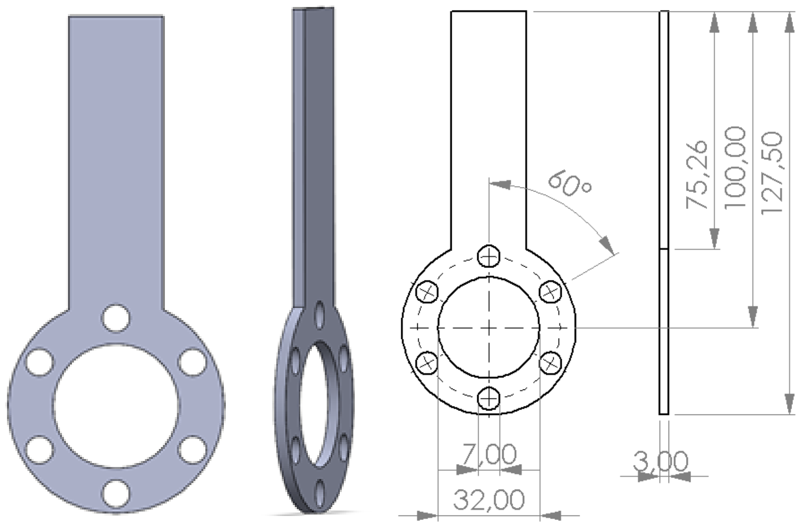
IV. Components to be produced

In this appendix, a detailed overview of all components which have to be manufactured is given. Both 2D sketches and 3D views are provided. For all components, the dimensions are given in mm. For this appendix, no figure numbering is used.

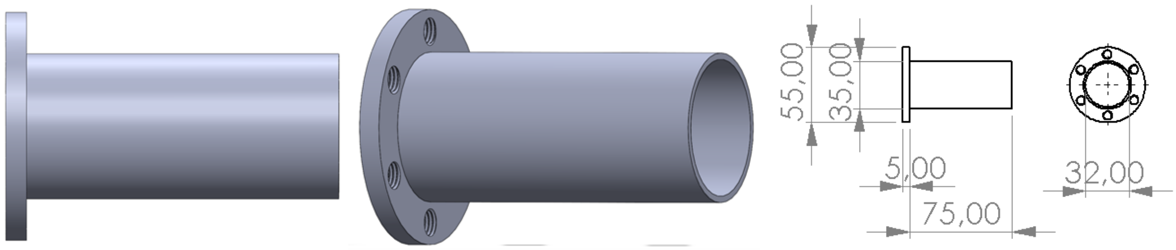
i. Spindle positioner



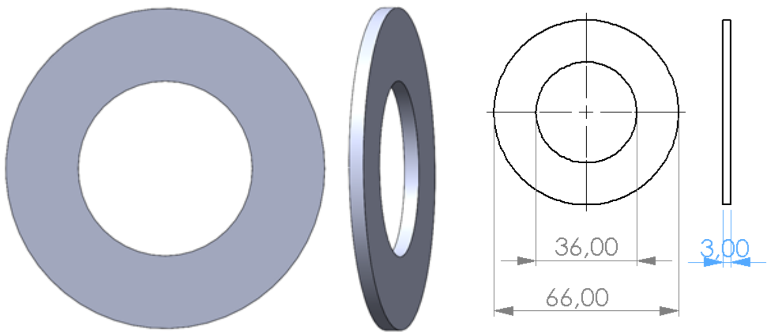
ii. Position fixator nut part 1



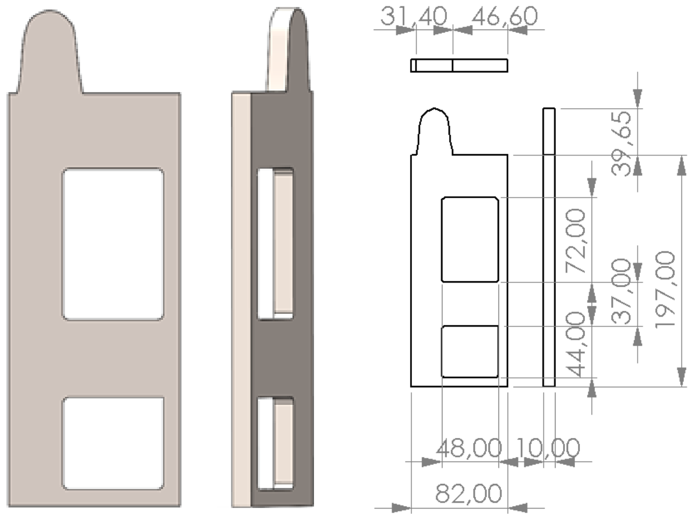
iii. Position fixator nut part 2



iv. Blockade

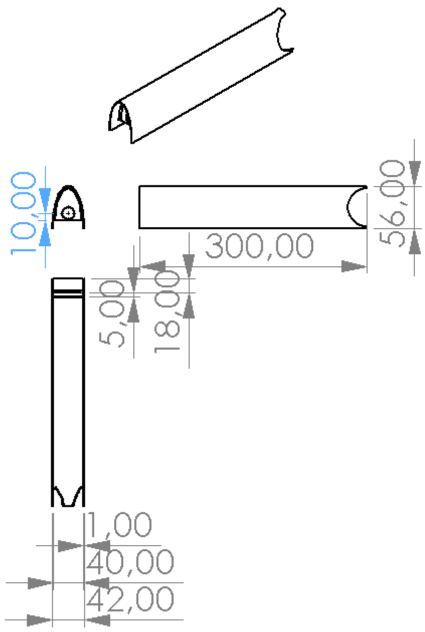


v. Connector



vi. Wheel axes

The upper and lower wheel axis both are the same, and the left and right part are mirrored in the centre.



V. Price list of elements which must be bought

Flange nut 22x5: Flensmoeren Brons • Trapeziumdraad - Machinefabriek Harderwijk B.V.
Right threaded €35.65
Left threaded €43.15

Spindle 22x5: Trapeziumdraad Spindels staal • Trapeziumdraad - Machinefabriek Harderwijk B.V.
Right threaded 50cm: €6.65
Left threaded 50cm: €8.27

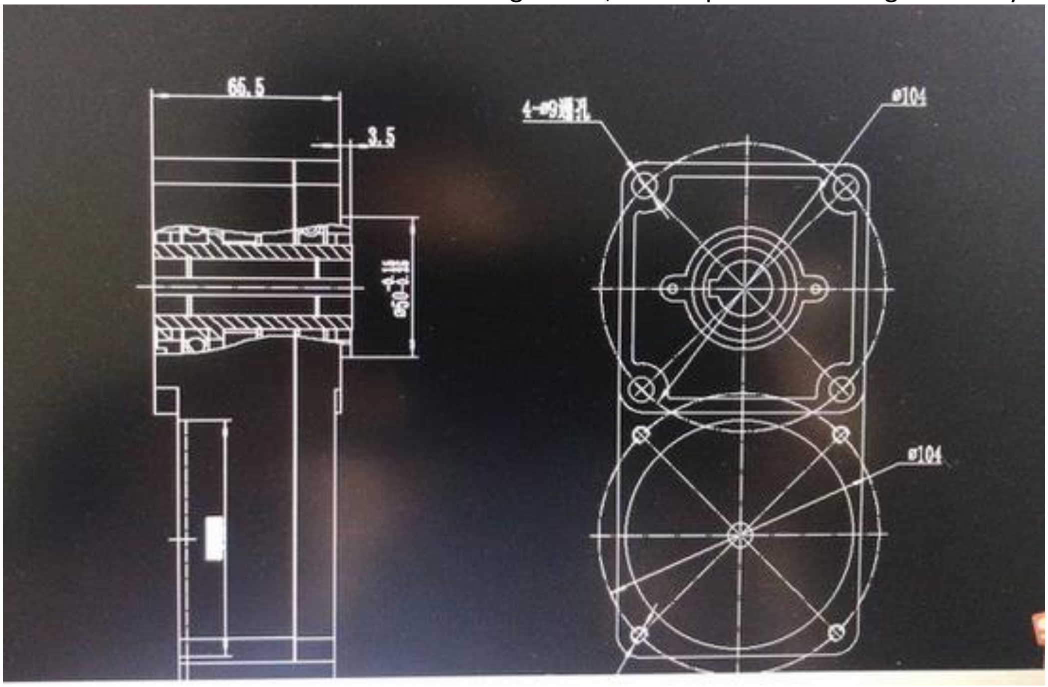
Motor: 86BL130 €57.17
China Brushless DC Motor 86bl130 800W3000 to 2.5n. M Motor High Speed and High Torque in Stock - China 2.5n. M Motor, Nmrv (made-in-china.com)

Disk spring: 4x S4342 = €3.08 S4342 - Amatec Technische Veren

Reed switch: MK31
https://standexelectronics.com/viewer/pdfjs/web/viewer.php?file=https%3A%2F%2Fstandexelectronics.com%2Fwp-content%2Fuploads%2F2015%2F05%2FMK31_V01.pdf

VI. Gearbox

Shown below is a sketch of the motor and gearbox, as was provided through email by the supplier.



VII. Validation of the requirements in the final concept

Validation of stability and model properties requirements, as discussed in section 5.6.

Category	#	Requirement	Fulfilled?	Comment
Stability	1	Position center of mass	YES	
	2	Upright position <10km/h	YES	
	3	Upright position while braking	YES	
	4	Switch on Δt<0.2s	PARTLY	Within 0.5s
	5	Little energy required	PARTLY	Should theoretically be possible, but must be tested in practice.
	6	Absorb movements frontal plane	YES	
	7	Upright position at stance	YES	
	8	Identical wheel position	YES	
	9	Stability in turns	YES	Is expected to be the case, but again, this must be checked in practice.
	10	Tilt in turns	YES	
	11	Ground contact wheels	YES	This was the case with the original Feetz trike, which is the basis on which this prototype is build.
Model properties	12	Up to 50kg luggage at the front	PARTLY	Basket is missing, because the focus of this project shifted to the stabilizing mechanism. But it is designed in such a way, that a basket can easily be fixated to the steering axis of upper wheel axis.
	13	Possible to have a bike rack at the back	YES	
	14	Max. 75cm width	NO	80.5cm width, but 118.1cm long.
	15	Use easy and intuitive steering method	YES	
	16	Step-in between 25 and 30cm height	YES	
	17	Should be usable for persons between 1.60 and 1.80m	YES	
	18	Max. user weight 100kg	YES	
	19	Usable with & without motorized support	NO	
	20	Cost approx. €3500,-	UNSURE	Highly depends on the price of the motor and the costs for production of the frame and steel elements.
	21	No wear-out within 3 years	UNSURE	Is not expected, but depends if the choice of material changes.
	22	Use durable materials	YES	
	23	Simple replacement worn materials	YES	Single elements can be replaced when worn out.