André Bianchessi

Design of bicycle low speed stabilizer

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"Pass on what you have learned"
– Master Yoda

Abstract

Anyone who has ever commuted by bicycle knows just how unpleasant braking, stopping and then restart riding can be. Stops lead to efficiency loss, high effort during departure, ergonomic discomfort and instability. Besides, research shows that they can also lead to many accidents: studies reported that most of the cyclists admitted to hospitals were involved in single-sided accidents (where no other party is involved), and that most of older riders' accidents happened at low speeds, with up to 20% of the total accidents happening while mounting/dismounting the bicycle. This work designed, prototyped and tested a completely mechanical and easy to manufacture solution which enables urban bicycle riders to stop their bicycles, remain stable and restart pedaling without ever needing to place feet on the ground.

Key-words: Bicycle, Comfort, Safety, Stop.

Resumo

Toda pessoa que já transitou com bicicletas no meio urbano sabe do desconforto decorrente da necessidade de frear, parar e recomeçar a pedalar a bicicleta. Paradas levam a instabilidade, perdas de eficiência, desconforto ergonômico e requerem grande esforço durante a partida. Além disso, pesquisas reportaram que elas podem também causar muitos acidentes: estudos mostraram que a maioria de ciclistas admitidos a hospitais estiveram envolvidos em acidentes *single-sided* (sem outra parte envolvida), e que a maioria dos acidentes com ciclistas mais velhos ocorreu em baixas velocidades, com até 20% do total ocorrendo enquanto os ciclistas montavam ou desmontavam de suas bicicletas. Neste trabalho, foi projetada, prototipada e testada uma solução completamente mecânica e de fácil manufatura que permite que ciclistas urbanos parem suas bicicletas, se mantenham estáveis e recomecem a pedalar sem colocar os pés no chão.

Palavras chave: Bicicleta, Conforto, Segurança, Parada.

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Glossary

- Chainstay: pair of tubes on a bicycle frame that run from the bottom bracket to the end of the rear fork
- Concept: combination of working principles
- Function structure: meaningful and compatible combination of subfunctions
- Solution principle: Concept
- Subfunction: building blocks of a technical system that abstractly, and independently of any particular solution, formulate a task executed by the system (Figure 3)
- Support mechanism: part of the manufactured prototype that attaches to the bicycle's chainstay, i.e. the whole prototype excluding the cables and the wrist throttle
- Working principle: combination between physical effects and material characteristics (surfaces, motions and materials)
- X[i,j, ... , k]: *Xi*, *Xj*, ... , *Xk*
- X[i:j]: *Xi*, *X(i+1)*, ... , *Xj*

Contents

1 Introduction

Bicycles are largely considered a good means of cheap, Eco-friendly and healthy transportation. Although one of the biggest causes of cycling discomfort, physical effort while pedaling, can be solved with the help of electric motors that are widely available, not many solutions exist that tackle the discomfort associated with bicycle stops. Since the stability of a bike decreases at low speed, riders normally need to stop and dismount their bicycles at intersections or "red-lights" before mounting and resuming their journey. This not only consists on a physical discomfort, but also a big risk factor, specially for older riders, since a large portion of bicycle accidents happen while mounting or dismounting the bicycle [5] or going up inclines, which tend to reduce cycling speed due to additional force requirements [6]. This work focuses on designing a solution that makes it possible for an urban bicycle rider to stop the bike, remain stable and resume pedaling without needing to place a foot on the ground.

2 Objectives

The main objective of this project is to design, through reasonably rigorous engineering design methods, a solution that improves the comfort and safety of an urban bicycle rider by making it possible to stop the vehicle at low speeds without having to dismount or place a foot on the ground for stability. The solution that is to be develop must preserve the original ridability characteristics of the vehicle, such as the ability to lean into turns, should be reliable and easy to install on regular bicycles.

3 Literature Review ans State of the Art

3.1 Preliminary research method

Since this project will involve the design and prototyping of a solution, we chose a renowned book that covers state of the art engineering design process, [10].

We performed a research of articles to review literature specific about this project's objectives. The searches were made on "Web of Science" website on the "Web of Science Core Collection" database. At first, they were performed without a rigorous method in order to test which keywords resulted in materials that best matched with this project. Finally, the searches were made with the following input, formatted for better visibility:

```
(bicycle OR bike OR bicyclist OR "cyclist" OR "cycling" OR two-wheeled) AND (
    (stop OR low-speed) AND (comfort OR balance OR stability) OR
    (stop OR low-speed) AND (fall OR falls OR accident OR accidents) OR
    (getting-on OR getting-off) OR
    (automatic AND deployed AND stabilizer)
)
```

Since the search was broad and included not only keywords related to bicycle stability but also bicycle accident statistics, it resulted in many articles (251). However, many of them were not directly related to this work's focus, and were easily identified as such by their titles. If their titles seemed relevant to this work, the abstract was read. If it still seemed to be appropriate, the whole article was then examined. Articles that were considered the most relevant are : [12], [9], [6], [5] and [7].

Some articles cited by the articles above were also used as reference for this work.

A search for patents using the "Google Scholar" website was also performed, using " automatically deployed bicycle stabilizer" as search parameter. The search resulted in more than 10000 results, but the ones after the first couple result pages did not seem related to this work, based on their title and year of publication. The patents that were considered relevant are shown in Table 1.

Lastly, the standard "Google" search engine was used to search for existing products similar to what this works focus on implementing. "automatic bicycle stabilizer" was used as search entry, but everything found on the first few pages was either too complex to be easily-installed on any regular bicycle, or wasn't retractable.

Patent name	**Patent Code**
Stabilizer system for vehicles	US5419575A
Automatically deployed bicycle support	US9266574B1
Bicycle training aid with dynamically deployable balancing features	US7556277B2
Motorcycle automatic balancing stand and methods	US6845999B2
Low-speed motorcycle stabilizer for riders with limited leg mobility	US20190185088A1

Table 1 – Patents selected during literature review

3.2 Research summary

Although we found no articles that focused on the design of deployable automatic bicycle stabilizers, some that contain important information related to this work were discovered.

An international review of bicycle accidents done in 2014 [11] showed that worldwide, on average, 17% of fatal injuries to cyclists were caused by single-sided bicycle accidents, i.e. accidents in which no other bicycle is involved, and that between 60% and 95% of cyclists admitted to hospitals or treated at emergency departments were victims of such accidents.

The situation for older riders is even worse, since older bicycle riders (65 y.o. or older) were reported to have up to 6 times higher mortality rates in bicycle accidents when compared to other adult groups [7]. In the Netherlands alone 12,000 older cyclists required medical assistance in 2016 due to single-sided bicycle accidents. Most of these accidents happened at low speed, and 20% while mounting or dismounting the bicycle [5].

Our project's solution could not only improve the riders comfort, but also prevent many injuries and life losses.

The stability of how a motorcycle can be a theoretically and experimentally modeled and studied are detailed in [12].

[9] and [6] contains descriptions of solutions that could be used or served as inspiration for this work such as the design of a tilt indicator sensor that can be used to measure a two-wheeled vehicle roll angle and other systems that try to lower elderly riders accident risk.

3.3 State of the art

Although many modern two-wheeled vehicle stabilizers are or being developed in academia and industry, no device with the same objectives as the one proposed to be designed in this work has been found on the literature, since most of the modern solutions rely on gyroscopic effects or automatic steering for stability and, therefore, do not meet the "easy installation to any bicycle" requirement of this project.

Despite the fact that inspiration, experience and intuition are critical to the engineering design process, a systematic design methodology, which was used on this work and is described in [10], is something one can learn and implement that can improve the quality of the solutions that are to be designed without relying on chance. For that reason, the lack of modern solutions for problems subject to constrains similar to this work's ones did not pose a big problem.

4 Systematic Engineering Design

This work's design methodology is almost entirely based on the systematic guidelines to engineering design explained by [10], which provides a comprehensive design methodology for all phases of planning, design and development processes of technical systems. The book's content was constructed by means of examinations of technical guidelines and the literature about product development's historical background, fundamentals and generally applicable problem solving and evaluations methods.

Companies who applied the said systematic approach have stated that it increases the probability of finding good solutions, eases the managing of large complexities from problems and shows, despite the prolongation of the conceptual design phases, a reduction of overall duration of product development projects. We made the decision to follow this systematic approach based on those reasons, and in order to produce a more detailed description of how the solutions were achieved to aid their further development in the future. Since not only the results but also the methods of this work are of interest, information about schedules and how documents, such as the requirements list, developed through the process is also displayed.

We have done as advised by the authors of [10] and, since not all methods were required nor useful, have adapted the described design methodology to best fit this work's schedule and objectives. The work was separated in 4 main phases:

- Planning and task clarification
- Conceptual design
- Embodiment & Detail design
- Manufacture & Testing

Figure 2 illustrates the sequence of the design process' main phases, their working steps and milestones.

4.1 Planning and Task Clarification

This phase has to present in the form of a *requirements list* the answer to the following questions: what objectives must the solution that will be developed satisfy? Which properties must it have and not have? The *requirements list* is a document in which all demands (characteristics that *must* be fulfilled) and wishes (properties that are considered to make the products better) are specified. It is clear that the requirements list should be reviewed, refined, amended and extended as needed through the process. It should be as precise as possible, and just as extended as necessary to proceed to next working step. On it's first version, for example, it only needs to contain information that is necessary to define solution concepts, that influence the product structure and that determine the overall embodiment of the product.

In order to compile the first version of requirements list, the following steps can be taken:

1. Define basic and attractiveness-related market demands.
2. Define customer-specific requirements.
3. Identify requirements in the form of broad statements using the checklist in Figure 1, and by idealizing scenarios considering all stages in the product's life (what might happen, and how the product should react).
4. Develop the statements more clearly, and refine them quantitatively if possible.
5. Differentiate between demands and wishes.

To document how the requirements list was updated through the design process, Figures 9, 10, 7 and 8 show the list's versions. Section 5.1 shows the modifications history.

4.2 Conceptual Design

An important concept on this stage is *function structure*. Technical systems are designed to solve a problem; to execute a task. A *function structure* can be seen as a meaningful and compatible combination of *subfunctions*. *Subfunctions* are building blocks of a technical system that abstractly, and independently of any particular solution, formulate a task executed by the system. They can be represented as in Figure 3 by showing the relationship between energy, material and signal inputs and outputs.

During Conceptual Design, a basic solution path is determined by means of the specification of a *solution principle* (or *concept*), which is a combination of *working principles*, which in turn consist of a combination between physical effects and material characteristics (surfaces, motions and materials). In other words: A combination of surfaces, motions, materials and physical effects make up a *working principle*. The combination of *working principles* form a *working structure*, which is a solution to the system's *function structure*. A *principle solution* is born once a *working structure* is firmed up (defined more concretely).

The main steps of this phase are:

1. Abstract and identify the essential problems

Main headings	Examples
Geometry	Size, height, breadth, length, diameter, space requirement, number, arrangement, connection, extension
Kinematics	Type of motion, direction of motion, velocity, acceleration
Forces	Direction of force, magnitude of force, frequency, weight, load, deformation, stiffness, elasticity, inertia forces, resonance
Energy	Output, efficiency, loss, friction, ventilation, state, pressure, temperature, heating, cooling, supply, storage, capacity, conversion.
Material	Flow and transport of materials. Physical and chemical properties of the initial and final product, auxiliary materials, prescribed materials (food regulations etc)
Signals	Inputs and outputs, form, display, control equipment.
Safety	Direct safety systems, operational and environmental safety.
Ergonomics	Man-machine relationship, type of operation, operating height, clarity of layout, sitting comfort, lighting, shape compatibility.
Production	Factory limitations, maximum possible dimensions, preferred production methods, means of production, achievable quality and tolerances, wastage.
Quality control	Possibilities of testing and measuring, application of special regulations and standards.
Assembly	Special regulations, installation, siting, foundations.
Transport	Limitations due to lifting gear, clearance, means of transport (height and weight), nature and conditions of despatch.
Operation	Quietness, wear, special uses, marketing area, destination (for example, sulphurous atmosphere, tropical conditions).
Maintenance	Servicing intervals (if any), inspection, exchange and repair, painting, cleaning.
Recycling	Reuse, reprocessing, waste disposal, storage
Costs	Maximum permissible manufacturing costs, cost of tooling, investment and depreciation.
Schedules	End date of development, project planning and control, delivery date

Figure 1 – Checklist for making a requirements list
Source: [10]

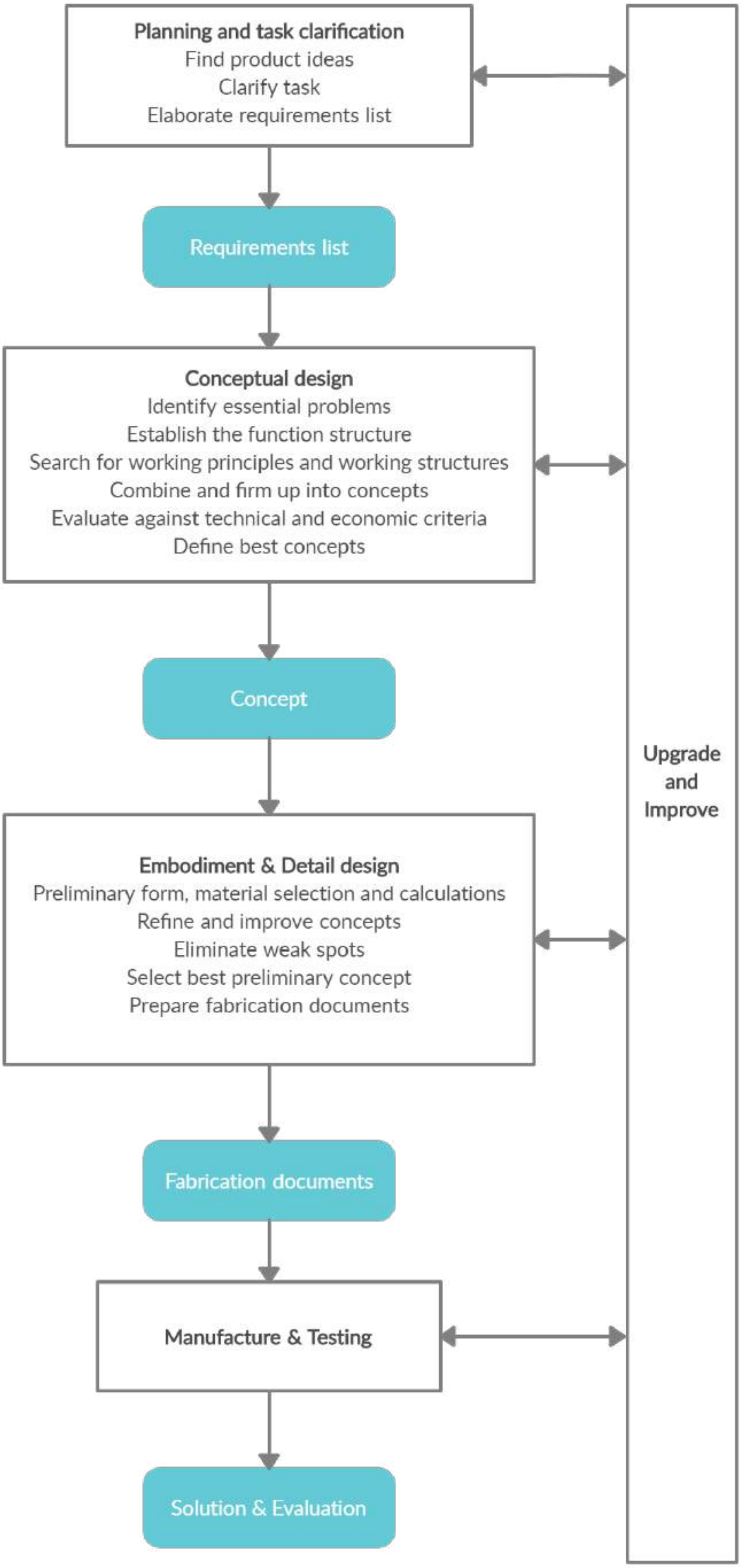

Figure 2 – Steps in Design Process

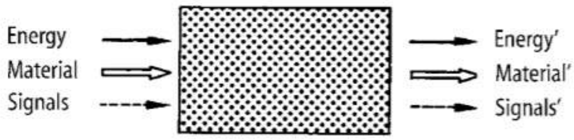

Figure 3 – Subfunction representation
Source: [10]

2. Establish the overall function structure
3. Search for working principles
4. Create working structures
5. Firm up working structures into concepts
6. Evaluate and select best concept

The aim of the *abstraction* step is to free the designer from fixation on conventional ideas and to make it possible for original solutions to emerge. This is achieved by the identification of the *crux of the task*, by ignoring the particularities of the task at hand and focusing on what's general and essential. To identify the essential problems from the requirements list, the following abstractions can be performed:

1. Eliminate personal preferences
2. Omit requirements that have no direct impact on the desired solution and essential constrains
3. Transform quantitative into qualitative data and reduce them to essential statements. Generalize and repeat as far as it's purposeful
4. Formulate the essential problem as a solution-neutral statement

Broadening the problem formulation is also essential on this step, and can be performed by successive step-by-step enquiries to discover if a more broad task formulation might lead to promising solutions. How far the task can be broadened depends on the problem's constrains.

Once the overall problem has been formulated, an *overall function structure*, i.e. a function structure to the whole system involved in the problem, can be indicated in a solution-neutral way using one function block, as in Figure 3, representing the functional relationships between *inputs* and *outputs* of the system. The overall function will, then, probably be too complex, i.e. the relationships between inputs and outputs will not clear, the required physical processes will be relatively intricate and the function will involve a relatively large amount of components and assemblies. To solve this, the overall function should be broken down into subfunctions. This way, one may determine subfunctions to

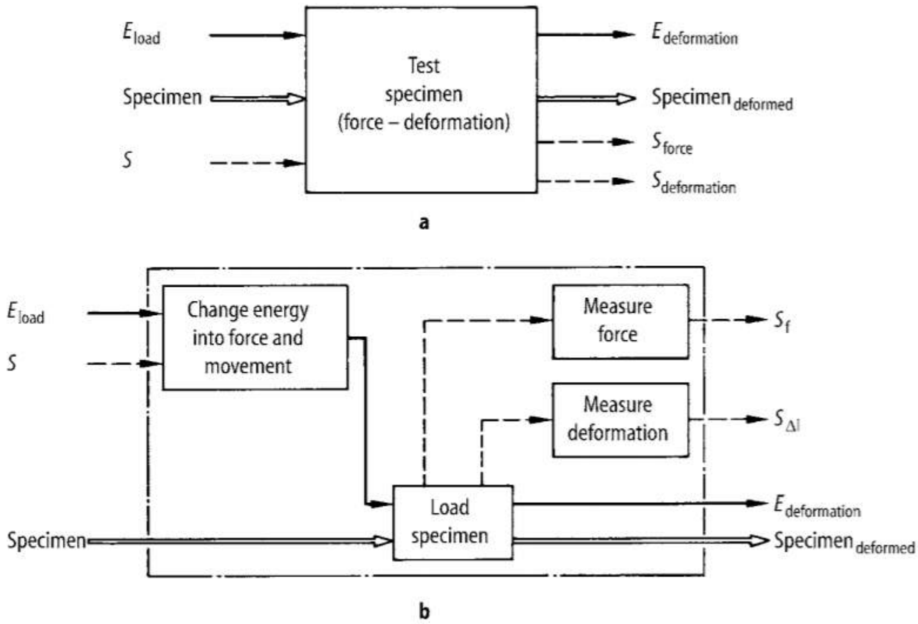

Figure 4 – Example of function block (a) and it's subfunctions (b)
Source: [10]

which solutions can be found more easily, for their lower complexity. It is recommended that the breaking down of functions focuses on the *main flow* of the technical system, which can be of energy, material or signal, and that the *auxiliar flows* and their subfunctions should be considered after a basic function structure to the main flow has been found. Subfunctions should be continuously broken down until the search for their solutions seems promising, or if existing assemblies can be assigned directly to them. An analysis of the resulting function structure should make it clear which subfunctions require new solutions and which have already known solutions. Figure 4 exemplifies a function structure from a tensile testing machine broken down into subfunctions.

The next step consists on the development of working structures. Working principles should be found for each subfunction in the function structure, and they should be combined into working structures and classified. The most promising working structures should be given a more concrete quantitative and qualitative definition, so that they can again be classified and a principle solution can be selected.

4.2.1 Evaluation and selection method

For the evaluation and selection of solutions, we used *Objectives trees* and the assessment of values proposed by VDI 2225. [10] explains both aspects of the method in detail.

Objectives trees are schemes used to determine weights, i.e. real number that represents one criterion's relative contribution to overall value of solution, for criteria used to evaluate a solution. The procedure to construct an *Objectives tree* is the following:

- Using the requirements list, define decision relevant and independent objectives with a positive formulation (the higher the value for a given objective, the better the solution)

- Separate the objectives according to levels of decreasing complexity (a higher level equals a lower complexity), and set them out, connecting objectives and subobjectives, such as in Figure 5. For example: O_1 could be *economic efficiency of engine*, O_{11} and O_{12} could be, respectively, *low running costs* and *low repair costs*

- Determine the weighting factors level by level: Starting from one objective, determine the relative weights (values from the left, painted green, at circles in Figure 5) for the subobjectives on a lower level. The relative weights must be defined such that their sum the for every "child" subobjective (subobjectives connected to the same "parent" objective) is equal to one. The absolute weight for an objective (values from the right, painted yellow, at circles in Figure 5) is, then, the multiplication of it's relative weight and it's "parent" absolute weight.

  On level 4 in Figure 5, for example, subobjective O_{1111} and O_{1112} have relative weightings of 0.25 and 0.75, respectivelly, with respect to O_{111} (note that $0.25+0.75 = 1$). The absolute weighting of O_{1111} is then $0.25 * 0.34 = 0.085$.

Once the criteria and their weights have been determined by the *Objectives tree*, every solution is assessed a value v_i for each criterion c_i, which has a weight w_i. The overall value of each solution is then given by $\sum v_i w_i$. The possible values for v_i range from 0 to 4 and correspond, respectively, to:

- far bellow average
- bellow average
- average
- above average
- far above average

The solution with the highest overall value is selected as the best solution.

4.3 Embodiment & Detail Design

During this stage of the design process, the concept of the technical product is further developed and firmed up. Required calculations are performed, the overall layout

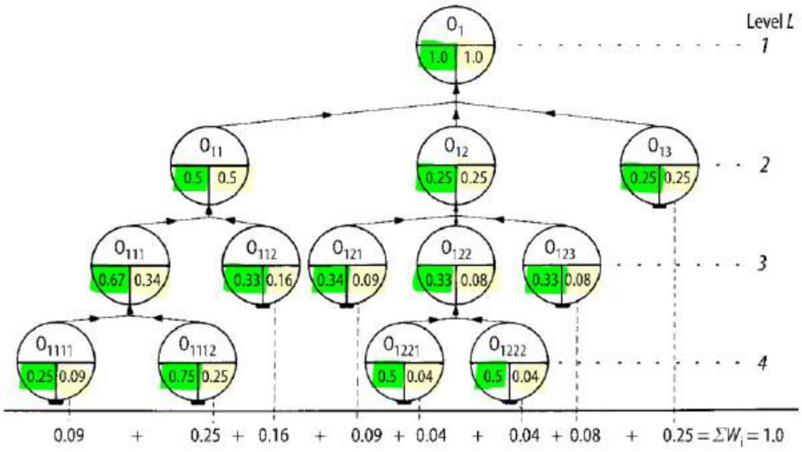

Figure 5 – Example of Objectives Tree
Source: [10] (Addapted)

of the concept is defined, and, lastly, manufacture documents (technical drawings) are elaborated.

With the manufacture documents, the design process can move to the Manufacture & Testing stage, in which prototypes are manufactured and tested.

5 Planning and Task Clarification

Firstly, a schedule was estimated based on the time available for the project and our experience. Some adaptations were made through the project, and the last version of the schedule is shown in Figure 6.

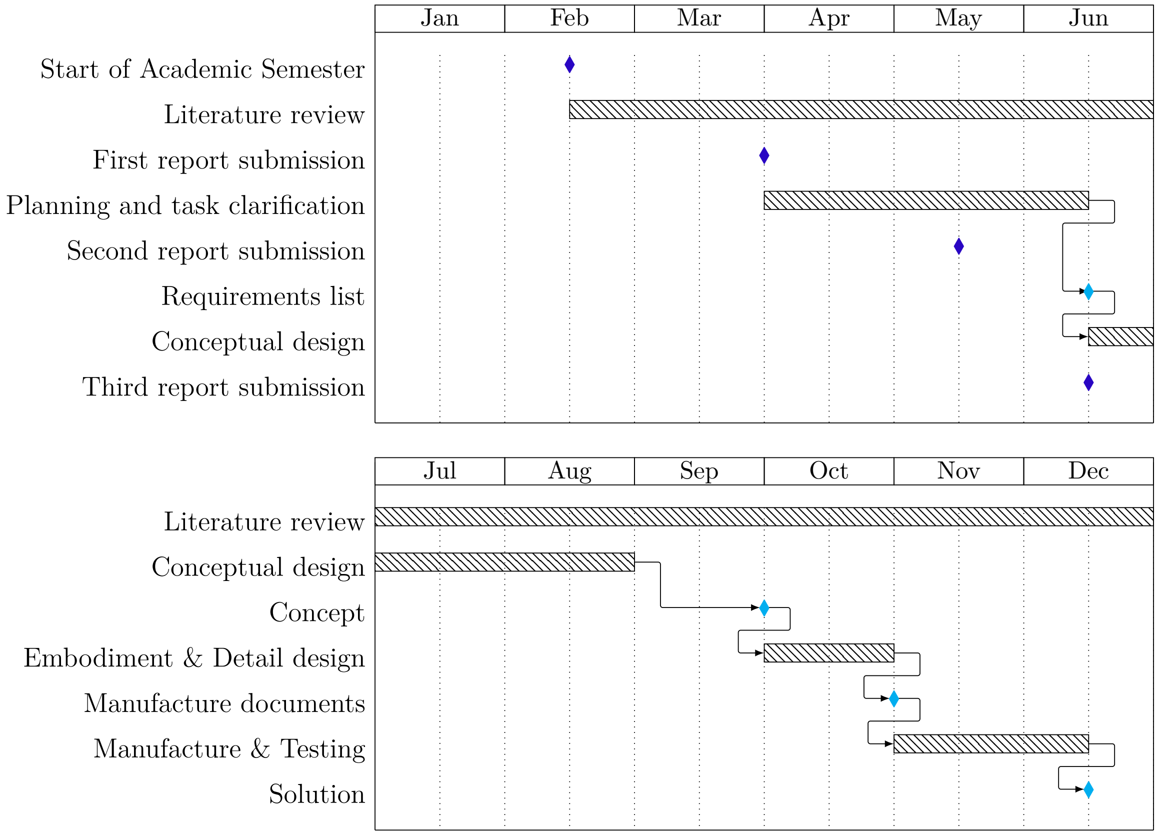

Figure 6 – Project Schedule

As shown in Figures 9 and 10, a preliminary requirements list was developed based on the understanding of the problem that was acquired during the literature review, and by following the methods in section 4.1. Some requirements that may not be obvious are explained hereafter:

1_d Protruding the vehicle thickness could drastically worsen it's maneuverability

$2_w/3_w$ These are wishes related to the aesthetics of the products, since a device that is discrete and hidden could be more easily adopted

5_d A quick deployment is essential to ensure stability as soon as the user needs it

8_d The need of recharging would reduce the reliability of the solution, and would require riders to change their routine (by making sure the device is always charged) for the product to be functional. This could *kill* one of the key characteristics of bicycles, which is it's practicality

14_d We considered ease of installation essential for cyclists to consider start using the product on bicycles they already own

15_d Since this project was conducted in 2019, during the COVID-19 pandemic, the tools available for prototype manufacture were reduced. Therefore, ease of manufacturing was a demand

Section 5.1 shows changes that were made to the requirements list throughout the project, and Figures 7 and 8 show the project's final requirements list.

5.1 Requirements List Update History

The changes made between versions of the requirements list were the following:

5.1.1 From version 1 to version 2

8_d, 9_d, 10_w and 11_w were removed. 21_d and 22_d were added.

During the first iteration of the conceptual design phase, the requirements list was revisited multiple times while developing the function structure. The need of subfunctions related to the electrical sensing and actuation made it clear how making the product automatic would increase it's complexity (and, therefore, cost, maintenance needs etc.). That added complexity would, we believe, not necessarily translate to a better result to its end user.

Cycling requires a power much larger than what should be required to activate or deactivate the device, and although the vast majority of bicycles only have mechanical components (such as breaks and gears), they continue to be widely used. This leads us to believe that so long as the de/activation of the solution requires the application of small forces and is not mentally demanding (so that the rider doesn't lose focus), automatic de/activation is not a requirement.

The function structure of an automatic and an user activated solution would greatly differ. For that reason, after establishing that automatic de/activation was not necessarily a demand, we chose to define in the requirements list if we would design an automatic or entirely mechanical system. We only saw a potential relatively low comfort improvement on an automatic solution, despite worse costs, maintenance needs and ease of installation. Therefore, a rigorous decision method was not necessary, and we chose to require the solution to be strictly mechanical and easily de/activated.

Requirements List

Version 2

$N_{(d/w)}$: requirement (demand/wish) number N

Geometry

1_d Doesn't protrude vehicle thickness when retracted

2_w Not too wide when deployed

3_w 'Hidden' when retracted

4_d Adapts to uneven ground

Kinematics

5_d Quick deployment

Forces

6_d Maintains stability of 100kg person dis/mounting

7_d Resists riding vibration

Energy

21_d Strictly mechanical components

Safety

12_d Hand/feet entanglement safe

13_d Electrical shocks safe

Ergonomics

14_d "Plug and play" with any bicycle (easy to install)

Figure 7 – Requirements List: Final Version (Page 1)

Production
15_d Manufacturable at common metalwork shop
Operation
16_d Reliable
17_d Silent operation
22_d Easy to de/activate
Maintenance
18_d Low maintenance
Costs
19_w Cost as low as possible
Schedules
20_d As seen in 6

Figure 8 – Requirements List: Final Version (Page 2)

Requirements List

VERSION 1

$N_{(d/w)}$: requirement (demand/wish) number N

Geometry

1_d Doesn't protrude vehicle thickness when retracted

2_w Not too wide when deployed

3_w 'Hidden' when retracted

4_d Adapts to uneven ground

Kinematics

5_d Quick deployment

Forces

6_d Maintains stability of 100kg person dis/mounting

7_d Resists riding vibration

Energy

8_d No recharging needed

Signals

9_d Speed and/or tilt sensor triggers deployment

10_w Easy to turn on/off

11_w Indicates on/off

Safety

12_d Hand/feet entanglement safe

13_d Electrical shocks safe

Ergonomics

14_d "Plug and play" with any bicycle (easy to install)

Figure 9 – Requirements List: First Version (Page 1)

Production

15_d Manufacturable at common metalwork shop

Operation

16_d Reliable

17_d Silent operation

Maintenance

18_d Low maintenance

Costs

19_w Cost as low as possible

Schedules

20_d As seen in 6

Figure 10 – Requirements List: First Version (Page 2)

6 Conceptual Design

The *crux of the problem*, determined as explained in section 4.2, is the following: **With small effort from the user, mechanically deploy/retract system that grants roll stability**. *Roll* motion is understood as the rotation around an axis parallel to the ground which connects the front and rear wheel.

6.1 Finding an Overall Function Structure

By using methods explained in section 4.2, after some iterations, an overall function structure (Figure 11) was determined. The overall function structure represents the use-case in which the rider deploys the stabilizer (which is retracted) when nearing a stop. The function structure for the use-case in which the rider retracts the stabilizer is represented in Figure 12. We chose the overall function structure considering the case in which the rider deploys the stabilizer because the other use-case's function structure is just a slightly simplified version of said function structure. Besides, since a simple deactivation is a demand in the Requirements List, a solution for the deployment use-case should also satisfy the retraction use-case.

The inputs to the overall function structure consist on energy supplied by the user (rider) and gravitational potential energy associated with height of the rider's center of mass. Without considering energy losses, the output is only energy which is associated with displacement of material (elastic potential energy, for example).

The subfunctions are explained hereinafter:

- Convert Energy - Converts a movement from the rider (such as a wrist or finger movement) to a form of displacement energy so that it can be transmitted
- Channel Energy - Transmits displacement energy
- Apply Force - Generates a quick movement used to move the stabilizer
- Move Stabilizer - Moves mechanism and extends stabilizer
- Touch ground - Provide forces normal to the ground that stop bicycle's roll motion

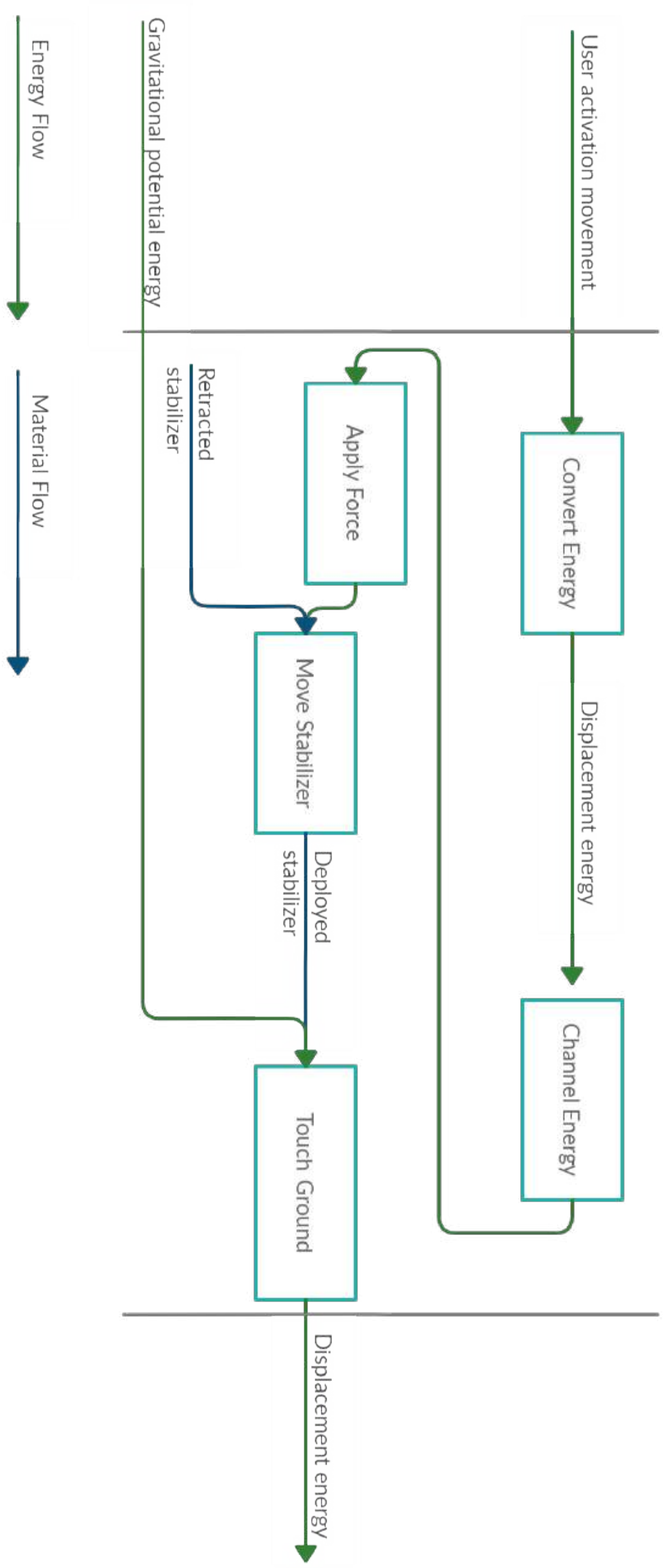

Figure 11 – Overall Function Structure

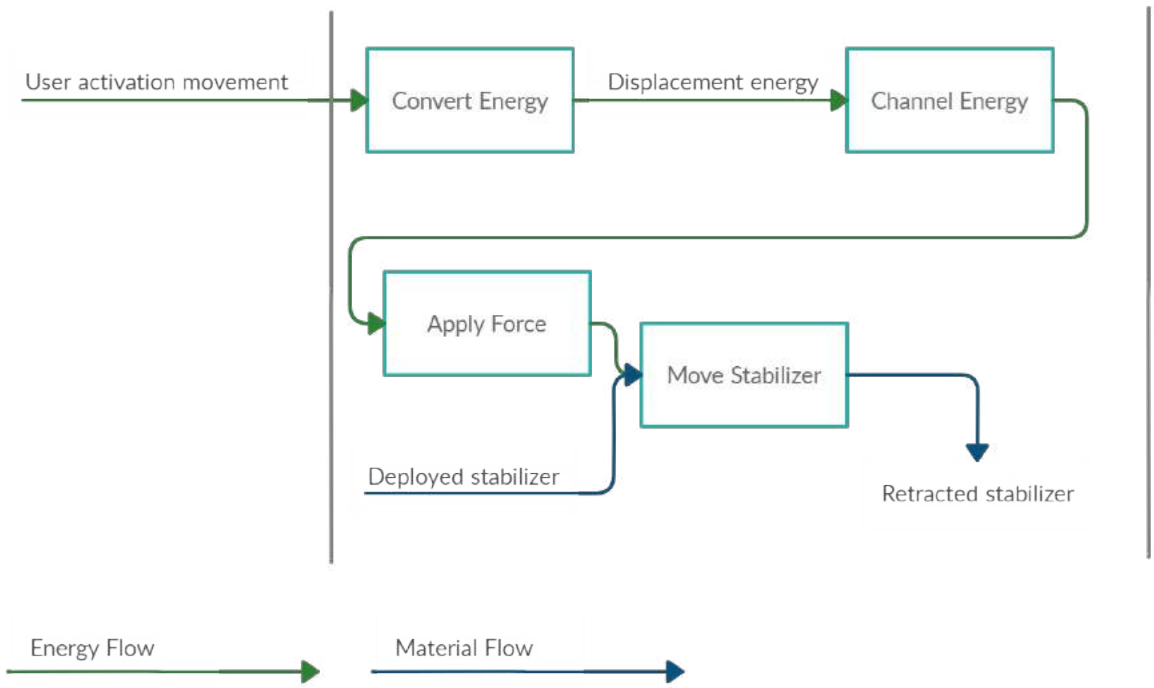

Figure 12 – Retraction Function Structure

6.2 Searching for Working Principles

6.2.1 Convert Energy

With safety and ease of use in mind, we focused the search for working principles for this subfunction on existing products used by cyclists and motorcyclists that are attached to the handlebars: break levers, gear shifters and twist throttles. The working principles elaborated for this subfunction, referred to as 1 and 2, are shown in Figures 13 and 14, respectively.

A solution with the working principle 1 can be easily purchased, because it's widely used in motorcycles. Besides, it can be easily installed on bicycles handles. Lastly, the rider can apply a much larger force using the working principle 1 when compared to working principle 2. Therefore, working principle 1 was considered far superior to working principle 2, and the working principle 2 has not been considered as an option for the development of the working structure.

6.2.2 Channel Energy

[10] provides classifying criteria for physical principles that can be used for any working principle. Since the solution has to be completely mechanical, the suitable physical principles for this subfunction, according to said classifying criteria, must be classified as *Mechanical*, *Hydraulic* or *Pneumatic*. Therefore, we have searched for working principles

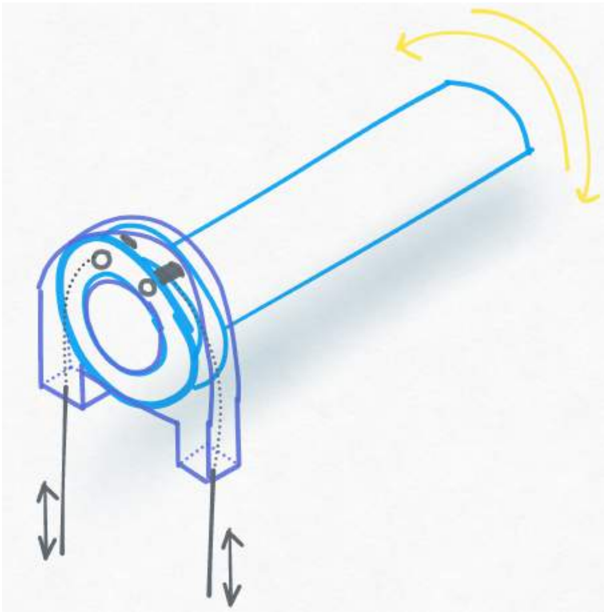

Figure 13 – *Convert Energy* Working Principle 1

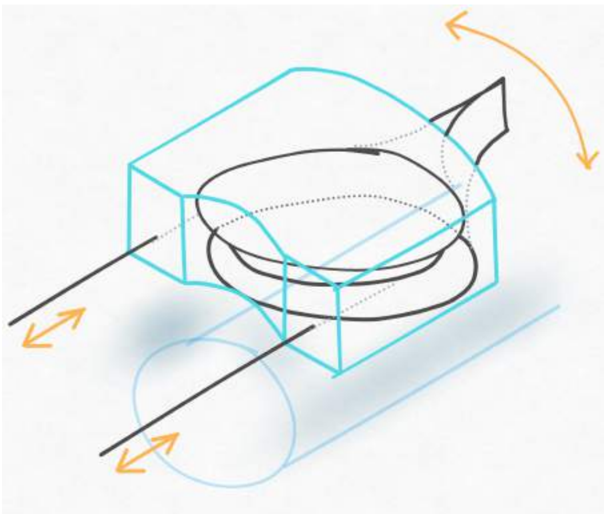

Figure 14 – *Convert Energy* Working Principle 2

that transfer displacement energy using mechanical, hydraulic or pneumatic physical principles.

The possible working principles we found were: cables, hydraulic hoses and pneumatic hoses. As in subsection 6.2.1, a preliminary selection was made. Since systems with hydraulic and pneumatic hoses are much more expensive and require more maintenance (as seen in bicycles mechanical and hydraulic brakes), we decided that cables would be considered the only working principle for this subfunction. We would alter this assumption and consider hydraulic and pneumatic solutions only if a viable working structure could not be conceived with the usage of cables.

6.2.3 Apply Force

The main source for inspirations for working principles to this subfunction was the mechanism animations catalogue created by Dr. Nguyen Duc Thang, which is available at his Youtube channel [13]. Another working principle which was also considered (Figure 23) is commonly seen in *double action OTF knifes*. The working principles for this subfunction are shown from Figures 15 to 23.

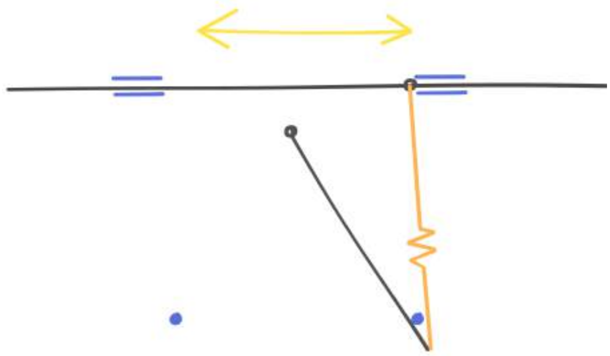

Figure 15 – *Apply Force* Working Principle 1

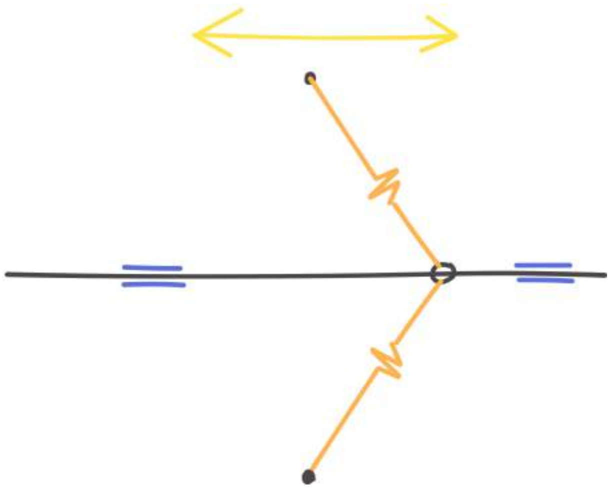

Figure 16 – *Apply Force* Working Principle 2

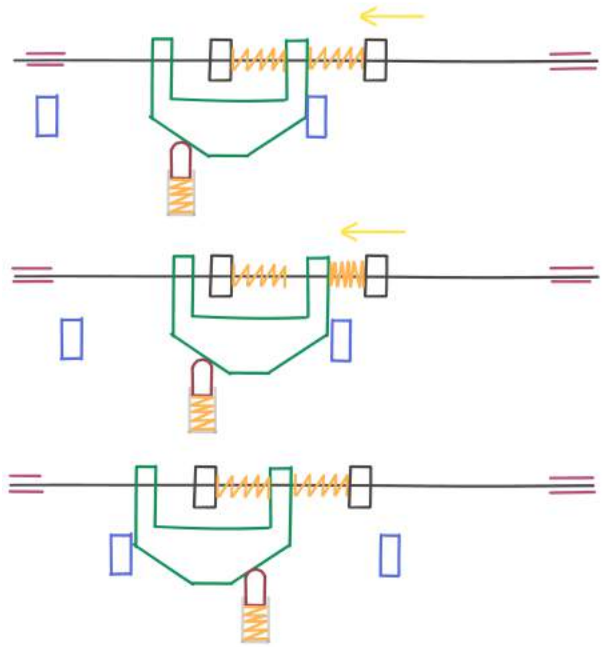

Figure 17 – *Apply Force* Working Principle 3

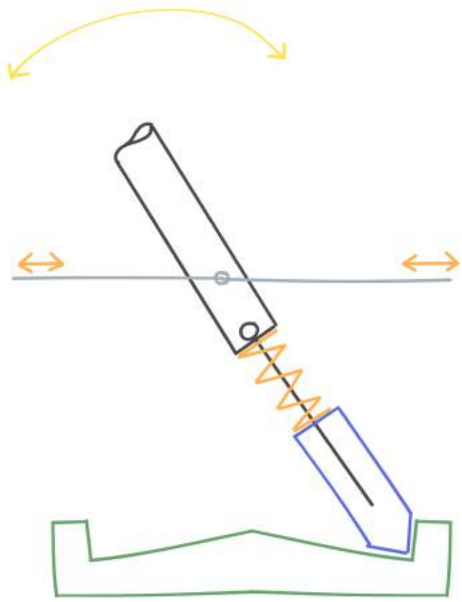

Figure 18 – *Apply Force* Working Principle 4

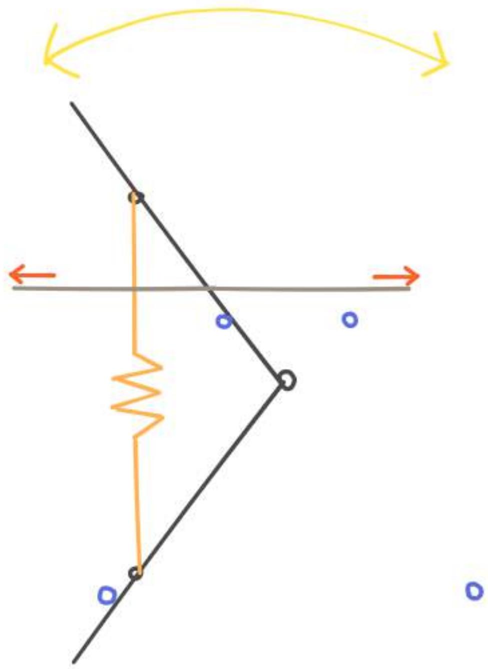

Figure 19 – *Apply Force* Working Principle 5

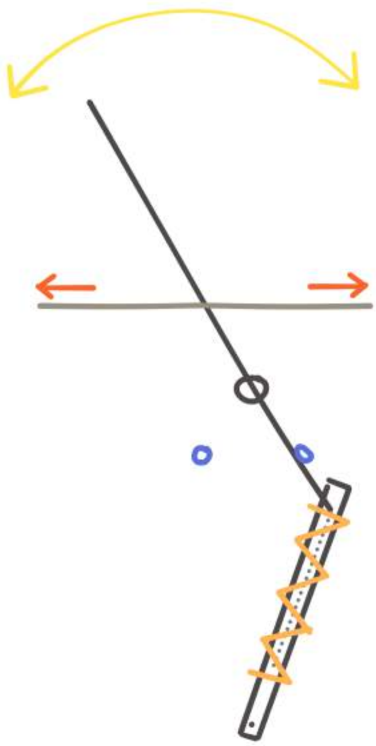

Figure 20 – *Apply Force* Working Principle 6

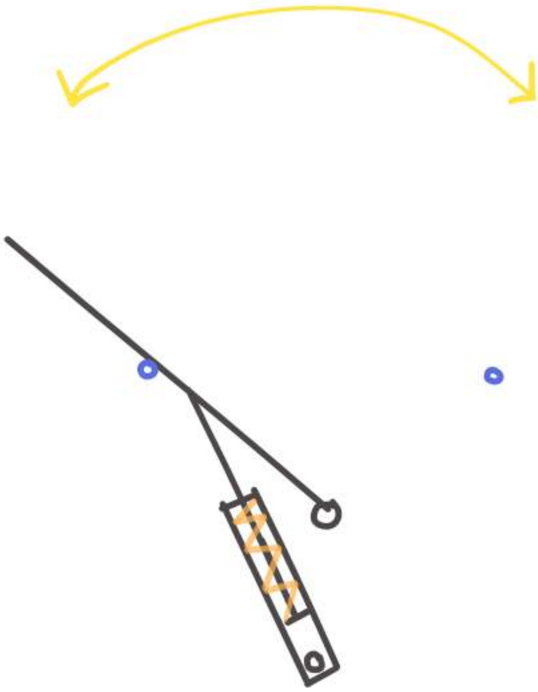

Figure 21 – *Apply Force* Working Principle 7

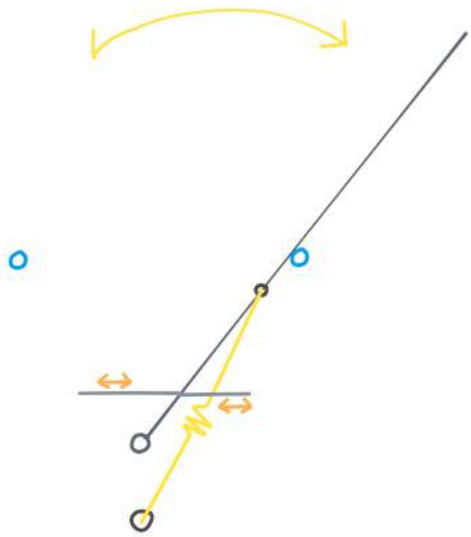

Figure 22 – *Apply Force* Working Principle 8

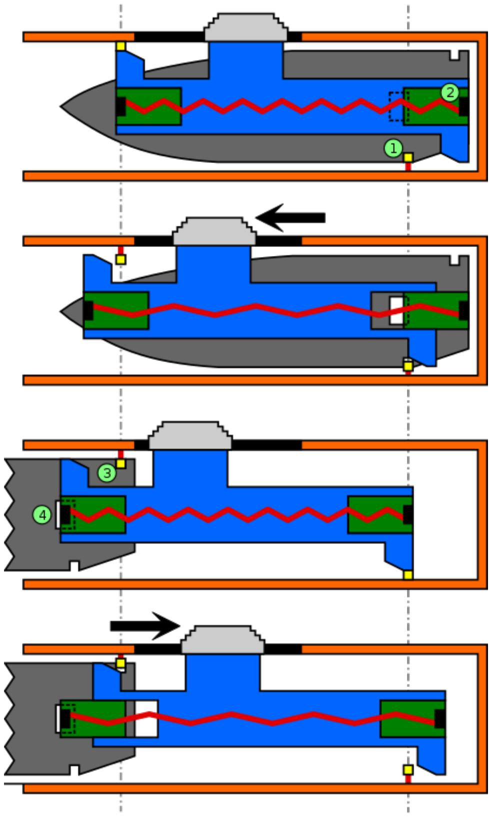

Figure 23 – *Apply Force* Working Principle 9
Source: [14]

6.2.4 Move Stabilizer

With brainstorming sessions and by researching common solutions used in bicycles kickstands, we developed the simple working principle 1 which is shown in Figure 24 (only the left side of the solution is shown; another symmetrical mechanism is also attached to the right chain stay) . We were able to find other working principles by looking at solutions used in aircraft landing gears, such as the F16 model airplane landing gear in Figure 25, but it became clear that most of those solutions were more complex adaptations of working principle 1, with extra bars that are necessary to withstand high loads those components may face. We understand that such working principles would only make sense to our working structure if working principle 1 could not be rigid enough with relatively thin components. Therefore, we made some rough calculations to check if working principle 1 was adequate.

Because of the relatively small forces involved and the possibility of slippage between the stabilizer and the ground, we considered buckling not to be an issue. We then tested the maximum stresses that would occur at the root of the stabilizer when a rider would mount the bicycle. On that condition's worst case, the rider's weight would be applied at the pedal, and reactions would appear on the stabilizer and at the wheels. Figure 26's left sketch shows the forces on the left side of the bicycle. Considering the rider's weight to be of $1kN$, $p = 100mm$, $s = 150mm$ and $h = 368mm$ (radius of 29" wheel), we arrived at the approximate forces and moment at the root of the stabilizer, shown in Figure 26's right sketch. We then considered a squared cross section with side l and thickness d. Using beam stress equations ($\sigma = \frac{-yM}{I} + \frac{N}{A}$, $\tau = \frac{VQ}{Ib}$) and assuming a thin section ($l/2 - d \approx l/2$), we arrived at the stresses at top, middle and bottom of the cross section, respectively show in equations (6.1) to (6.3):

$$\left[\sigma_{top} = -\left(\frac{620}{l^2 - (l-2d)^2} + \frac{l101}{\frac{l^4-(l-2d)^4}{6}}\right) , \tau_{top} = 0\right] \tag{6.1}$$

$$\left[\sigma_{middle} = -\frac{620}{l^2 - (l-2d)^2} , \tau_{middle} = \frac{251\frac{3dl^2}{4}}{l(l^4/12 - (l-2d)^4/12)}\right] \tag{6.2}$$

$$\left[\sigma_{bottom} = -\left(\frac{620}{l^2 - (l-2d)^2} - \frac{l101}{\frac{l^4-(l-2d)^4}{6}}\right) , \tau_{bottom} = 0\right] \tag{6.3}$$

Assuming $l = 2cm$ and $d = 3mm$ and aluminum material (276 MPa yield strength), we calculated a critical *Von Mises yield criterion* safety factor of 2.67.

Since we found it safe to assume that working principle 1 was rigid enough to withstand the necessary loads with thin components, we did not pursue more sophisticated working principles for this subfunction. However, we did define variations of working principle 1 with regards to where the device is attached (chain stay or rear wheel mount). We didn't consider a different rotation direction for the swing-arm because the opposite from the one shown in Figure 24 could result in entanglement between pedals and the device, since the length of the stabilizer has to be about the same of the wheel's radius, which is about the same of the chain stays'.

- Working principle 1 - Attached to chain stay
- Working principle 2 - Attached to rear wheel mount

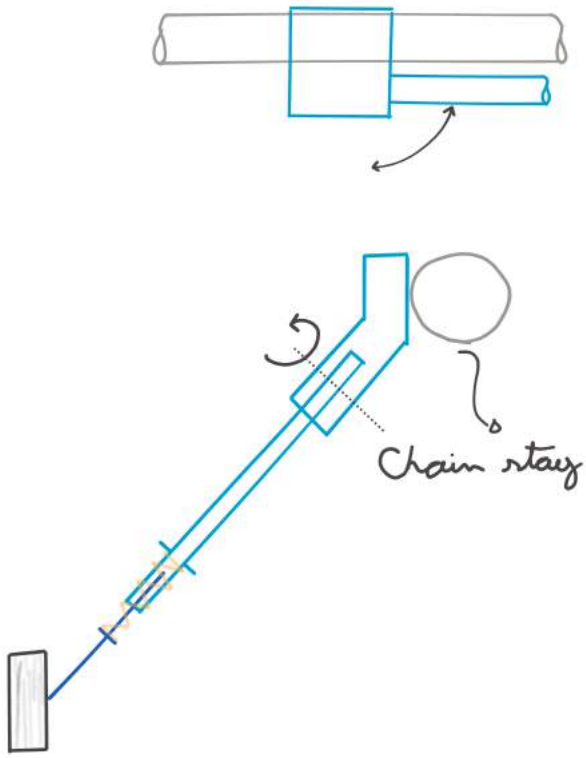

Figure 24 – Left side of *Move Stabilizer* Working Principle 1
& *Stabilize Roll Motion* Working Principle 1

Figure 25 – F16 model airplane landing gear
Source: aliexpress.com

Figure 26 – From left to right:
Forces when rider is mounting bicycle
Forces acting at stabilizer's root

6.2.5 Touch Ground

Once extended by the previous subfunctions, the stabilizer is responsible for providing stability for the bicycle. What is not defined by the other subfunctions and must be specified at this subfunction is how the stabilizer interacts with the ground, i.e. the stabilizer's "foot". Since this is a relativelly simple subfunction, the working principles were determined intuitivelly. We defined 5 possible working principles:

- Working Principle 1: Wheel with spring suspension on stabilizer's arm
- Working Principle 2: Wheel without spring suspension on stabilizer's arm
- Working Principle 3: Ball caster with spring suspension on stabilizer's arm
- Working Principle 4: Ball caster without spring suspension on stabilizer's arm
- Working Principle 5: No moving parts on the tip, just direct contact between stabilizer's "foot" and the ground

6.3 Defining Concepts

On this part of the Conceptual Design, the working principles are selected and combined into working structures. The most promising working structures are then more concretely defined and classified, so that the best Concepts (or principle solutions) can be selected to the Embodiment & Detail Design phase.

6.3.1 Viable Working Structures

Table 2 lists the labels for working principles for each subfunction.

W.P. / Subf.	1	2	3	4	5	6	7	8	9
Convert Energy	CoE1								
Channel Energy	ChE1								
Apply Force	AF1	AF2	AF3	AF4	AF5	AF6	AF7	AF8	AF9
Move Stabilizer	MS1	MS2							
Touch Ground	T1	T2	T3	T4	T5				

Table 2 – Subfunctions and Working Principles Labels

Since there were only 1 option for *Convert Energy* and *Channel Energy*, compatibility only had to be checked for the other 3 subfunctions.

MS[1:2] were clearly compatible with T[1:5]. To better evaluate compatibility, rough sketches were made with AF[1:9] and MS1 (since MS[1:2] only differ in fixation to the bicycle, evaluating compatibility with MS2 was not necessary).

The working principles that produce linear motion output (AF2, AF3 and AF9) were considered not to lead to promising working principles. Although the linear motion could be transformed into rotation, solutions to this issue would introduce unnecessary complexity and increase in the amount of links used. Similarly, working principles that required an additional swim-arm (AF5 and AF6) were also discarded.

Therefore, as shown if Figures 27 to 30, the working principles considered compatible with MS[1:2] were: AF1, AF4, AF7 and AF8.

It is important to note that the said Figures are only conceptual representations of how the working principles could be combined; positions and dimensions are not precisely represented.

In Figures 28, the input movement is transferred to the swim-arm with a gear and gear teeth on the swim-arm. That is only one of the many possible transmissions that could be used between input movement and swim-arm rotation. In light of the many possible solutions, the transmissions have not been drawn in all Figures that represent viable combinations between MS[1:2] and AF[1,4,7,8] (27 to 30) and were only better specified latter in the design process.

Lastly, is was noted that AF8 is basically a more complex adaptation of AF7 so that the spring works under compression and not extension. For that reason, we discarded AF8 for now, and would only reconsider it viable if the work of the spring in extension became an issue.

Then, the working structures considered promising were 24 in total:

CoE1 - ChE1 - AF[1,4,8] - MS[1:2] - T[1:5]

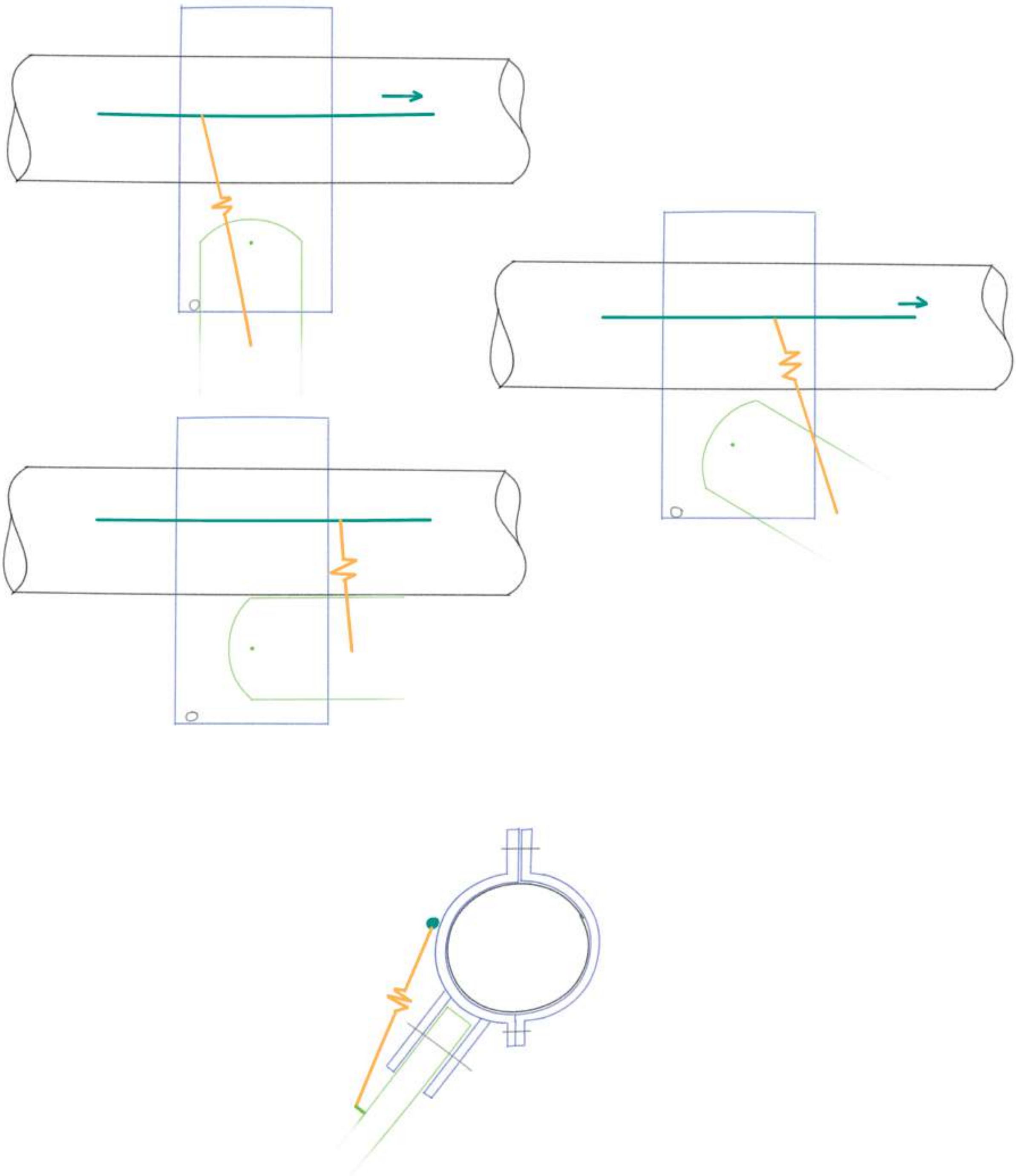

Figure 27 – Rough sketch of combinations between *AF1* and *MS1* (Table 2)

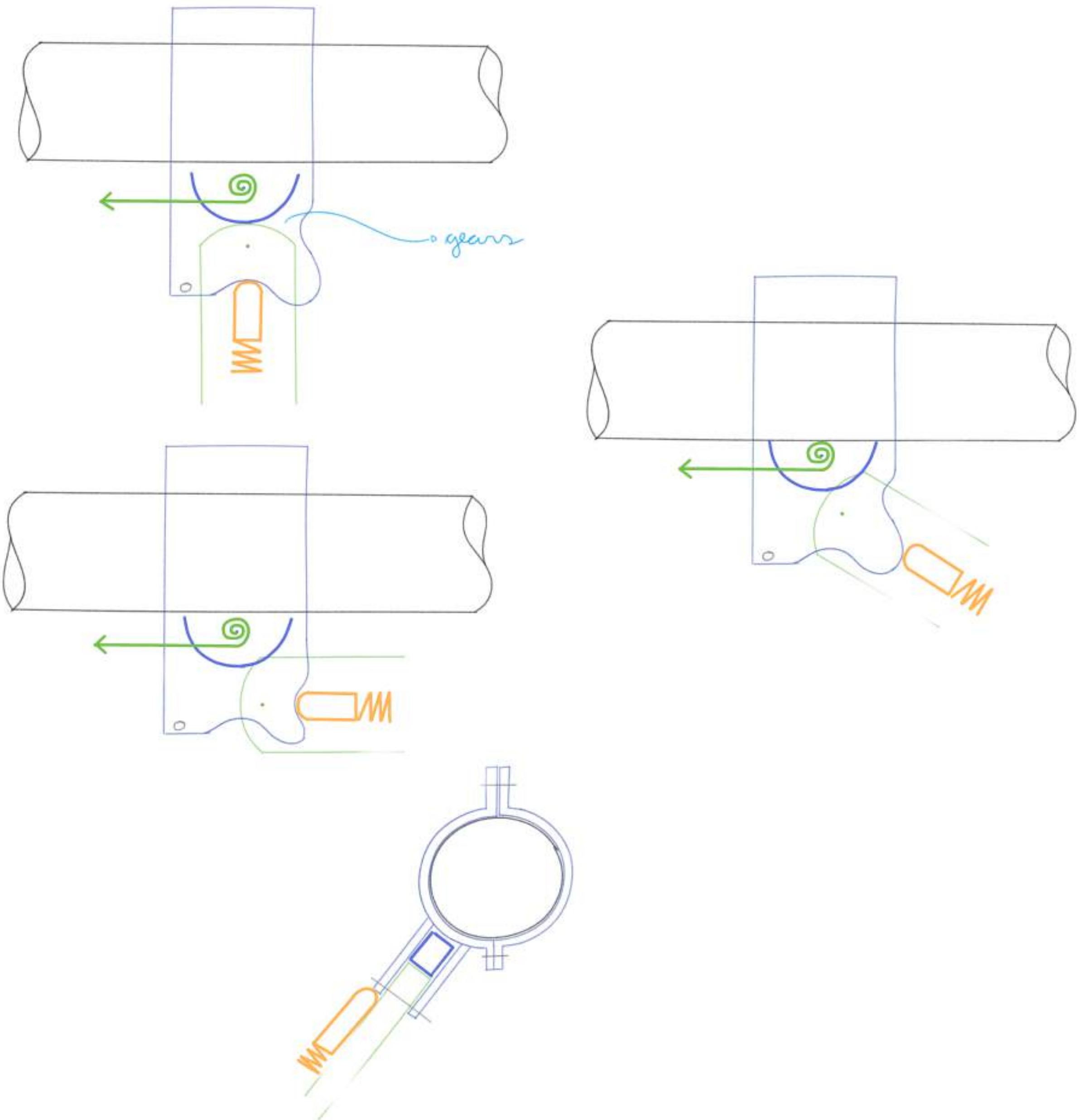

Figure 28 – Rough sketch of combinations between *AF4* and *MS1* (Table 2)

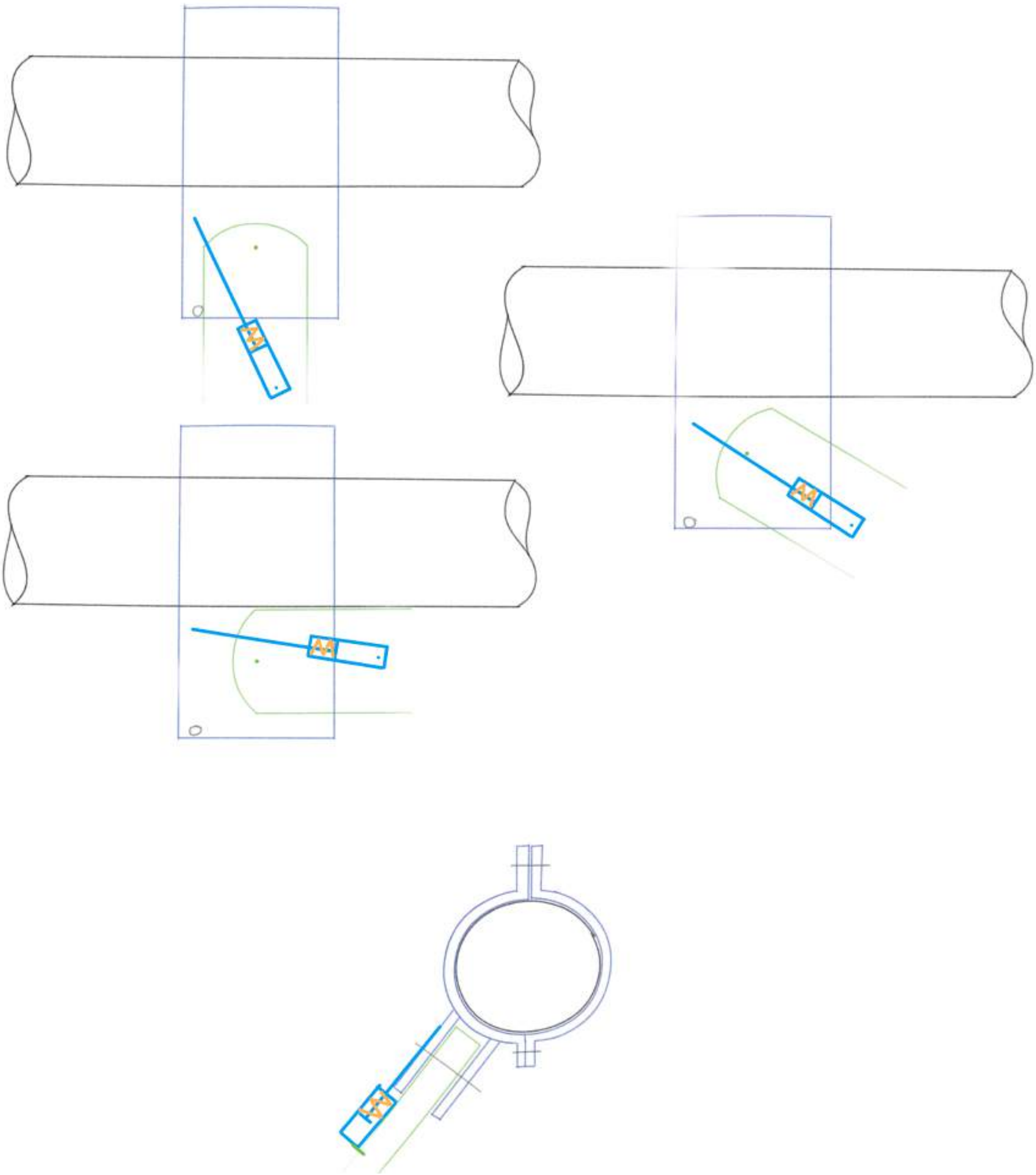

Figure 29 – Rough sketch of combinations between *AF7* and *MS1* (Table 2)
Transmission between input motion and swim-arm not represented

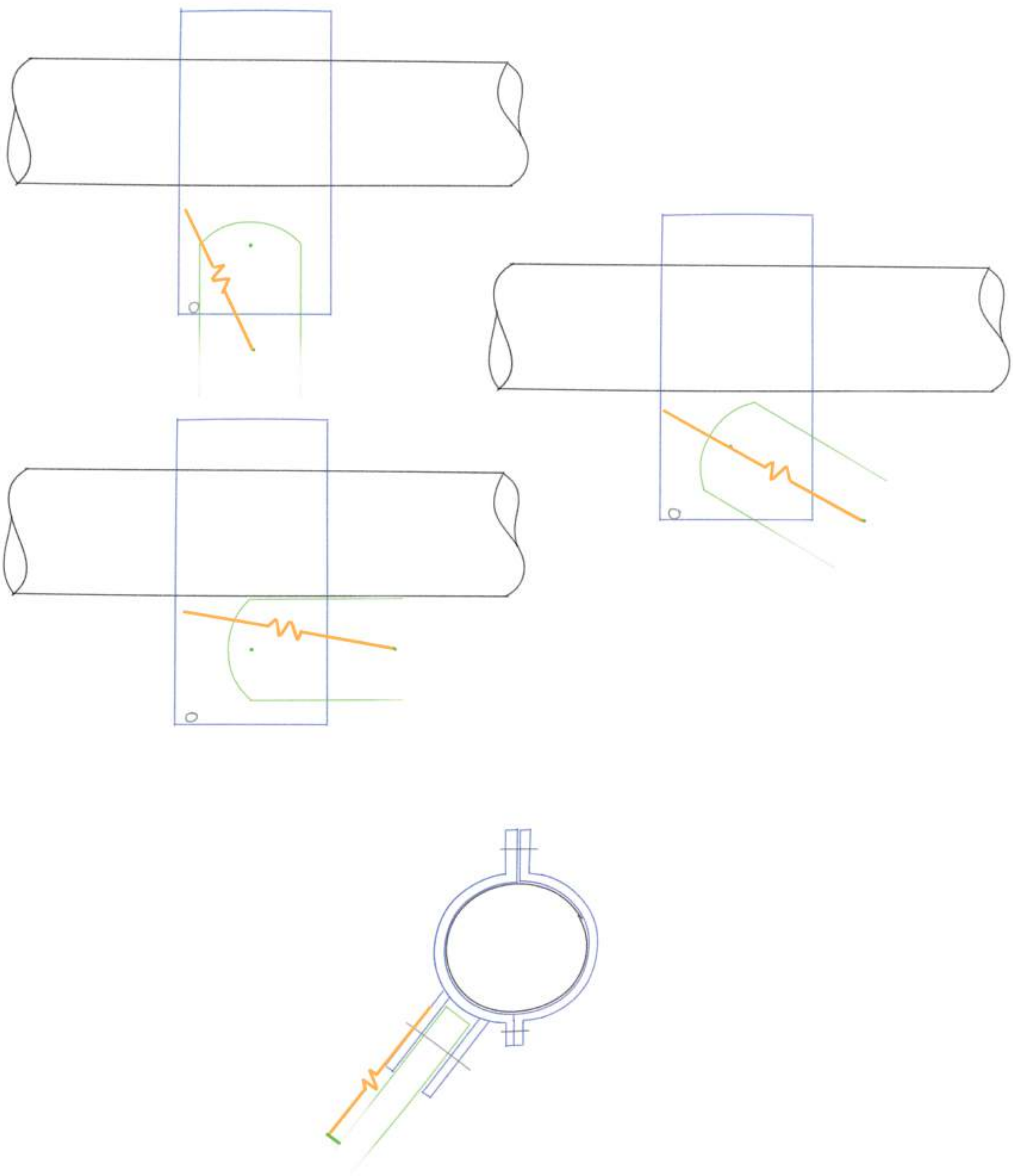

Figure 30 – Rough sketch of combinations between *AF8* and *MS1* (Table 2)
Transmission between input motion and swim-arm not represented

6.3.2 Evaluation and selection of working structures

All viable working structures were compatible with one another and with the overall task, could fulfill the demands in requirement list and were expected to be withing permissible costs. A selection process was then necessary, which was performed as stated in subsection 4.2.1.

The objectives selected for the objectives tree were the following:

- O_1 User friendliness
  - O_{11} Low maintenance
  - O_{12} Easy installation
  - O_{13} Smooth operation
    - O_{131} Smooth deploy/retract action
    - O_{132} Smooth when retracted/deployed
  - O_{14} Discreet appearance
  - O_{15} Low weight
- O_2 Easy to manufacture
  - O_{21} Low number of parts
  - O_{22} Simple components
  - O_{23} Low manufacture precision required

Note that some apparently trivial objectives such as *low cost* were not added for they are directly associated with other objectives.

Figure 31 shows the *Objectives Tree*. The weightings for each objective were the following:

- O_{11} - 0.21
- O_{12} - 0.21
- O_{131} - 0.042
- O_{132} - 0.063
- O_{14} - 0.091
- O_{15} - 0.084
- O_{21} - 0.09
- O_{22} - 0.15
- O_{23} - 0.06

The viable working structures, that were previously defined in subsection 6.3.1, are determined by permutations of the working principles AF[1,4,8], MS[1,2] and T[1:5]. Since all these working principles involved are compatible with one another, a selection process can be performed on each one of the working principles separately.

As seen in Tables[3:5], the working structure with the highest Overall Value was CoE1 - ChE1 - AF4 - MS1 - T4. However, testing would be necessary to assess if T5 wasn't unsafe or would cause too much discomfort when deployed. Therefore, we considered that T4 could be used if necessary, and the working structures chosen to be further developed were:

CoE1 - ChE1 - AF4 - MS1 - T[4,5]

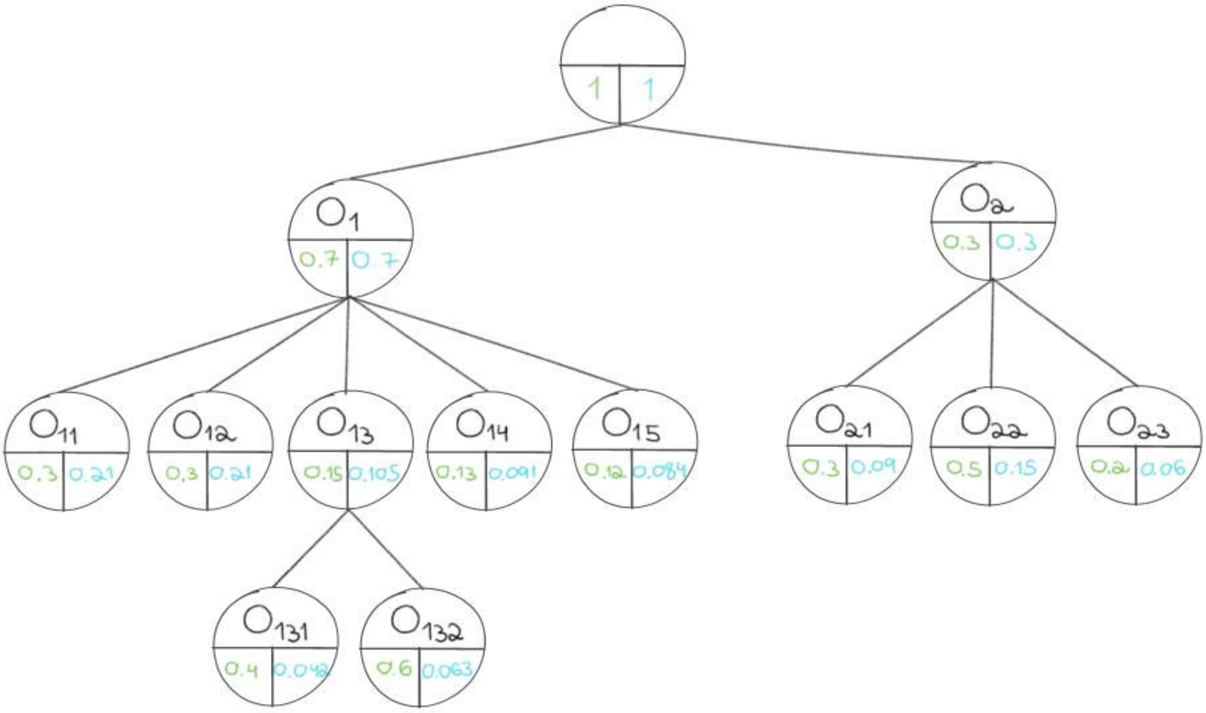

Figure 31 – Objectives tree for selection process

	O_{11}	O_{12}	O_{131}	O_{132}	O_{14}	O_{15}	O_{21}	O_{22}	O_{23}	Overall Value
usepackage AF1	2	2	1	2	1	2	2	2	2	1.867
AF4	1	2	1	2	1	1	1	1	1	1.273
AF8	2	2	3	2	3	2	2	1	1	1.923

Table 3 – Evaluation of working principles AF[1,4,8]

	O_{11}	O_{12}	O_{131}	O_{132}	O_{14}	O_{15}	O_{21}	O_{22}	O_{23}	Overall Value
MS1	1	2	2	2	2	2	2	2	2	1.79
MS2	2	1	2	2	1	2	2	2	2	1.699

Table 4 – Evaluation of working principles MS[1,2]

	O_{11}	O_{12}	O_{131}	O_{132}	O_{14}	O_{15}	O_{21}	O_{22}	O_{23}	Overall Value
T1	1	2	1	4	1	1	1	1	2	1.459
T2	2	2	2	3	2	2	2	2	2	2.063
T3	2	2	2	2	2	2	2	1	2	1.85
T4	2	2	3	1	3	3	3	2	2	2.244
T5	2	4	4	0	4	4	4	4	4	3.328

Table 5 – Evaluation of working principles T[1:5]

6.4 Analysing the dynamics of the deployment/retraction mechanism

Before moving to the *Embodiment & Detail Design* phase, we analyzed the deployment/retraction mechanism to better understand its dynamics, which would be essential for choosing the appropriate spring and parts' dimensions. We modeled the mechanism with an ideal spring, point mass and uniform bar, as seen in Figure 32. Note that torques are considered positive if they act on the direction of increasing θ, and negative if they act on the direction of decreasing it.

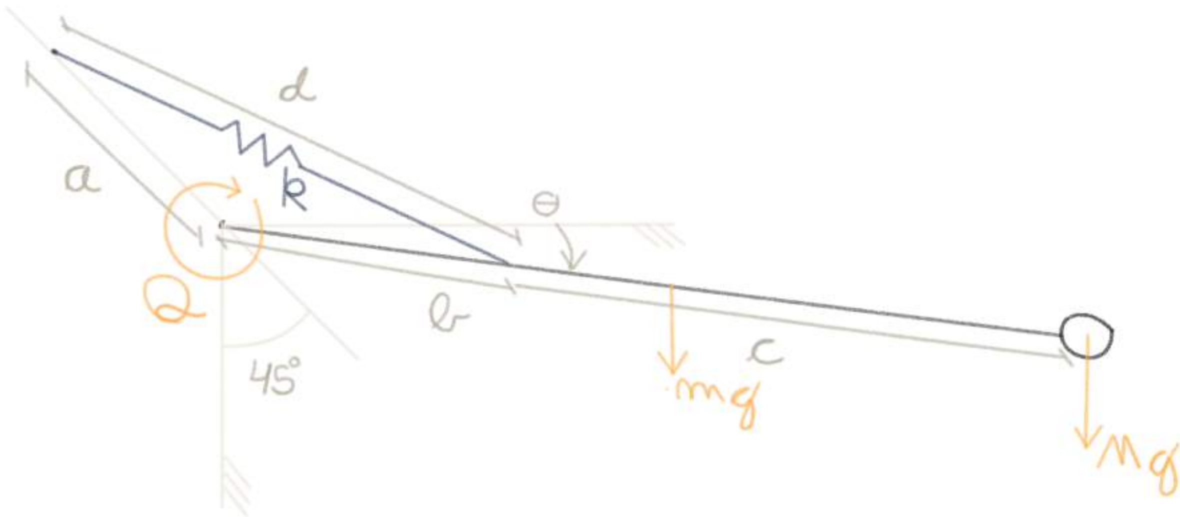

Figure 32 – Mechanism model

Applying the cosine law in triangle $a,\ b,\ d$ we obtain equation 6.4:

$$d(a,b,\theta) = \sqrt{a^2 + b^2 + \sqrt{2}ab(\cos(\theta) + \sin(\theta))} \tag{6.4}$$

With Lagrangian Mechanics and Generalized Forces, equation (6.5) is obtained, where d_0 is the spring's undeformed length and τ is the resulting torque on the swing-arm.

$$\tau = Q + \cos(\theta)g(b+c)\left(m/2 + M\right) + \frac{abk}{\sqrt{2}}(\cos(\theta) - \sin(\theta))\left(\frac{d_0}{d(a,b,\theta)} - 1\right) \tag{6.5}$$

As seen in equation (6.5) the resultant torque is composed by the summation of moments provided by the external moment applied at the bar, Q, by the system's weight, $\tau_w = \cos(\theta)g\left((b+c)m/2 + bM\right)$, and by the spring mechanism, $\tau_s = -\frac{abk}{\sqrt{2}}(\cos(\theta) - \sin(\theta))\left(\frac{d_0}{d(a,b,\theta)} - 1\right)$. Hereinafter, we analyze the spring mechanism's contribution.

$$\tau_s = \frac{abk}{\sqrt{2}}(\cos(\theta) - \sin(\theta))\left(\frac{d_0}{d(a,b,\theta)} - 1\right) \tag{6.6}$$

Knowing that the spring should always be under tension $d(a, b, \theta) > d_0$, analyzing equation (6.6) we can conclude that:

$$\begin{aligned} 0 \leq \theta < \pi/4 \Rightarrow \tau_s < 0 \\ \pi/4 < \theta \leq \pi/4 \Rightarrow \tau_s > 0 \end{aligned} \tag{6.7}$$

However, Equation (6.6) by itself doesn't show how τ_s changes with respect to θ, and where it is maximum/minimum. To assess that information, we analyzed the equation's derivative with respect to θ.

Differentiating (6.6) with respect to θ we get:

$$\frac{\partial \tau_s}{\partial \theta} = \frac{abk}{\sqrt{2}} \left[(\cos(\theta) + \sin(\theta)) \left(1 - \frac{d_0}{d(a,b,\theta)} \right) + (\cos(\theta) - \sin(\theta)) \left(\frac{-d_0}{d(a,b,\theta)^2} \right) \frac{\partial d}{\partial \theta} \right] \tag{6.8}$$

Since $0 \leq \theta \leq \pi/2$, $\cos(\theta) + \sin(\theta) > 0$. Also, since the spring should always remain tensioned, $d(a, b, \theta) > d_0$; which implies $\left(1 - \frac{d_0}{d(a,b,\theta)}\right) > 0$. Therefore:

$$(\cos(\theta) + \sin(\theta)) \left(1 - \frac{d_0}{d(a,b,\theta)} \right) > 0 \tag{6.9}$$

When analyzing $(\cos(\theta) - \sin(\theta)) \left(\frac{-d_0}{d(a,b,\theta)^2}\right) \frac{\partial d}{\partial \theta}$, two cases must be considered:

$0 \leq \theta < \pi/4$:

- $\cos(\theta) - \sin(\theta) > 0$
- It can be geometrically seen that, in this case, an increase in θ causes d to also increase. Therefore: $\frac{\partial d}{\partial \theta} > 0$

$\pi/4 < \theta \leq \pi/2$:

- $\cos(\theta) - \sin(\theta)) < 0$
- In this case, an increase in θ causes d to decrease. Therefore: $\frac{\partial d}{\partial \theta} < 0$

Thus, for $0 \leq \theta \leq \pi/2$:

$$(\cos(\theta) - \sin(\theta)) \left(\frac{-d_0}{d(a,b,\theta)^2} \right) \frac{\partial d}{\partial \theta} < 0 \tag{6.10}$$

One of the two summed therms of equation (6.8) is positive, and the other is negative. In order to determine sign of (6.8), it is then necessary to compare results from (6.9) and (6.10).

Assuming $\frac{\partial \tau_s}{\partial \theta} \leq 0$:

$$(\cos(\theta) + \sin(\theta)) \left(1 - \frac{d_0}{d(a,b,\theta)}\right) \leq (\cos(\theta) - \sin(\theta)) \left(\frac{d_0}{d(a,b,\theta)^2}\right) \frac{\partial d}{\partial \theta} \tag{6.11}$$

From (6.4):

$$\frac{\partial d}{\partial \theta} = \frac{ab(\cos(\theta) - \sin(\theta))}{d(a,b,\theta)} \tag{6.12}$$

The domain for θ is $0 \leq \theta \leq \pi/2$, $\theta = 0$ is a point of:

- Minimum for $\cos(\theta) + \sin(\theta)$
- Maximum for $\cos(\theta) - \sin(\theta)$
- Minimum for $d(a,b,\theta)$, as seen can be seen in Figure 32.

Thus, we can also conclude that, in the valid domain, $\theta = 0$ is a point of:

- Minimum for $\left(1 - \frac{d_0}{d(a,b,\theta)}\right)$
- Maximum for $\frac{d_0}{d(a,b,\theta)^2}$
- Maximum for $\frac{\partial d}{\partial \theta}$

This means that when $\theta = 0$, the left side of equation (6.11) has it's minimum possible value, and the right side has it's maximum. If (6.11) is false even on this condition, it'll also be false for any other valid θ, which would prove our hypothesis ($\frac{\partial \tau_s}{\partial \theta} \leq 0$) to be false; and result, by contradiction, in equation (6.13),

$$\left[(\cos(\theta) + \sin(\theta)) \left(1 - \frac{d_0}{d(a,b,\theta)}\right) > (\cos(\theta) - \sin(\theta)) \left(\frac{d_0}{d(a,b,\theta)^2}\right) \frac{\partial d}{\partial \theta} \right] \Bigg|_{\theta=0} \Rightarrow \frac{\partial \tau_s}{\partial \theta} > 0 \tag{6.13}$$

which can be written as:

$$d_0 < \frac{(a^2 + b^2 + \sqrt{2}ab)^{3/2}}{a^2 + b^2 + (1+\sqrt{2})ab} \Rightarrow \frac{\partial \tau_s}{\partial \theta} > 0 \tag{6.14}$$

Equation (6.14) implies that as long as $d_0 < \frac{(a^2+b^2+\sqrt{2}ab)^{3/2}}{a^2+b^2+(1+\sqrt{2})ab}$, we can be sure that τ_s is minimum at $\theta = 0$ and maximum at $\theta = \pi/2$.

As for the weight's torque contribution:

$$\tau_w = \cos(\theta) g(b + c)\,(m/2 + M) \tag{6.15}$$

By (6.15), we can conclude that $0 \leq \theta \leq \pi/2 \Rightarrow \frac{\partial \tau_s}{\partial \theta} < 0$. Therefore τ_w is maximum at $\theta = 0$ and minimum at $\theta = \pi/2$.

To summarize:

- $\tau = Q + \tau_s + \tau_w$
- $\tau_w > 0\ ,\ \frac{\partial \tau_w}{\partial \theta} < 0\ \forall \theta$
- τ_w is maximum at $\theta = 0$ and minimum at $\theta = \pi/2$
- $0 \leq \theta < \pi/4 \Rightarrow \tau_s < 0$
- $\pi/4 < \theta \leq \pi/2 \Rightarrow \tau_s > 0$
- $d_0 < \frac{(a^2+b^2+\sqrt{2}ab)^{3/2}}{a^2+b^2+(1+\sqrt{2})ab} \Rightarrow \frac{\partial \tau_s}{\partial \theta} > 0$
- $d_0 < \frac{(a^2+b^2+\sqrt{2}ab)^{3/2}}{a^2+b^2+(1+\sqrt{2})ab} \Rightarrow \tau_s$ is maximum at $\theta = \pi/2$ and minimum at $\theta = 0$

7 Embodiment & Detail Design

7.1 Transmission between cable and swing-arm

To assess if a reduction would be necessary in the transmission between cable and swing-arm movement, we estimated the the swing-arm's masses and the maximum forces and displacements that the user can provide to the deployment/retraction mechanism.

7.1.1 Estimating maximum force and displacements available to the deployment/retraction mechanism

To assess the maximum moment and displacements the user can provide, a literature research was performed. We searched for "wrist torque" on *google* search engine and found [15], which measured maximum torque in pronation position of 10 participants (all asymptomatic, male and from 22-31 years old) to be of 8.3 ± 3.1Nm for flexion and 6.5 ± 1.4Nm for extension.

We considered the user can provide a maximum moment of 5.1Nm on flexion or extension, and a maximum an angular amplitude of 90°.

Image 33 shows the dimensions of a twist throttle we had available that fits on a bicycle's standard handlebar. It can be seen that the distance from where the force from the cable is applied to the throttle to it's center of rotation to be of 22.25mm. In that case, the maximum force provided to the cable by the user is given by $F \cdot 22.25 \cdot 10^{-3} = 5.1 \Rightarrow F = 229.21$N, and, the corresponding maximum linear displacement, $d = 90/360 \cdot \pi \cdot 44.5 \Rightarrow d = 3.4$cm

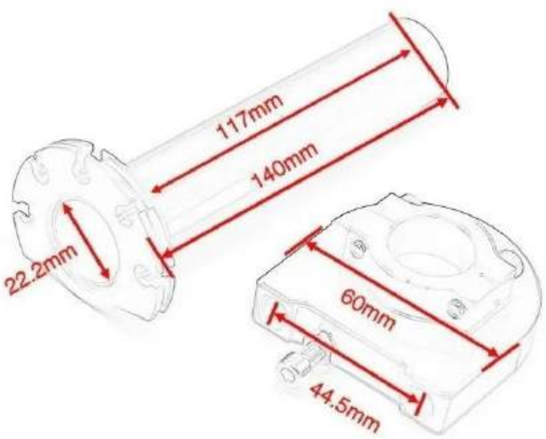

Figure 33 – Twist throttle
Source: mercadolivre.com.br

Since the force is transferred to the mechanism through a cable, because of the friction involved, the available force at the end of the cable is smaller than the force provided by the user. *Bowden cables* are a type of flexible cable composed of an inner cable and an outer housing, as seen in Figure 34. Since they are widely used in bicycles to transfer mechanical forces, we considered *Bowden cables* to model how friction loss would occur.

We used the Capstan equation to estimate the "tension lost" with friction. Figure 35 shows a flexible string wound around a cylinder. μ is the sliding friction coefficient between the line and the cylinder, F is the force applied to the string and F_0 is the resulting force at the end of the string. According to the Capstan equation: $F_0 = \frac{F}{e^{\mu\alpha}}$.

Figure 34 – Cut-away Bowden cable. From left to right: protective plastic coating, helical steel wire, inner sleeve to reduce friction and inner steel cable
By Baran Ivo
Source: [1]

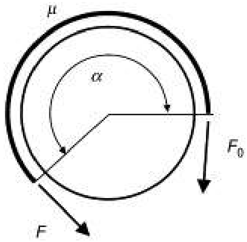

Figure 35 – Illustration of Capstan equation
Source: [3]

Figure 36 shows the approximate path the cables should have on the bicycle. We considered the cable curves 45° from the handlebars to the down tube, and 45° in the opposite direction to meet the chain stays, where the cable must be divided so that stabilizers on both sides can be deployed. The only curves considered were those on the bicycle's plane (as in Figure 36). This way we have that: $F_1 = \frac{F}{e^{\mu\pi/2}}$ and $F_0 = F_1/2$, which leads to $F_0 = \frac{F}{2 \cdot e^{\mu\pi/2}}$. We have, then, that the maximum force available for the mechanism is given by: $\frac{F}{2 \cdot e^{\mu\pi/2}}$. However, since ease of deployment/retraction was part of the requirements list, we multiplied that value by 0.4 to arrive at the maximum force available to the mechanism, F_{max}, given by (7.1)

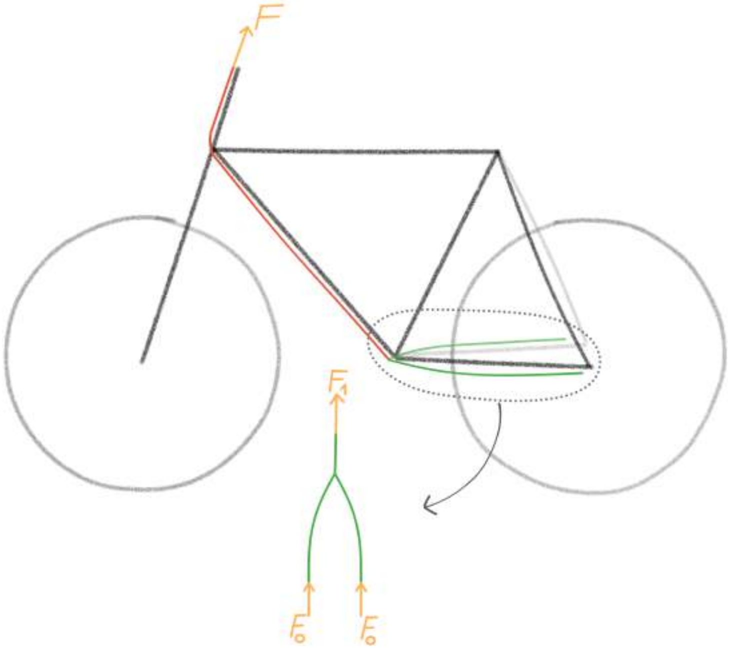

Figure 36 – Path of each cable output from the twist throttle

$$F_{max} = 0.4 \cdot \frac{F}{2 \cdot e^{\mu\pi/2}} \tag{7.1}$$

For the friction coefficient μ, we chose the the friction coefficient for PTFE (Teflon) and stainless steel, since these materials are the most commonly used in bicycle Bowden cables: 0.04 (Source: [2], [4]). Plugging that value for μ in equation (7.1) we get: $F_{max} \approx 43N$

To summarize: We considered the maximum force available to the mechanism to be, approximately, 43N, and the maximum displacement, approximately, 3.4cm.

7.1.2 Estimating deployment/retraction mechanism's length and masses

As seen in Figure 32, the swing-arm from the mechanism is composed of two parts: a bar and a tip, which makes contact with the ground. We further developed two working structures, using either working principles T4 or T5. Since T4 would require larger forces to be provided by the user, we considered that that working principle would be used, and modeled the swing-arm considering that its tip would be a ball caster. To estimate the length and mass from the bar, we used the dimensions from subsection 6.2.4. The length and volume of the bar, in that case, would be of $\sqrt{150^2 + 368^2}$mm $\approx$ 400mm and $\sqrt{150^2 + 368^2} \cdot (20^2 - (20 - 2 \cdot 3)^2)mm^3 \approx$ 81100mm^3. Considering that it would be made of aluminum with a $0.00271 g/mm^3$ density, it's mass would be of, approximately, $220g$. We estimated the mass of the ball caster using the information from the Pololu manufacturer (pololu.com) and from the Banana Robotics online store (bananarobotics.com). The heaviest option we found, which is entirely constructed of aluminium, has a mass of $35g$, which we considered to be the mass of the ball caster in our analysis.

Equation (6.5) then becomes:

$$\tau = Q + 0.4g\cos(\theta)\,(0.22/2 + 0.035) + \frac{abk}{\sqrt{2}}(\cos(\theta) - \sin(\theta))\left(\frac{d_0}{d(a,b,\theta)} - 1\right)$$

The chose for a and b has a major implication on how the mechanism will look, and how high the value of k will need to be. Choosing higher values for a and b allows a spring with smaller elastic constant to be used, but would make the design less slim/minimalist. For this estimation we chose $a = 3cm$ and $b = 15cm$.

From equation (6.14) we have that d_0 has to be smaller than 12cm. A large d_0 is has the benefit of reducing the relative maximum elongation from the string, but causes a larger k to be necessary. For this analysis, we chose $d_0 = 10$cm.

With $g = 9.8$ the equation on motion then becomes:

$$\theta = Q + 0.5684\cos(\theta) + \frac{0.0045k}{\sqrt{2}}(\cos(\theta) - \sin(\theta))\left(\frac{0.1}{\sqrt{0.0234 + 0.0064(\cos(\theta) + \sin(\theta))}} - 1\right) \tag{7.2}$$

7.1.3 Determining minimum spring's elastic constant

The spring's elastic constant has to be large enough to ensure that the mechanism remains "locked" when no moment is being provided, i.e., $\tau < 0$, $(Q, \theta) = (0, 0)$ in equation (7.2). In that case: $k > 425N/m$.

As seen in Figure 37, as k increases, the amplitude for the resulting torque on the deployment/retraction mechanism, τ, also increases. Also, a higher k leads to a larger interval for θ in which the mechanism retracts with $Q = 0$, which is the region where $\tau < 0$. Therefore, a larger k requires the user to provide a smaller motion before the retraction continues with just the force provided by the spring, but requires the user to provide a larger $|Q|$ to guarantee retraction of the mechanism.

Considering that the maximum torque the user can provide in counter clockwise direction is Q_{max}, the maximum value for k is given by defining $\tau(\theta = \pi/2) = 0$ in equation (7.2), and is written in equation (7.3).

$$k_{max} = 746 \cdot Q_{max} \tag{7.3}$$

If a reduction was not necessary, the force from the user would be transmitted to the swing-arm by a wheel fixed to it. A larger wheel would require a smaller force to

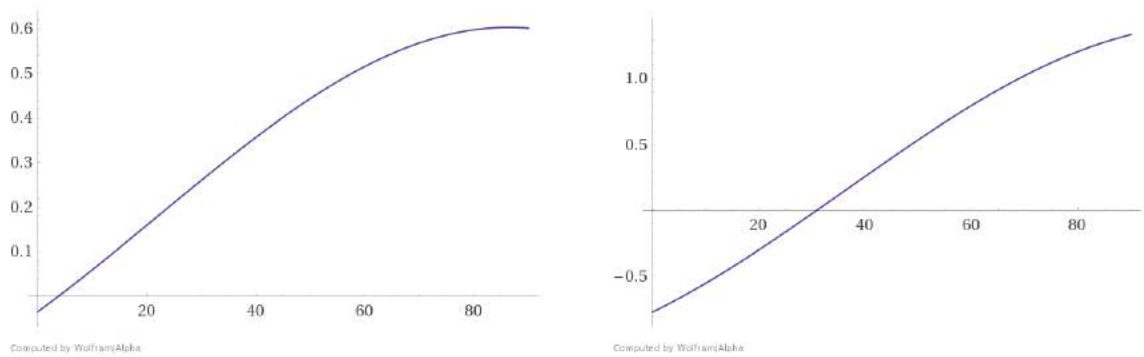

Figure 37 – τ from equation (7.4) for $(k, Q) = (450, 0)$ and $(k, Q) = (1000, 0)$, respectively. θ in degrees in horizontal axis

be provided by the user. With the appearance of the mechanism in mind, we considered the maximum diameter of said wheel to be of $5cm$. In that case, we have that $Q_{max} = 5cm/2 \cdot F_{max} = 1.075Nm$. By equation (7.3), $k_{max} = 803N/m$.

To summarize: We considered that the force from the user is transmitted to the swing-arm by means of a wheel with a diameter of $5cm$ fixed to the swing arm. The spring's elastic constant k must be larger than $425N/m$, but smaller than $803N/m$ for the deployment/retraction mechanism to function properly.

Choosing $k = 700N/m$, equation (7.2) becomes equation (7.4), which is plotted for when the user is not providing any force ($Q = 0$), is providing F_{max} force for deployment ($Q = 1.075$) and is providing F_{max} force for retraction ($Q = -1.075$) in Figures [38 - 40], respectively.

$$\theta = Q + 0.5684\cos(\theta) + 2.23(\cos(\theta) - \sin(\theta))\left(\frac{0.1}{\sqrt{0.0234 + 0.0064(\cos(\theta) + \sin(\theta))}} - 1\right) \tag{7.4}$$

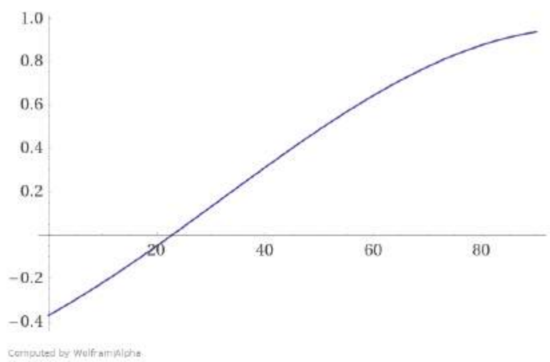

Figure 38 – τ from equation (7.4) for $Q = 0$ (θ in degrees in horizontal axis)

Given that the user can provide a linear displacement of $3.4cm$, the maximum angular displacement that can be provided to the swing-arm is of $\frac{3.4}{5\pi}360° = 77.9°$. As seen

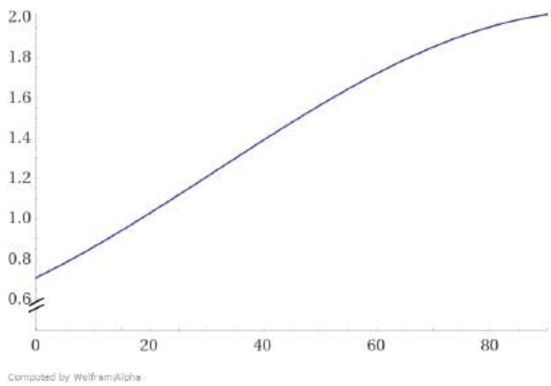

Figure 39 – τ from equation (7.4) for $Q = 1.075$ (θ in degrees in horizontal axis)

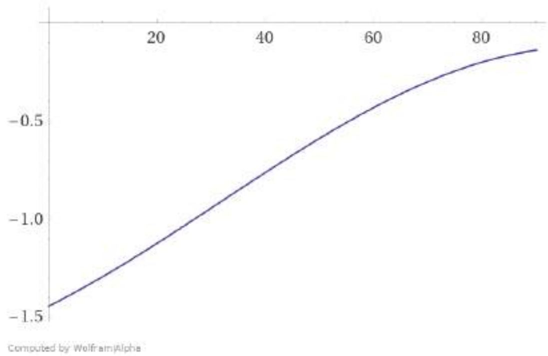

Figure 40 – τ from equation (7.4) for $Q = -1.075$ (θ in degrees in horizontal axis)

in Figure 40, the resulting torque on the swing arm is considered negative when the user applies F_{max} in the direction of retraction.

Given the maximum angular displacement the user can provide, this means that the user can provide enough force to retract the mechanism from $\theta = 90°$ until $\theta = 12.1°$. However, from Figure 38 we can see that the resulting torque is counter-clockwise for $\theta = 12.1°$ even if $Q = 0$. This means that the user can successfully retract the mechanism. Similarly, it can also be seen that the user can successfully deploy the mechanism in the conditions we considered.

In conclusion: given the characteristics we expect the deployment/retraction mechanism to have ($a = 3cm$, $b = 15cm$, $c = 400mm$, $220g$ swing-arm, $d0 = 10cm$, $k = 700N/m$ and PTFE Bowden cable to transfer force from handlebars to the mechanism), a simple transmission (a wheel fixed to the swing-arm) of $5cm$ in diameter will be sufficient for deployment and retraction motions, even if we choose to attach a ball caster to the swing-arm's tip.

7.2 Solution specification

The solution's details are specified hereinafter:

Rotary motion from the user is converted to linear motion using a motorcycle twist throttle, as the one in Figure 33.

The linear motion is transmitted to the mechanism that supports the bicycle using bicycle Bowden cables and a pair of mechanisms that "split" each cable that comes out of the twist throttle, shown in Figures 41 and 42. This way, there are, in total, 4 cable outputs. For each direction of wrist rotation that the user can provide, 2 of those cables are pulled.

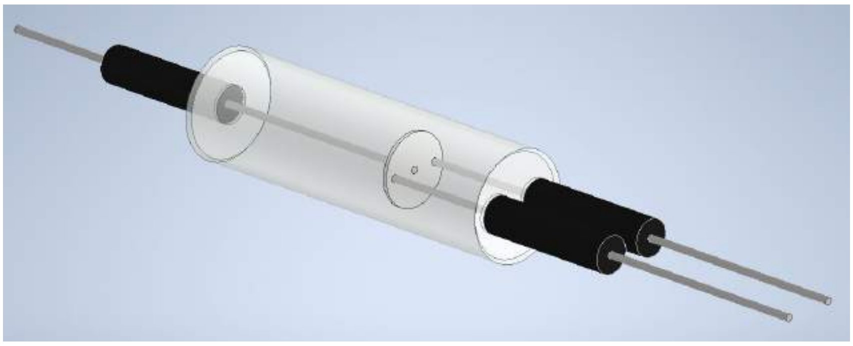

Figure 41 – CAD model of mechanism that "splits" Bowden cable

Figure 42 – Commercially available mechanism that "splits" Bowden cable
Source: bicimoto.com.br

One mechanism that supports the bicycle, Figures 44 to 47, is attached to the left chainstay of the bicycle, and a symmetrical one is attached to the right side. The cables are connected as illustrated in Figure 43: One cable output from one of the mechanisms that "split" a cable is attached to the left support, and the other cable output is attached to the right support. The same is done with the other mechanism that "splits" the other cable. The cables are then attached to the support mechanisms in a way that the swing-arm from both of them rotate in the same direction when the user rotates the twist throttle.

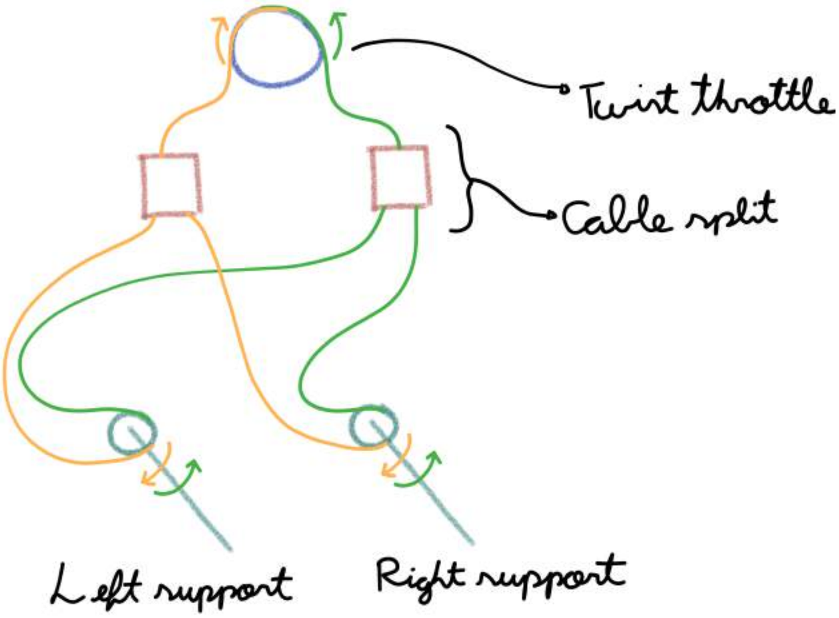

Figure 43 – Diagram of connections between twist throttle, mechanisms that split cables and mechanisms that support bicycle

The technical drawings of the parts that make the left-side support mechanism are show in Figures 69 to 78 (see Annex).

To further verify that the structure would not fail, as calculated analytically in subsection 6.2.4, a static structural finite element analysis was performed on a simplified version of the solution (the dimensions were kept the same, but some features of the model were suppressed).

The analysis was performed using Autodesk Inventor, the avarage element size was set to $0,070$ (fraction from the bounding box length), the minimum element size was set to 0.2 (fraction of average size), grading factor was set to $1,500$ and the maximum turn angle was of 60°. The structure was modeled using solid (tetrahedron) elements. Similarly to what we considered in the analytical analysis, we considered a vertical force of 410N applied to the tip of the swing-arm (the force magnitude was determined by equilibrium of moments in the left-side image from Figure 26, where h and s have been measured from the CAD model and p was considered 100mm), as seen in Figure 48. We considered the highlighted surfaces in Figure 49 to be fixed. All parts were considered to be made of aluminum 6061.

Figure 50 shows the safety factor distribution after the analysis. The minimum safety factor, which happened at the root of the swing-arm, was of 2.61. Thus, we assumed that the solution developed would not fail statically during operation.

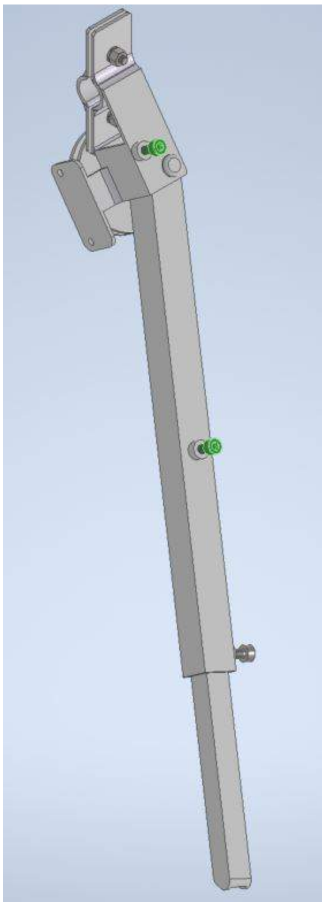

Figure 44 – Left-side mechanism that supports bicycle
Rubber band (not shown) is connected between green screws

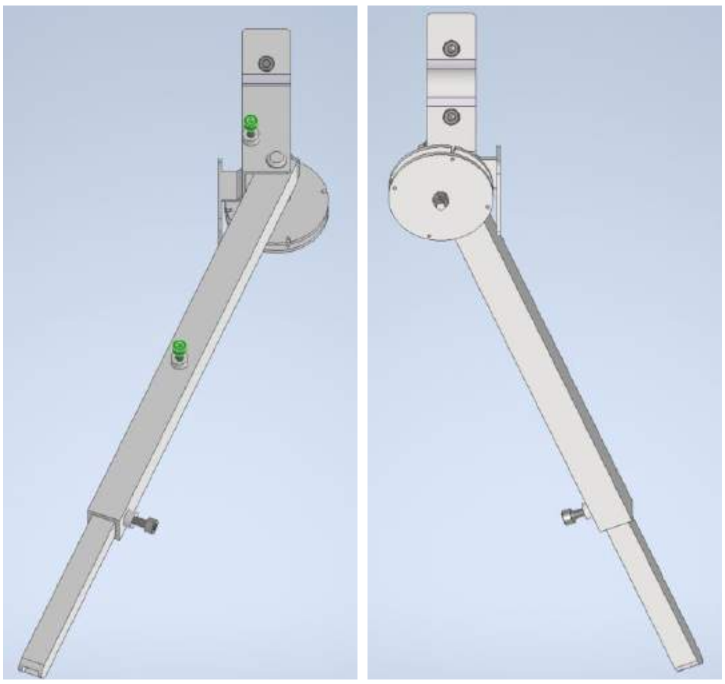

Figure 45 – Front and rear view of left-side mechanism that supports bicycle
Rubber band (not shown) is connected between green screws

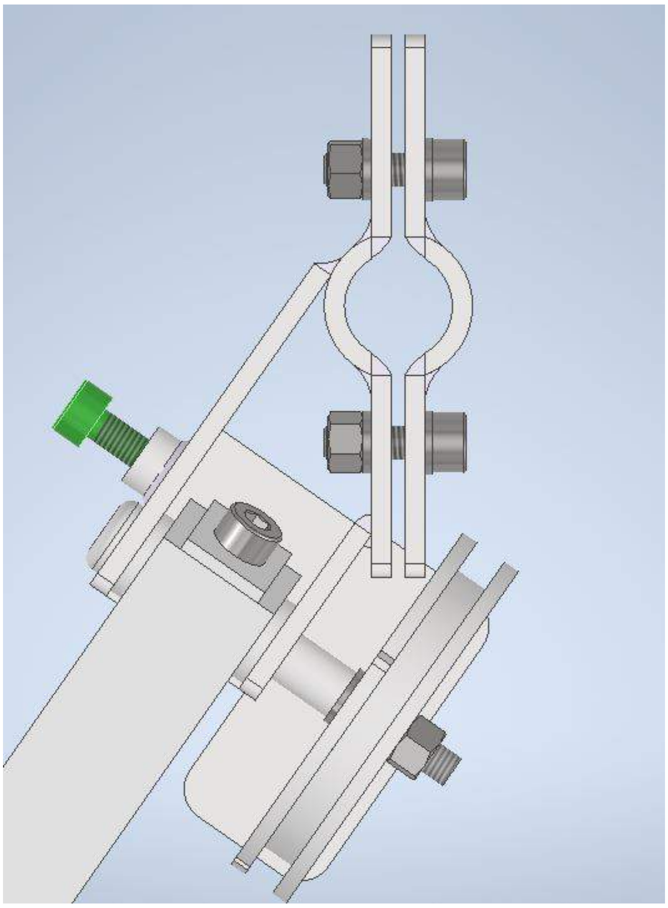

Figure 46 – Zoomed-in right-side view of left-side mechanism that supports bicycle

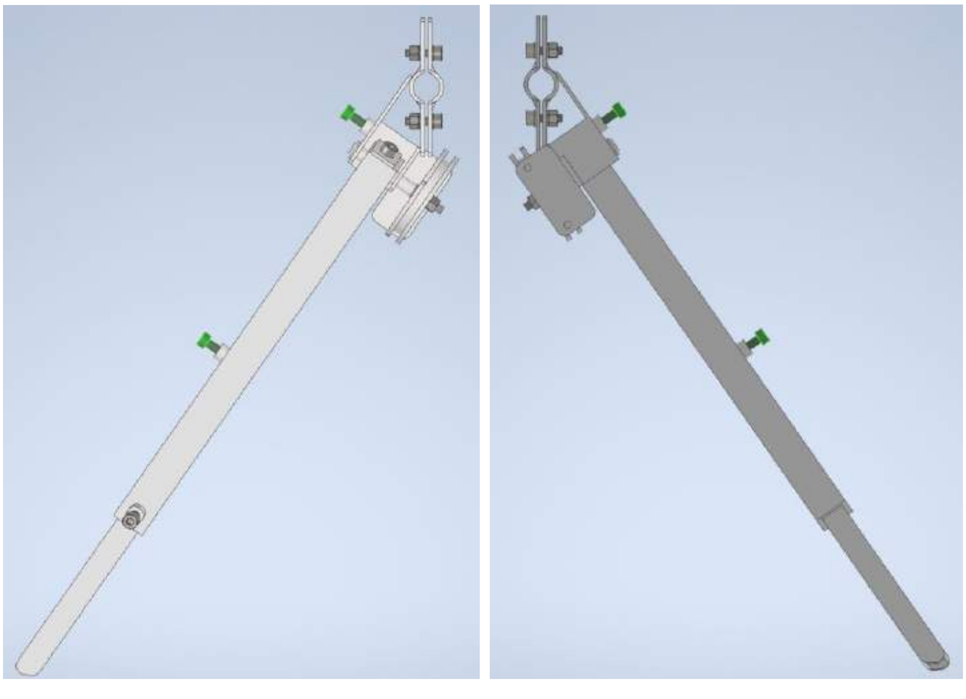

Figure 47 – Right and left-side view of left-side mechanism that supports bicycle
Rubber band (not shown) is connected between green screws

Figure 48 – Direction of force with magnitude 410N applied to support mechanism in finite element method static structural simulation

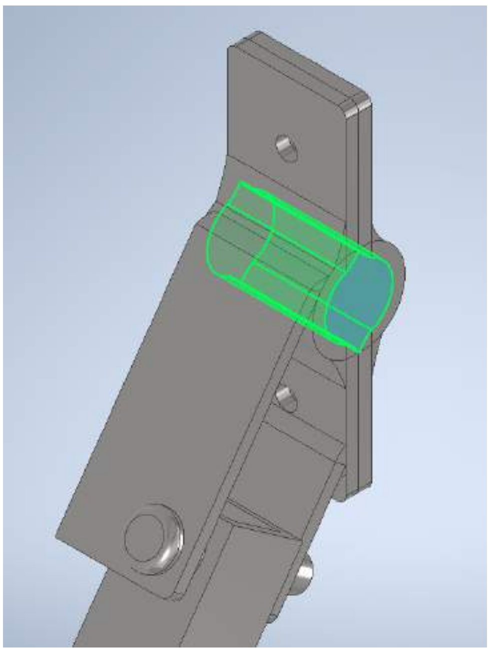

Figure 49 – Surfaces set as *fixed* in finite element method static structural simulation

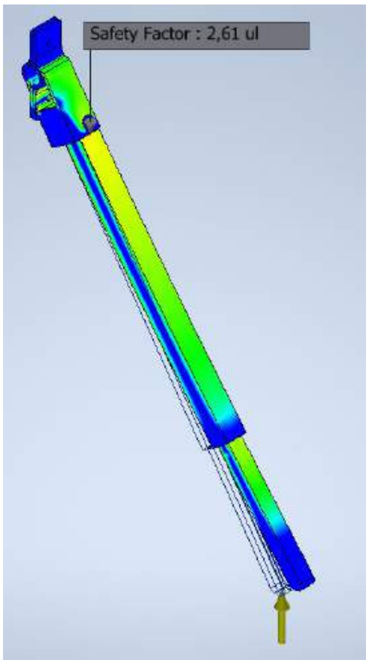

Figure 50 – Result of finite element method static structural simulation. Tones closer to blue represent higher safety factors, and tones closer to orange represent lower safety factors. Lowest safety factor (2.61) is indicated

8 Manufacture & Testing

8.1 Prototype specification

To test the solution we developed, we manufactured a prototype. We did not have a "regular" sized commuter bicycle at our disposal, but we did have a *bmx* style (with 20” wheels) available. Although said bicycle did not match the bicycle size to which the solution was designed, the overall operation of the solution and the user experience would be very similar on regular sized commuter bicycles and the one we had available.

The resulting forces on the support mechanism when the rider is supported by it would be smaller on the *bmx* than on regular sized bicycles, for the center of gravity is closer to the ground on the smaller bicycle. However, we had determined by analytical (subsection 6.2.4) and numerical (section 7.2) methods that the solution would not fail statically for the forces it would be subjected to during operation. Therefore, we did not consider that experimentally validating the structural integrity on the regular sized commuter bicycles was necessary for validating the overall solution. This way, validating the overall solution on a smaller bicycle would not only be sufficient, but also provide the benefit of easing and lowering costs of the manufacture process.

Given the symmetry of the solution, we also chose to manufacture and test only the left-side support mechanism. This would not only reduce costs and time needed to manufacture, but also allow us to test if a support in both sides was, in fact, necessary.

The dimensions for the prototype are the same as for the original solution, except for the swing-arm, in Figure 79 (Annex), which had to be made shorter.

The prototype was manufactured using stainless steel, for it was the material the manufacturer had available, and purchasing new material was particularly difficult because of the COVID-19 pandemic. A latex rubber band, shown in Figure 59, was used as deployment/retraction mechanism spring in the prototype. It was fixated to the screws on the swing-arm using auxiliary wires, and the friction from the latex itself. Cables were fixated on the swing-arm’s reel using motorcycle cable fasteners, as seen in Figure 58.

It is important to note that the prototype was designed with ease of assemble in mind. Only 2 tools were required to attach the device to the bicycle: an 8mm Allen key and wrench, as seen in Figure 60. Duct/insulator tape or zip-ties are also required to attach cables to bicycle frame.

Figure 51 shows the assembled prototype, and Figures 52 to 58 show the prototype installed on the bicycle.

Figure 51 – Assembled prototype and the required tools for its installation

8.2 Testing

Because of the COVID-19 pandemic, we did not consider it reasonable to invite participants which do not live together to test our solution. The tests were performed by the author of this text (referred to as subject A) and his mother (referred to as subject M), which live together at the same place.

In total, 3 tests were performed:

1. Installation test by subject M (Figure 61)
2. Departure/stop test in a controlled environment by subject A (Figures 64 and 63)
3. Departure/stop test at the street by subject A and M (Figures 65 to 68)

Subject A did not participate in test 1 for we wanted the installation process to be tested by a person with less experience with tools and mechanical assemblies.

On test 1, the time necessary to install the prototype was measured, and subject M was asked to assess how easy she considered the installation procedure.

On test 2, the rider executed two sequences:

- Start mounted at the bike at standstill, with the support mechanism deployed and both feet on the pedals. Begin pedalling and, once in motion, retract support

Figure 52 – Bicycle with prototype installed

mechanism (Figure 63)

- Starting unmounted with both feet on the ground and the support mechanism retracted, mount the bicycle and begin pedalling. Deploy the mechanism, brake bicycle and, as the bicycle looses speed, lean slightly left (Figure 64)

After this test, small necessary adjustments were identified and performed before the test 3.

Subjects A and M, one after the other, started test 3 by riding the bicycle on a calm street executing turns to assess the bicycle's maneuverability. Then, again one after the other, they executed the complete stop/depart sequence:

1. Start riding the bicycle with the support mechanism retracted
2. Deploy the mechanism
3. Gradually brake the bicycle and, as the bicycle looses speed, lean slightly to the left
4. Stand still for a moment and readjust pedals position
5. Start pedalling and, once in motion, retract support mechanism

Both subjects then discussed their experiences and explained what they enjoyed and what they thought should be improved in the prototype.

Figure 53 – Close-up view of the deployed support mechanism

Figure 54 – From left to right, top to bottom: sequence of pictures showing the swing-arm's motion during retraction of the support mechanism

Figure 55 – Close-up view of the support mechanism attached to the bicycle

Figure 56 – Close-up view of the twist throttle

Figure 57 – Close-up view of the support mechanism showing the where cables are connected

Figure 58 – Close-up view of the support mechanism showing the reel part and cable fastener screws

Figure 59 – Latex rubber band used in prototype
Source: mercadolivre.com.br

Figure 60 – Steps required to install the prototype to a bicycle
From left to right: fasten screws and nuts at the chainstay and fasten screws at the twist throttle

Figure 61 – Prototype installation test

9 Results

In test 1, approximately 10 minutes were necessary for the installation of the prototype. Subject M considered that the installation was very easy.

After test 2, we noticed that, depending on the floor's surface and on how hard the rider would lean onto it, the support mechanism's fixation to the chainstay could slip and rotate. A quick way we found to fix this and proceed testing the prototype was to add a nail to where the mechanism attaches to the bicycle's chain stay, as in Figure 62. This way, the support mechanism was no longer kept in place only by friction.

Figure 62 – Adaptation made between test 2 and 3 to prevent rotation of support mechanism

Figures 63 to 68 show examples of stop/departure sequences executed at test 3. Both subjects were able to, multiple times and without placing feet on the ground, successfully deploy the support mechanism, remain supported by it, start pedaling and retract the mechanism. They both considered that the effort and attention required to deploy/retract the mechanism were very low, and that the deployment/retraction was quick, silent and reliable. They agreed that, when retracted, the prototype didn't affect the bicycle's maneuverability and both felt stable and comfortable while supported by the mechanism, even when moving (such as adjusting pedals position). Both stated to have enjoyed the overall experience when using the prototype.

We noticed in some tests that the swing-arm touched the ground before reaching it's travel limit if the rider was leaning left when deploying the mechanism.

Figure 63 – Pictures from footage of departure during test 2

Figure 64 – Pictures from footage of stop during test 2

Figure 65 – Pictures from footage of subject A executing stop/depart sequence (part 1)

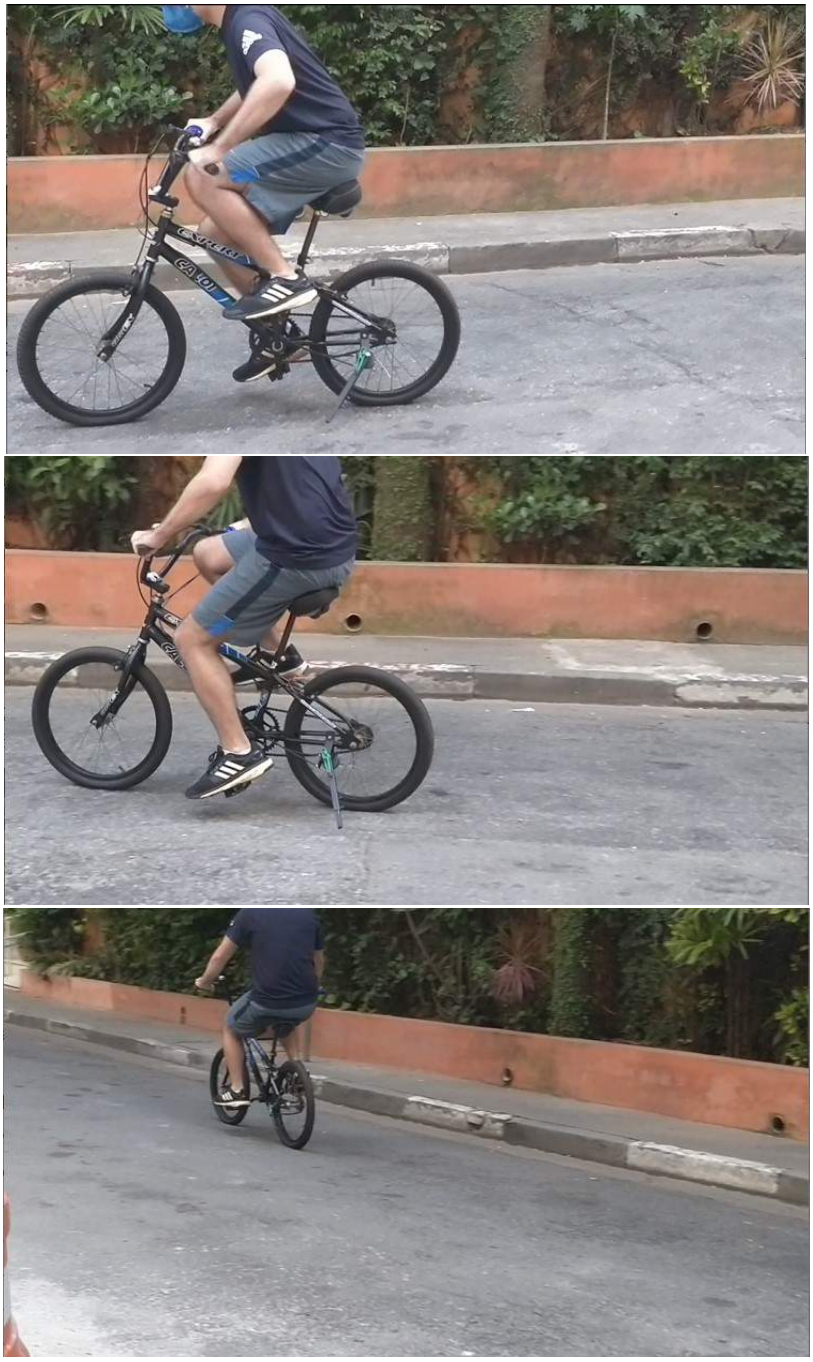

Figure 66 – Pictures from footage of subject A executing stop/depart sequence (part 2)

Figure 67 – Pictures from footage of subject M executing stop/depart sequence (part 1)

Figure 68 – Pictures from footage of subject M executing stop/depart sequence (part 2)

10 Conclusions

We conclude that the solution we developed is a success. Based on the assessments made by the tests' participants, all requirements from the project's requirement list were met, and the project's main objective (chapter 2) was achieved.

The usage of just one support mechanism (and not one on each side of the bicycle) showed to be sufficient for some users. Despite adding weight, cost and etc., using two supports might be necessary for some users who look for a solution that does not require the rider to lean to one specific side while the bicycle looses speed with braking.

Two further enhancements that can be made to the solution we developed were detected: A more robust mechanical lock to the support mechanism, similar to the adaptation in Figure 62, should be incorporated to the solution. To prevent the swing-arm from hitting the ground before reaching it's end of travel, a mechanical limiter that stops it perpendicular to the chainstay (as seen in top right of Figure 54) could also be incorporated.

11 Personal comments

This chapter was left for the personal reflections I, André Bianchessi, wanted to make about my experiences during this project. This is, of course, a scientific work; but, being it an undergraduate dissertation, I believe some meditations about the advantages of the scientific approach itself when compared to a purely intuition-based approach can be valuable.

A thought that might come to mind when viewing the prototype we manufactured is: why on earth would a 70+ pages dissertation be necessary to design a *bicycle kickstand*? There is, in fact, merit to that point. If I had just gone to someone experienced with metalwork and roughly described the project's objective, we would possibly, after some trial and error, have a functioning solution ready relatively quickly. However, there are some major caveats to that approach, which we avoided with the methods we used.

At first, as seen in the bibliography review, we firmly believed we had to pursue a fully automatic solution with sensors, batteries and actuators. The design methodology we used forced us to formulate the problem in a solution neutral way and to identify the essential problem we were trying to solve and what its constraints were. Only then did it became clear that a purely mechanical solution would make much more sense, and we drastically changed a path we thought we would chase. The search for working principles allowed us to find a very large solution field and, by evaluating each possible solution, we had a lot of control and confidence that our design was approaching an optimal solution.

The models we developed throughout the design process helped us understand some effects that are not obvious at first sight, and to know what we had to focus to ensure our solution was possible and likely to work. The analysis of the dynamics of the deploy/retraction mechanism showed us that we must be careful with what values we choose for the final product's transmission reel diameter and spring's initial length and elastic constant. The analysis of the available forces and displacements made us realize how important it was to ensure that the cables don't make unnecessary turns when the prototype is installed on the bicycle, and showed us that the user should be able to provide enough force and displacements for the mechanism to function properly. The structural analysis we performed gave me confidence to allow my mother to test the prototype without fearing it might break.

Although it's clear that what we did was far from rocket science, the approach we took reminds me of a quote from former astronaut Chris Hadfield: "No astronaut launches to space with their fingers crossed. That's not how we deal with risk". The solution always has to be verified no matter the models or methods used, but it pleases me that at no time during the design process did we cross our fingers and just blindly hoped for something to work.

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Annex

ANNEX A – Solution's technical drawings

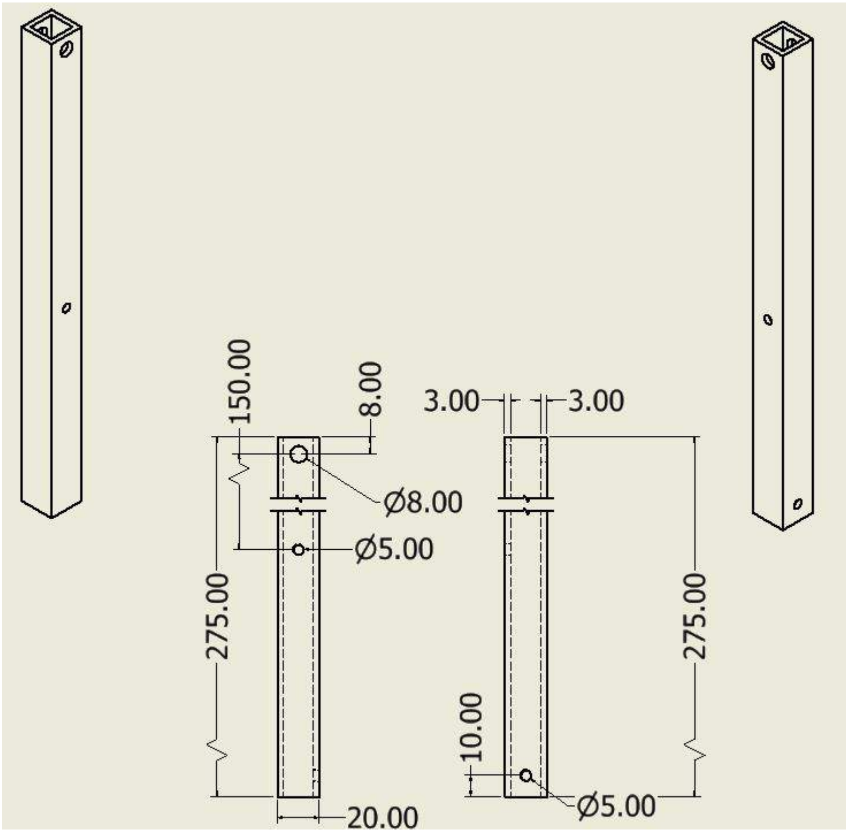

Figure 69 – Drawing of solution's swing-arm root part

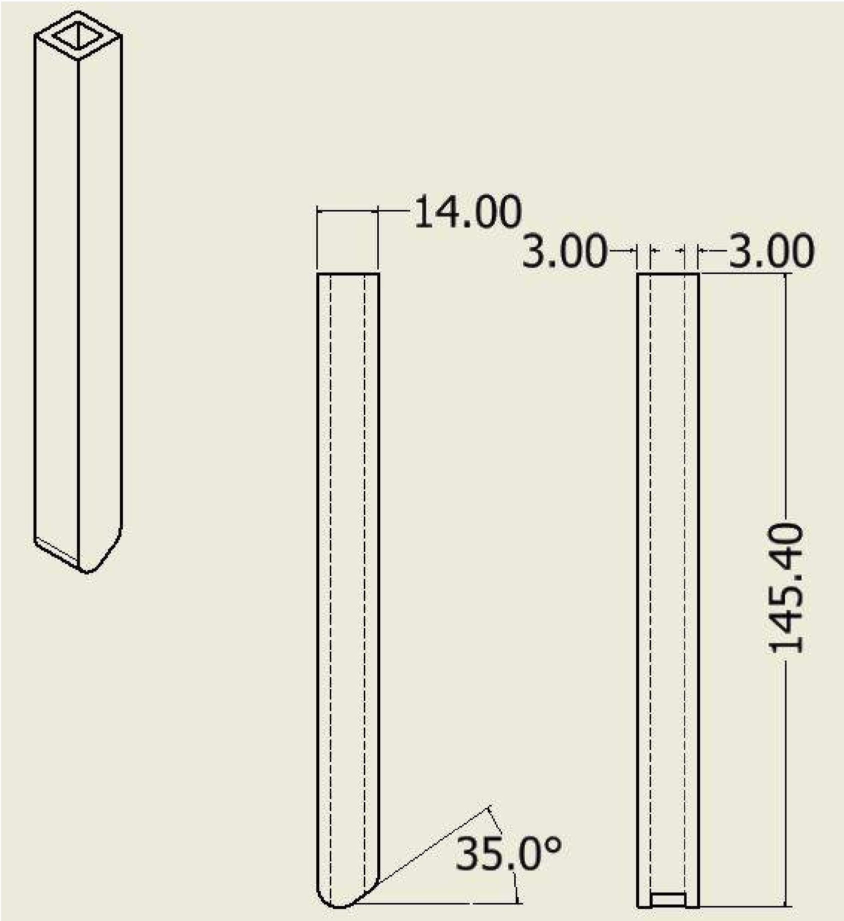

Figure 70 – Drawing of solution's swing-arm tip

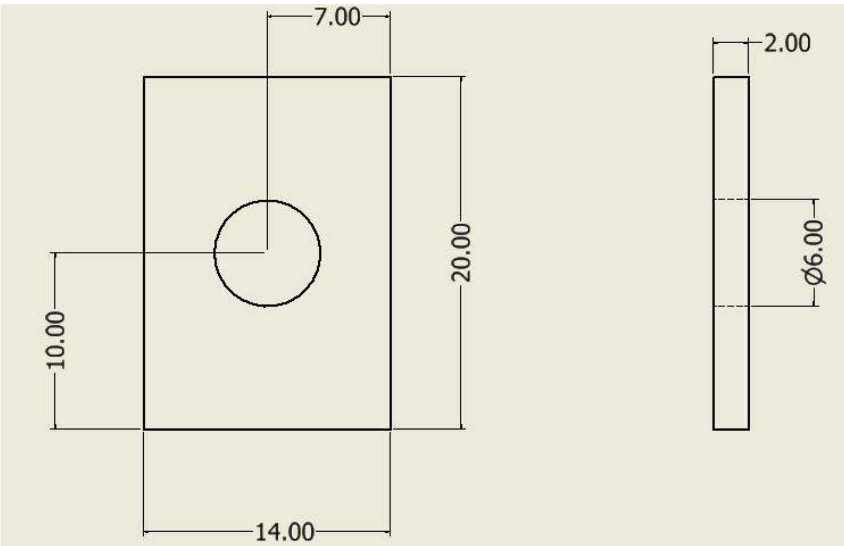

Figure 71 – Drawing of solution's swing-arm "lid"

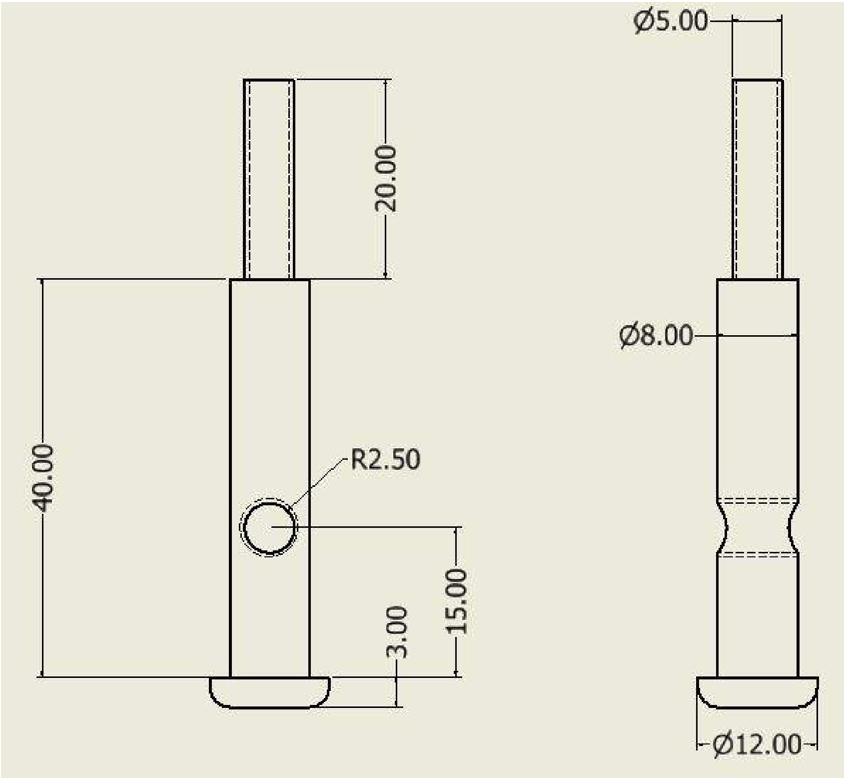

Figure 72 – Drawing of solution's shaft

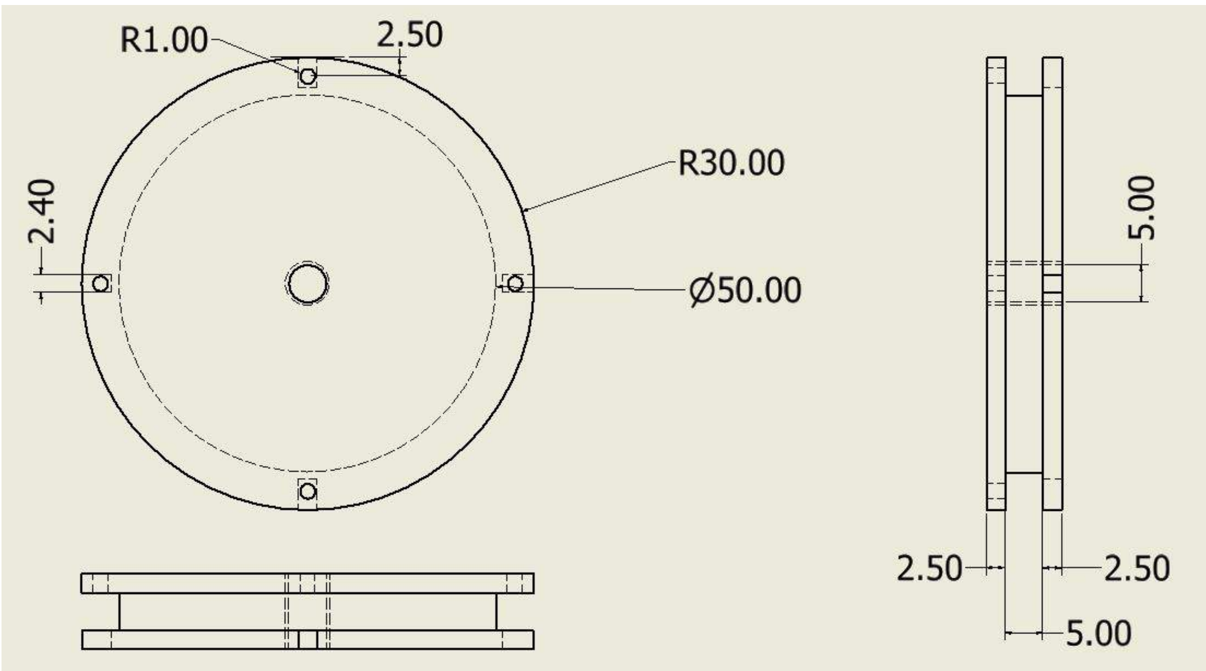

Figure 73 – Drawing of solution's reel

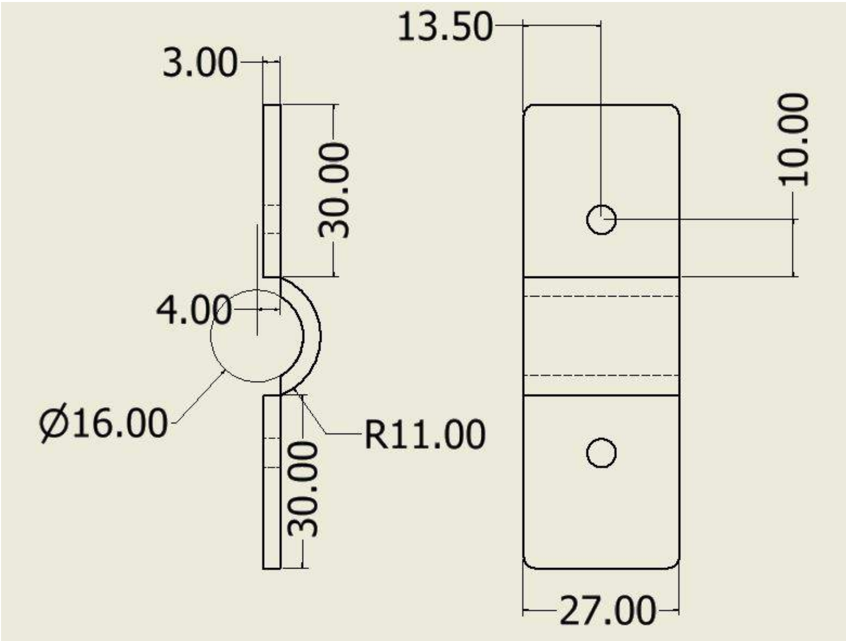

Figure 74 – Drawing of solution's chainstay fixation sleeve

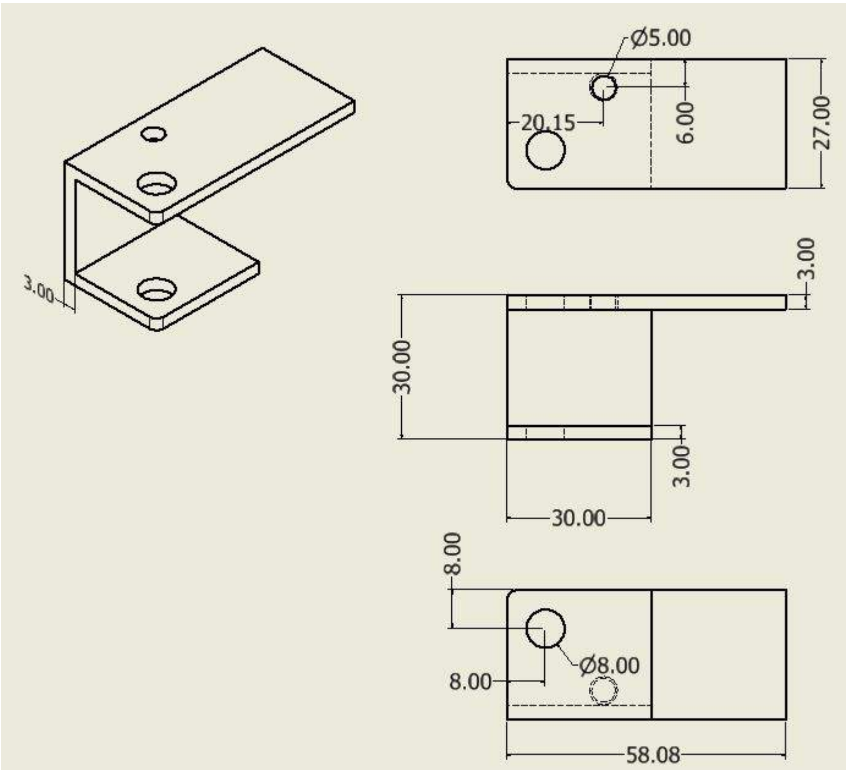

Figure 75 – Drawing of solution's swing-arm mount

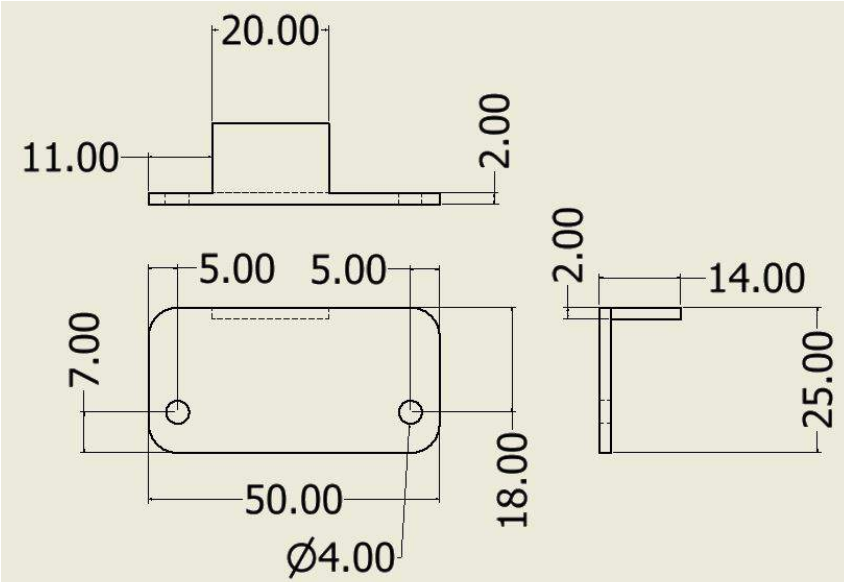

Figure 76 – Drawing of solution's cables mount

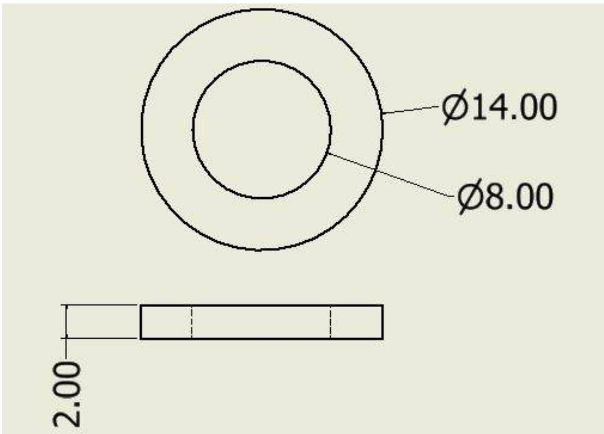

Figure 77 – Drawing of solution's spacers

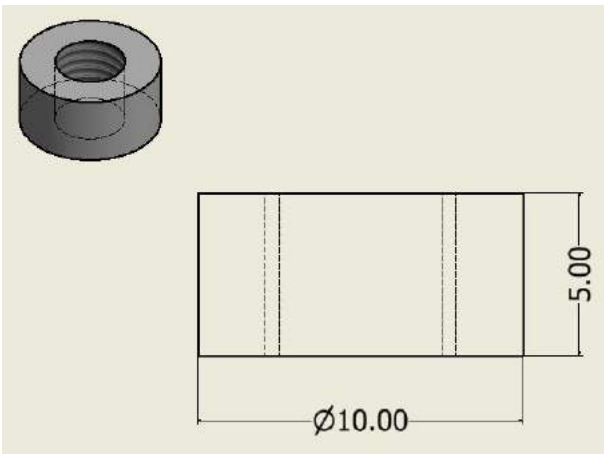

Figure 78 – Drawing of solution's auxiliary thread cylinders

ANNEX B – Technical drawing of prototype's modification to original solution

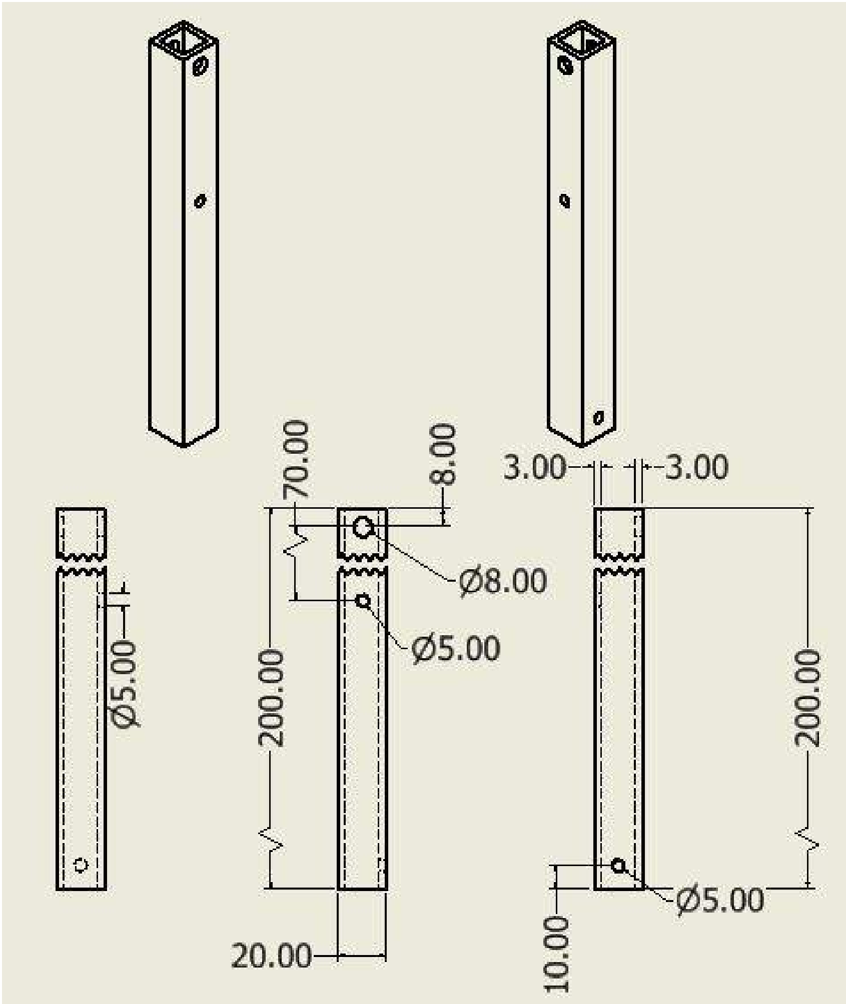

Figure 79 – Drawing of prototype's swing-arm