Design of light, crash-worthy, self-driving bike

Bachelor's thesis in Mechatronics

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BACHELOR'S THESIS 2021

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Cover: Picture of plastic bike

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Abstract

Autonomous vehicles are becoming more popular in today's society. An important factor when it comes to autonomous vehicles is safety. To test how well autonomous vehicles can recognize obstacles such as bicycles or pedestrians, self-driving plastic bikes are needed. Volvo Cars, Veoneer, Autliv and AstaZero are partners in this project.

In this bachelor's thesis a plastic bicycle is constructed and presented.

The result is a plastic bicycle with some dysfunctional steering capabilities. The front wheel steering is too heavy and the tubes and joints are not sturdy enough to keep it in place when turning the steering wheel. These types of issues can be solved with future iterations of the plastic bike. According to the stress analysis the bike is capable of carrying a weight of 300 N. In conclusion a plastic bicycle is produced, although without the chances to verify the crashworthiness of the bike.

Keywords: Plastic, bicycle, 3D-printing, design, self-driving

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1. Background

Self-driving cars are becoming more and more prevalent in our everyday life, and a key part to their performance is how well they can recognize obstacles such as bikes or pedestrians. When testing how well autonomous vehicles recognize obstacles there is a possibility of the car crashing into the bike. A plastic bike will reduce the damage taken from the car in the case of a collision.

The project is done at the department of electrical engineering in Chalmers university. The goal is to do a research project in construction of a bicycle made of plastic. Veoneer, Autoliv, Volvo Cars and AstaZero are partners in this project.

The way to test vehicle safety systems is to have the bicycle driving a predefined course with a human-like dummy as the driver so that the vehicle's sensors can recognize it as if a human is riding the bike. In these tests there is a risk for the bike and the dummy to be hit by the car at high speed and therefore it is important to have a light crash-worthy autonomous bike. This report describes how a plastic light crash-worthy autonomous bike is constructed, its components and the assembly of them.

1.1 Contributions

A plastic bicycle is designed and constructed. The bike will thereafter be used in self-driving vehicles safety system testing. These tests would benefit from a self-driving bike made in plastic to easily replace potentially damaged parts and reduce the chance of damage on the testing car. The bicycle is analyzed from a mechanical standpoint to be able for it to be light yet stiff enough to resemble the properties that a regular bike has. The material which the bike is made of should also not be costly and it is preferable that some modular components of the bike survive the crash and can be reused in other test bikes. It should be possible to mount self-driving equipment in order to make the bike autonomous that is given by another research team at Chalmers. In short, the goal is to research and produce a light crash-worthy autonomous bicycle made in plastic.

1.2 Considerations and limitations

- The bike is able to carry around 30 kg, therefore the bike has no human usage and only works on a human like dummy.
- The bike is made of plastic and without a functioning breaking system.
- The project is done during the ongoing Covid-19 pandemic, this might cause delayed freighting of parts and the possibility of meeting, talking and viewing demonstrations of other similar projects more difficult.
- Plastic wheels are considered too time consuming and hard to incorporate with the self-driving to use for this project therefore regular bike wheels are used.

2. Breakdown of how the bike is constructed

2.1 Project implementation

The usual materials in bike construction have for over a century been using steel and in recent years even adapted to aluminium and sometimes carbon fibre for some higher-class bikes since the technologies have improved. Since the bicycle is constructed in plastic material the similarities of the constructions need to be taken into consideration. Steel has higher material strength than plastic, therefore the dimensions and widths of the construction parts cannot be equivalent.

2.2 Selection of plastic material

The material desired is a robust and solid type of plastic that works in a construction where some lifting capacity is required. The type of plastics that did fit most to the material needs are Plexiglas and Polycarbonate. Polycarbonate is a strong plastic that is often used in engineering

3D-printing limits the use of some materials since there is not a wide variety of material available for 3D-printing. Since the construction is robust it can be printed with PLA, the most generic material for 3D-printing. PLA does not have the best material characteristics but since the construction is robust it is suitable for use as the joint parts.

2.3 Software's used

2.3.1 Ansys GRANTA EduPack

Ansys Granta Edupack, earlier known as CES EduPack is a software used for material selection for mechanical design (University of Cambridge, 2021).

2.3.2 CATIA v5

CATIA is a software for computer-aided design (CAD). To create a 3D model of a mechanical part CAD is essential and is heavily used for the parts of the plastic bike. The program is used to comprehend the designs' real world stresses and test the robustness in a simulation before making the parts physically (Patel, 2021).

2.3.3 Ultimaker Cura

Cura is a simple free and open source 3D printer software. It is very easy to use and the 3D model for print can be prepared in minutes with recommended settings. The user can choose the print settings and define the speed and quality before printing (Ultimaker BV, 2021).

2.4 Construction of the plastic bike

It is decided to 3D-print joints and buy plastic tubes to assemble the frame, front fork and back fork. A bike model from ACEA is used to dimension the bike. There are some differences in the dimensions since the joint construction makes it harder to use the exact same lengths on the bike's plastic tubes. All angles on the bike construction are the same as in ACEA:s construction (ACEA, 2020). To verify all the angles and lengths of pipes the bike is assembled in CATIA V5.

The bike is self-driven with a motor in the front wheel. There is no need for a chain with paddles or a regular back wheel with gears for a chain. The effect of this is that a front wheel is used as the back wheel.

2.5 Parts constructed in CATIA V5

All the parts modelled in CATIA V5 are joints intended to connect the pipes or connect to wheels. Pipes are also modelled with the intention of helping simulation of forces on the bike and for assembling the bike in CATIA V5.

The following joints are constructed. More in depth description with pictures can be found in section 2.9:

- Head tube
- Front fork
- Back joint
- Pedal joint (joint connecting the tubes for where the pedals would be even though they are not made on this bike)
- Front wheel
- Back wheel
- Support (back wheel and front wheel)

Since the purpose of this bike is for crash testing some parts are not made for the bike such as a real bike saddle and pedals. Pedals are not needed since it is driven by a motor in the front wheel. Certain parts such as steering handles would only be cosmetic and would not impact the result (described in detail in section 1.1) and are therefore not made. There is a back joint that looks like a saddle but it is not made with the intention to be used as a saddle. It looks like a saddle and is placed where the saddle is in a traditional bike but it is never verified if it can be used as one.

2.6 Components outside of CATIA V5

An old front wheel from an earlier project is used as the back wheel. The front wheel is Crystalyte HS 2440 the size of 28 inches with motor. Bicycle hoses are Conti Tube Tour 28 (700C) All and Spectra 28” 35mm ventiland, outer tires are used from an old bike. SKF bearings 16005 are used for the turning mechanism, the dimensions of the bearings are 25x47x8 and fit the steering.

Pipes with the dimensions that are used in CATIA are ordered with two different types of materials and thickness. The thicker pipe is 4 meter long with a 60 mm diameter and made of the material polycarbonate, this is used as the main body. For the pipes connected to the wheels and steering 8 meters of plexiglass are ordered, the diameter of the material is 25 mm as are dimensioned in CATIA. These pipes are then sawed into smaller pieces in order for them to be used for the bike.

2.6.1 Costs

All materials presented in the table are for one plastic bike. If there are mass orderings of the products costs would probably be lower.

Article	Amount	Price (including VAT)	Total cost
Clear polycarbonate 60x2050 mm	2	2000 SEK	4000 SEK
Plexiglas 25x2000 mm	4	1111 SEK	4444 SEK
16005 SKF bearing 25x47x8	2	100 SEK	200 SEK
Crystalyte HS 2440	1	3000 SEK	3000 SEK
Conti Tube Tour 28 (700C) All	1	51 SEK	80 SEK
Spectra 28” 35mm ventil	1	89 SEK	89 SEK

2.7 3D-printing

To 3D-print parts the CAD files are saved in stl format to be used in the Ultimaker Cura program where the infill and detail on the part being printed can be decided. Infill is a measurement of how much of the 3D-print is solid to save material and time, only a certain percentage of the print is solid. The part of the model that is solid is instead printed in a certain pattern which makes it require less material and have similar characteristics of a solid piece. Everything is printed in the plastic PLA. Larger parts are printed with lower infill to save time and resources. A high infill would result in print times longer than three days and even up to five days (All3DP, 2021).

The print core used for all prints is AA0.4 meaning that the smallest detail printed could be 0,4 mm and a tolerance of about 0,4 mm. A smaller printer core would result in even longer print times and a larger print core in greater inaccuracy. This small inaccuracy of the printer resulted in holes being smaller in the printed model than in the CAD- model. A larger diameter is used in the CAD-models to achieve the wanted dimensions of the holes in the printed model. Colour for all 3D-printed parts is picked out of availability (Dwamena, 2021).

Parts and their infill:
Head tube (20%)
Front fork (20%)
Back joint(20%)
Pedal joint (20%)
Front wheel (100%)
Back wheel (100%)
Support front wheel (100%)

All the 3D-printing is conducted in the Chalmers CASE-lab which stands for Chalmers Autonomous Systems and Electronics lab. It is a Lab at Chalmers where 3D printers, laser engravers, vacuum forming machine and other equipment used in projects at Chalmers can be found (CASE, 2021). The Ultimaker 3 extended and Ultimaker S5 are the used 3D-printers. All prints are made with these (Ultimaker BV, 2021).

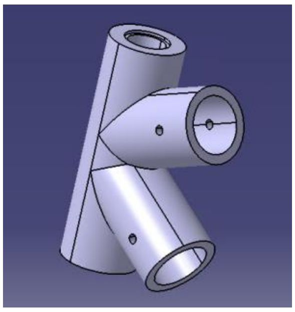
2.8 Stress analysis CATIA V5

A stress analysis is also performed in CATIA V5 to ensure that the bike would be able to carry a weight slightly below 30 kg. This weight is chosen with triple safety to ensure the plastic would not break and to compensate for the parts not actually being completely solid. The weight is also only applied to the back joint since that’s where the weight comes from of a bike rider, other forces coming from the bike rider's body are not taken into consideration. In reality the bike should be able to carry 10 kg in the form of a 6 kg dummy and the rest of the weight should be the self-driving equipment. This is a very reliable method of analysing since it is “98% accurate” (Írsel, 2018) combining this with the triple safety means the results acquired can be fully trusted. Complete analysis can be found in the appendix.

2.9 Parts explained in detail

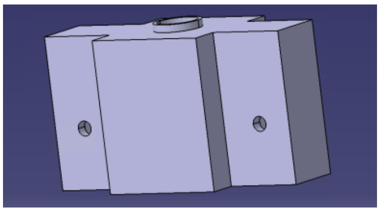
Here the parts are described in detail and their functions are explained. Multiple pictures of each part are included in the appendix.

Head tube:



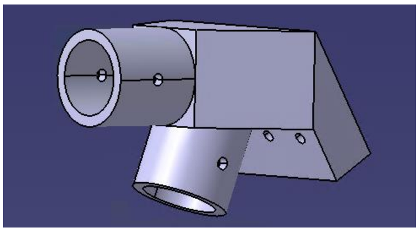
Consists of three hollow cylindrical tubes where two of them are connected to one of them in the shape of a V, one tube meant for the steering wheel tube to go through and with small indentations for the bearings to fit in. The two other hollow cylinders are placed so that the plastic tubes for assembly can fit through them and make out the frame of the bike. There are small holes in both of these cylinders so that the screws or cable ties can go through.

Front fork:



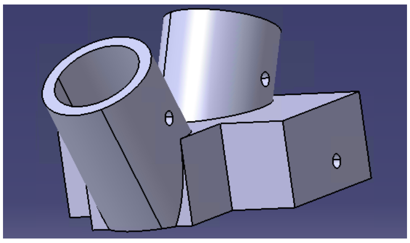
Is in the shape of a plus sign if viewed from above it is formed so that the steering tube can go through it and it also sticks out at the top of the hole so that a bearing does not get slowed by friction from the top. Underneath it has two holes for the two tubes for the front wheel and holes so that they can be mounted with screws.

Back joint:



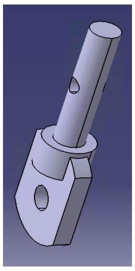
Two hollow cylinders consist of the pipes for the frame and are connected to a triangular piece as seen from above. There is also an angled rectangle with holes that makes it possible to connect the tubes for the back wheel. All holes have small holes at the sides so the tubes can be connected with screws or cable ties.

Pedal joint:



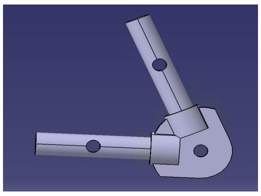
Two hollow cylinders for the frame sit on top of a “box”. Inside the Box there are holes which makes it possible to connect tubes for the back wheel. All these cylinders and holes have smaller holes at the side which makes it possible to secure the tubes with screws or cable ties.

Front wheel holder



These front wheel holders are the shape of an upside-down lollipop with a thicker part at the neck for the tubes to stay in place. There are also holes for the holders to hold the bike tire and so they can be connected to the tubes.

Back wheel holder:



Very similar to the front wheel holder but instead it is for the back wheel where two tubes connect for each holder at an angle.

Support:
This part is shaped oblong with holes at the sides that makes it possible to hold the front wheel stable and the steering possible.

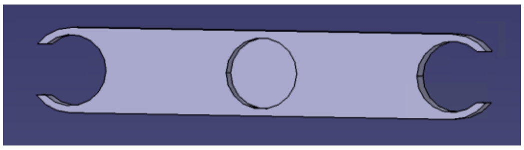


Figure 7

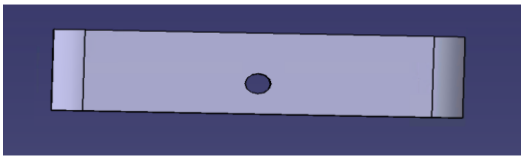


Figure 8

Figure 9

2.10 Environmental aspects

Plastic in general often impacts the environment negatively. All plastic materials have different impacts on the environment depending on how the material is being produced. The material used in the 3D-printed parts is PLA. PLA, also known as polylactic acid, is made of natural raw and renewable materials and can be recycled. Since a material choice of any plastic material had to be done PLA is the best choice as it is easy to use for 3D-printing with lower environmental effects compared to other plastic materials since PLA it is recyclable (V, 2019).
The material used for the tubes is Plexiglas and polycarbonate.

2.11 Bike testing

Method used to test the bike is to divide it into different parts for the tests, therefore if the bike will not be able to work as intended it will be less complicated to fix and replace the dysfunctional part.

The bicycle needs testing to verify the functioning of the different parts designed. The steering should be able to swing to both sides. This will be tested when the bike is being piloted.

The bike needs to hold at least the weight of a human dummy. For this to be verified a weight of 25 kg is being placed on the back joint to check the stability and that the construction is in no risk of shattering.

The testing phase takes place when the bike is fully physically constructed and mounted.

3. Implementation and assembly

3.1 3D-printed material

Parts are printed with 3D-printers in the CASE-lab and it is realised that parts are 1-2 millimetres smaller than in the CAD-model therefore measurements are adjusted to this in order for the tubes to fit into the holes. The parts mostly affected by this are the back joint and pedal joint since they take almost 1,5 days each to print therefore, they are printed a bit larger than needed to ensure fitting on the tubes. The front wheel holders needed multiple iterations because they are modelled after the back wheel since the front wheel had not arrived yet. The inner diameter of the tubes is smaller than anticipated and therefore this also required some remodelling of the front wheel holders. In order to save some time at least one of every part is printed when the tubes arrive and then modified if not able to fit with the tubes. One of the back wheel holders is very close to fit and since it is 100% infill it could be filed down until it fitted inside the smaller tubes.

3.2 Bearings

The bearings have low tolerance but are still made to fit around a 25mm tube it is very hard to fit them and requires a lot of strength applied in the right direction. This resulted in the bearings being able to be used as an element to keep the head tube and front fork in place while also being used for the turning mechanism.

3.3 Pipes

These are delivered with the length of 2 meters and are therefore needed to be cut to smaller pieces. They are cut using the measurements from the CAD-model which is based on the (ACEA, 2020) bike. Tubes are sawed to their desired measurements. The holes needed for assembly are carefully measured out and drilled.

3.4 Assembly

Nuts, bolts and metal spacers are used in assembly for the front wheel holder, back wheel holder, support and the front fork. The head tube, back joint and pedal joint are assembled to the tubes with zip ties.

3.5 Wheels

The back wheel is a front wheel from an older project that is not being used. The front wheel is a wheel with a motor inside. These are assembled to the bike by having the outer part of the bike hub axle going through the front wheel holder and for the back wheel the back wheel holders. To keep the wheels in place the nuts that came with the wheels are used.

4. Assembly

4.1.1 Assembly

When the material such as pipes and bearings arrived the mounting process of the bike started. The bike is assembled in the CASE-lab which is a lab with 3D-printers and other tools that make it possible to 3D print a bike and assemble it. All tools such as saws and drills are used from CASE-lab equipment. The pipes got sawed into given dimensions and later mounted with the 3D-printed joints with good fit. In most cases drilling is necessary, and a screw-nut is put for stability. On the 3D-printed joints plastic straps are also used for extra stability.

4.1.2 Problems in assembly

The plan was to use holes that are 10-millimetres in diameter. The smaller plastic tubes are too fragile to use a screw bit that drilled a 10-millimetre hole which led to the tube breaking and resulting in 10-15 centimetres of the tube needing to be thrown away. With a 7-millimetre screw bit it is possible to drill holes in the smaller tubes without any problems. This resulted in smaller screws having to be used instead of the 10-millimetre thick and sturdy ones.

Having printed some parts, the dimensions are 1-2 millimetres too small resulting in some parts having to be scraped and over dimensioned. This resulted in some “loose” joints. Meaning that after connecting the joint with screw or zip tie it still has some wiggle room.

The front wheel is a lot heavier than expected which the bike is not dimensioned for. Realising this at the end meant that there was no time to solve this problem properly.

5. Results

The result is a plastic bike that does not have good steering capabilities. The problem with the steering is that the front wheel is too heavy and the tubes and joints are not sturdy enough to keep it in place when turning. When turning the tubes bend a bit and the front wheel joints rotate in their place. The front wheel does not respond to turning at first then overcompensates. This will not work with self-driving equipment. This is tested by leading the bike around for 40 meters.

The back wheel works as good as a regular back wheel on a normal bike. The frame holds everything in place and the turning mechanism works as intended with the bearings. The plastic tubes do not bend anywhere except when the front wheel is used. The frame is rigid enough to be used everywhere except for the front wheel.

The bearings and tubes fill their purpose. The frame feels very rigid and could probably be made with thinner tubes. A weight test is never conducted since the front wheel is very hard to keep in place which is needed in order to get useful results from such a test. The bearings work very well and smooth they stay in place and even though they are not covered dust can not get in and cause further friction.

The stress analysis shows the bike is capable of carrying at least 300 N (about 30 kg). The deformation mesh shows some critical points where further joint design could improve the stability but since it holds for the target weight there is no deeper investigation put in this aspect.

6. Discussion and future recommendations

The bike did not work as intended since we were not prepared for the high weight of the wheel. The reason for this wheel being in the front is that the earlier self-driving bikes had the driving wheel in the front. This could be easily fixed by having the wheel with a motor at the back. In regular bikes the driving wheel is at the back and therefore the construction of the bike is modelled for that. The bike is very similar to a regular bike construction wise and therefore a driving wheel at the back will result in more stability. Perhaps with thicker tubes and a different construction at the front wheel part of the bike more stability can be reached and turning won't be an issue. Tighter tolerances for the front wheel holder assembly holes will also play a small part in the turning feature. A case could be made for not having hollow tubes in the front to avoid bending issues. There is also a possibility of stuffing the tubes with 3D printed material to make them more rigid. We believe having a regular front wheel and the driving wheel being at the back is the best solution. This is something we would have tested if we had more time. After testing that we would continue with investigating other possible solutions for the front wheel problem.

A problem we experienced when using CATIA V5 is that we did not know the computer aided design software well enough in order to create parts and have complex designs. A recommendation for the future is that students should get a basic introduction to surface modelling since knowing this would increase their ability to make complex designs for future iterations of the bike joints.

A possible and important improvement for future projects would be to use inward joints whenever possible since they provide the opportunity to not having to use fastening elements if the tolerances are good enough. This would greatly improve the modularity and the amount of work needed on the tubes since no drilling or holes in the joints would be needed. In our case we were having trouble using CATIA to its full potential only when we were done with all parts and had printed them we felt comfortable enough to implement such shapes. Another reason for the use of outward joints is that we first made the parts with another fastening concept in mind where having outward joints was beneficial. Later when this concept is scrapped some parts of the design are kept and only later it is realised that this is not optimal.

All parts are modular which means they can be used in future projects if seen fitting. The bearings are made for many more rotations than they will ever see in a bike steering wheel. Disassembling the bike is very easy which means salvaging old parts is no issue. The nuts, bolts and metal sheets are also very sparingly used meaning they could be used for future iterations if needed. The modularity of this particular bike allows for much future work to be done and many other possible solutions to be investigated. I believe that after a few iterations a very usable self-driving bike for crash testing will be engineered.

6.1 Conclusion

We were able to design and build a bike from scratch made of plastic. We did not manage to use the bike in crash tests nor did we manage to make it self-driving. The bike is modular, and every part could be 3D printed again with a new iteration if needed. The bicycle is light enough and stiff enough to have properties that resemble the properties of a regular bike. The material used for the bike is costly but if mass produced would most likely go down in price. 3D-printing is only as expensive as the material is and the 3D-printer is, which means that owning a 3D printer is the big cost. It is possible to mount self-driving equipment on the bike. Since the bike is very modular, we believe that it is possible that parts would survive a crash and could be used again. We did manage to research and produce a light crash-worthy autonomous bicycle although we did not get the chance to try some features out and verify the crashworthiness of the bike.

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Photos

Edin Smajic., Figure 1-9., screenshotted from CATIA V5., 2021
Edin Smajic., figure 1-3., Stress analysis computed by CATIA V5., 2021
Leonardo Chouha., Pictures of bike parts., screenshotted from CATIA V5., 2021

Appendix

Stress analysis of bike using CATIA V5

Analysis Bike
MESH:

Entity	Size
Nodes	146717
Elements	76658

ELEMENT TYPE:

Connectivity	Statistics
SPIDER	1079 (1,41%)
TE10	75579 (98,59%)

ELEMENT QUALITY:

Criterion	Good	Poor	Bad	Worst	Average
Stretch	68418 (90,53%)	7161 (9,47%)	0 (0,00%)	0,111	0,465
Aspect Ratio	21609 (28,59%)	51162 (67,69%)	2808 (3,72%)	10,659	3,211

Materials.1

Material	Plastic
0Young's modulus	2,2e+009N_m2
Poisson's ratio	0,38
Density	1200kg_m3
Coefficient of thermal expansion	6,84e-005_Kdeg
Yield strength	0N_m2

Static Case

Boundary Conditions

Figure 1

STRUCTURE Computation

Number of nodes	:	146717	
Number of elements	:	76658	
Number of D.O.F.	:	440151	
Number of Contact relations	:	0	
Number of Kinematic relations	:	3237	
Number of coefficients	:	39442	

Parabolic tetrahedron	:	75579	
Solid to solid fastened join	:	1079	

RESTRAINT Computation
Name: Restraints.1

Number of S.P.C : 39943
LOAD Computation

Name: Loads.1

Applied load resultant :

Fx	=	-2	.	095e-09	N
Fy	=	-3	.	000e+02	N
Fz	=	-1	.	142e-09	N
Mx	=	4	.	277e+02	Nxm
My	=	-3	.	164e-09	Nxm
Mz	=	-2	.	023e-01	Nxm

STIFFNESS Computation

Number of lines	:	440151			
Number of coefficients	:	15608694			
Number of blocks	:	32			
Maximum number of coefficients per bloc	:	499998			
Total matrix size	:	180	.	31	Mb

SINGULARITY Computation

Restraint: Restraints.1

Number of local singularities	:	0	
Number of singularities in translation	:	0	
Number of singularities in rotation	:	0	
Generated constraint type	:	MPC	

CONSTRAINT Computation

Restraint: Restraints.1

Number of constraints	:	43180	
Number of coefficients	:	0	
Number of factorized constraints	:	43068	
Number of coefficients	:	50523	
Number of deferred constraints	:	0	

FACTORIZED Computation

Method	:	SPARSE			
Number of factorized degrees	:	397083			
Number of supernodes	:	7548			
Number of overhead indices	:	1304385			
Number of coefficients	:	105917965			
Maximum front width	:	1707			
Maximum front size	:	1457778			
Size of the factorized matrix (Mb)	:	808	.	09	
Number of blocks	:	53			
Number of Mflops for factorization	:	4	.	372e+04	
Number of Mflops for solve	:	4	.	257e+02	
Minimum relative pivot	:	6	.	196e-04	

Minimum and maximum pivot

Value	Dof	Node	x (mm)	y (mm)	z (mm)
1.5254e+04	Tx	15503	-5.1140e+01	-5.9846e+02	5.7370e+02
1.7055e+10	Tz	10291	-1.7516e+01	-5.6921e+02	6.2654e+02

Minimum pivot

Value	Dof	Node	x (mm)	y (mm)	z (mm)
1.7478e+04	Ty	130260	3.5541e+01	-1.1162e+03	1.6072e+03
2.2142e+04	Tz	61521	-2.3464e+01	-1.0539e+03	1.0087e+03
3.0891e+04	Ty	99616	-6.8735e+01	-8.9894e+02	1.7608e+03
3.5124e+04	Tz	146462	-7.5571e+01	-1.1413e+03	1.2334e+03
4.3680e+04	Ty	51097	4.6917e+01	-1.0851e+03	3.5787e+02
4.3844e+04	Tz	99547	-7.6738e+01	-8.8150e+02	1.7410e+03
6.0208e+04	Tx	93594	-6.2621e+01	-6.0699e+02	1.5555e+03
7.3520e+04	Tz	61593	5.9325e+00	-9.4779e+02	9.9037e+02
8.5704e+04	Ty	82851	5.9285e+01	-1.1566e+03	1.2406e+03

Translational pivot distribution

Value	Percentage
10.E4 --> 10.E5	3.0220e-03
10.E5 --> 10.E6	2.3169e-02
10.E6 --> 10.E7	1.8216e+01
10.E7 --> 10.E8	7.7648e+01
10.E8 --> 10.E9	4.1069e+00
10.E9 --> 10.E10	2.7702e-03
10.E10 --> 10.E11	5.0367e-04

DIRECT METHOD Computation

Name: Static Case Solution.1

Restraint: Restraints.1

Load: Loads.1

Strain Energy : 6.250e-02 J

Equilibrium

Components	Applied Forces	Reactions	Residual	Relative Magnitude Error
Fx (N)	-2.0955e-09	1.6477e-09	-4.4780e-10	4.5244e-12
Fy (N)	-3.0000e+02	3.0000e+02	1.7880e-09	1.8065e-11
Fz (N)	-1.1423e-09	-4.7019e-10	-1.6125e-09	1.6292e-11
Mx (Nxm)	4.2774e+02	-4.2774e+02	-5.0954e-10	2.7769e-12
My (Nxm)	-3.1641e-09	2.5313e-09	-6.3276e-10	3.4483e-12
Mz (Nxm)	-2.0232e-01	2.0232e-01	-2.5450e-10	1.3870e-12

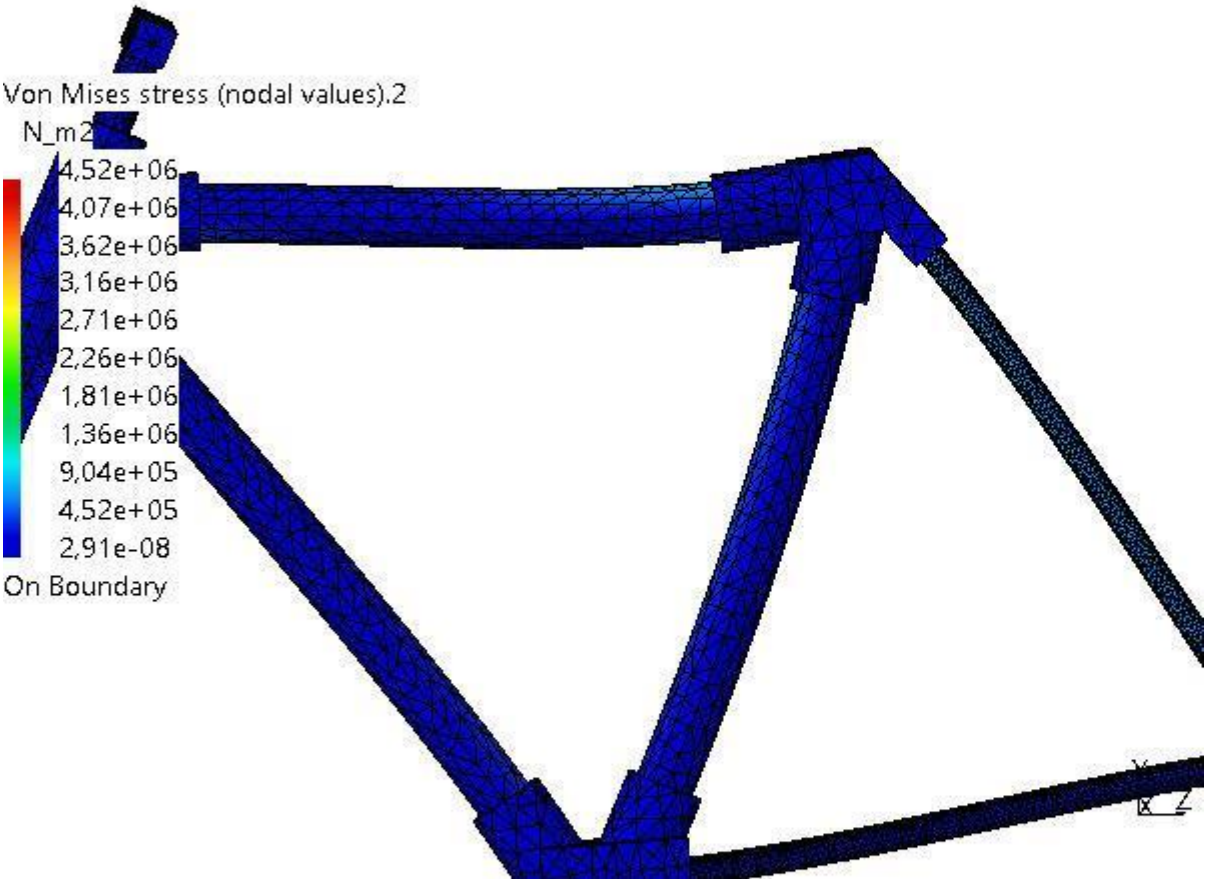
Static Case Solution.1 - Deformed mesh.1

Figure 2

On deformed mesh ---- On boundary ---- Over all the model

Static Case Solution.1 - Von Mises stress (nodal values).2

Figure 3



1D elements: : Components: : All
3D elements: : Components: : All
On deformed mesh ---- On boundary ---- Over all the model

Reaction Sensors

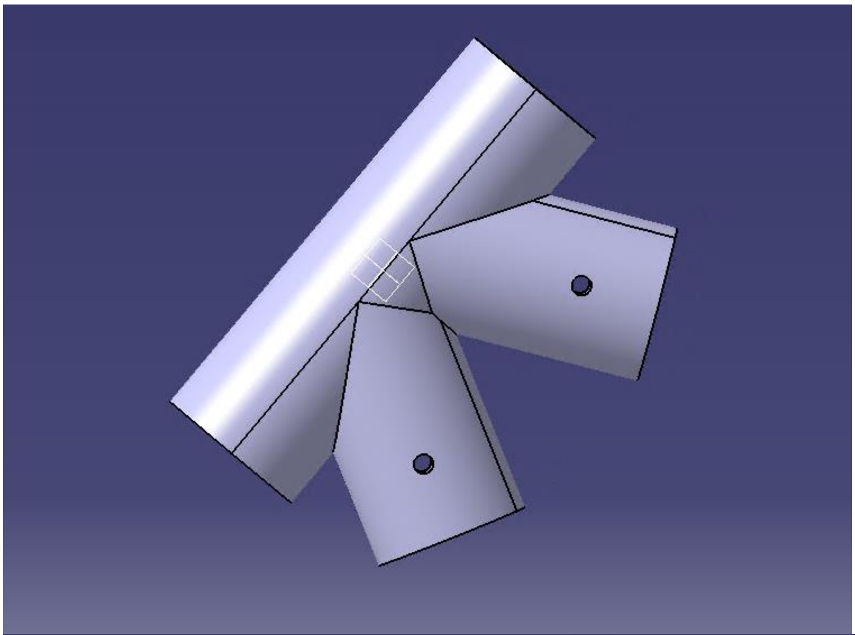
Sensor Name	Fx	Fy	Fz	Mx	My	Mz
Reaction Sensor.1	-0,88N	101,562N	-62,944N	-120,948Nxm	-4,926Nxm	-6,25Nxm
Reaction Sensor.2	-2,324N	-43,312N	-20,493N	37,42Nxm	-1,962Nxm	-0,097Nxm
Reaction Sensor.3	-1,317N	-69,629N	58,955N	12,774Nxm	-0,788Nxm	-0,709Nxm

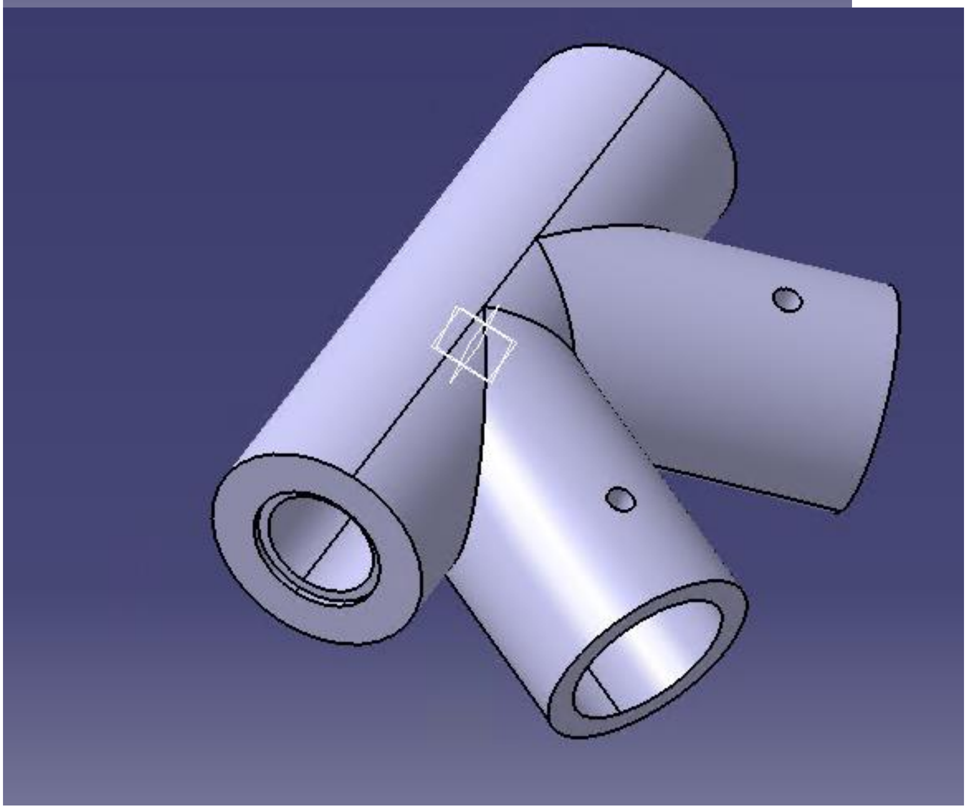
Global Sensors

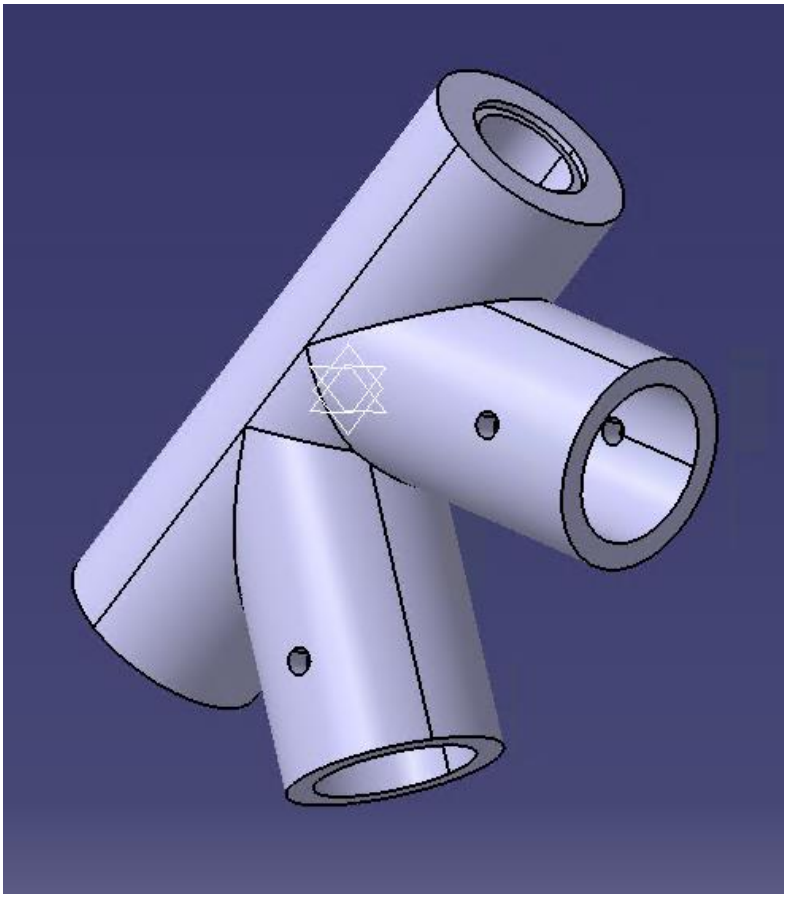
Sensor Name	Sensor Value
Energy	0,063J
Global Error Rate (%)	6,328392506

Pictures of parts

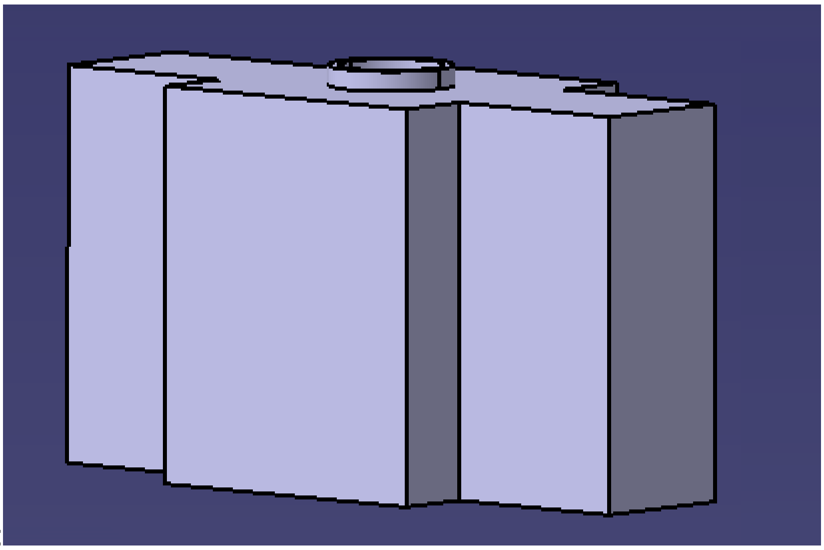
Head tube:







Front fork:



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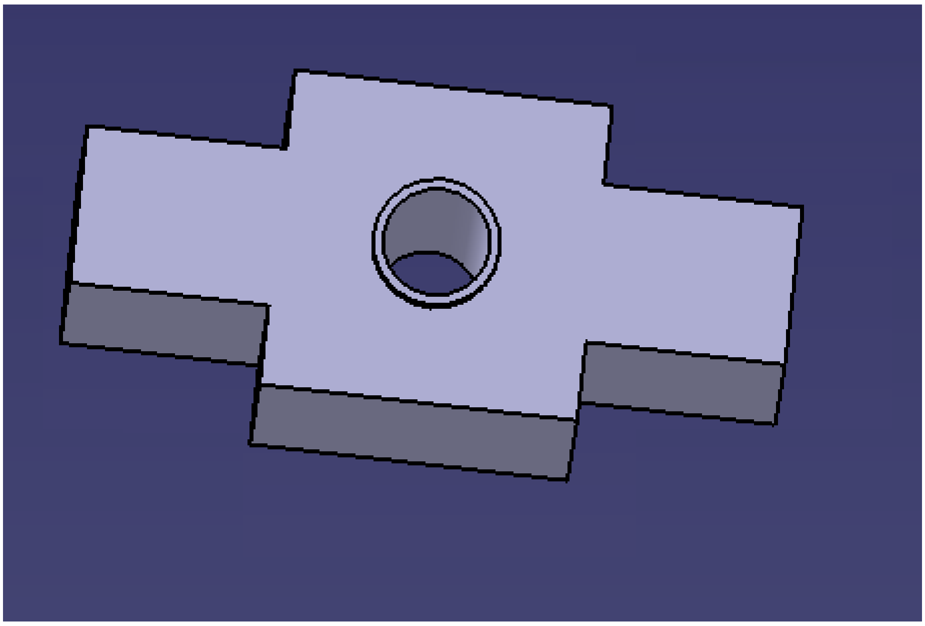
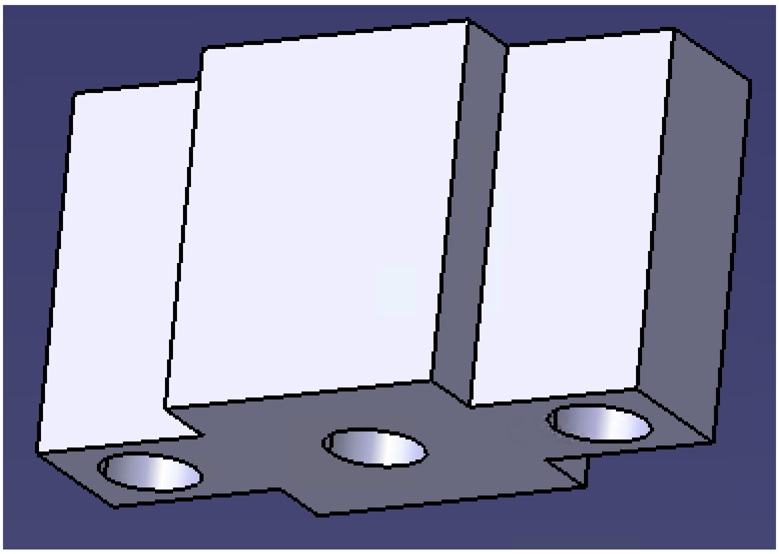
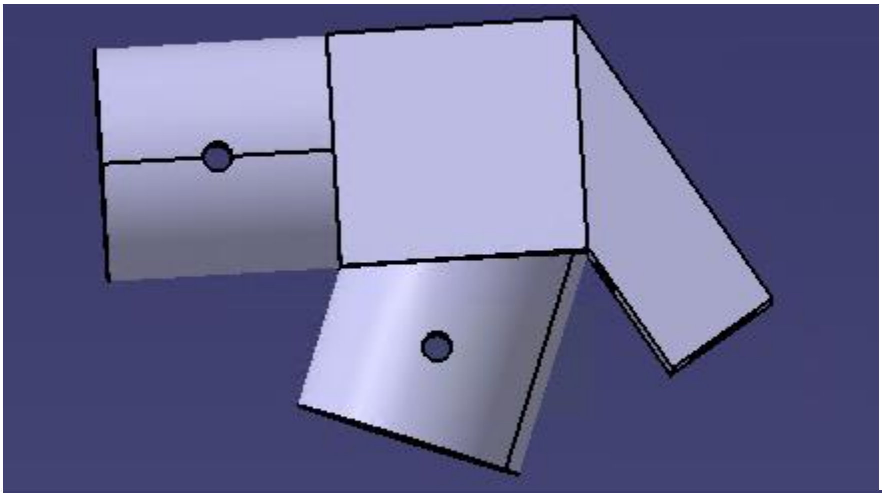
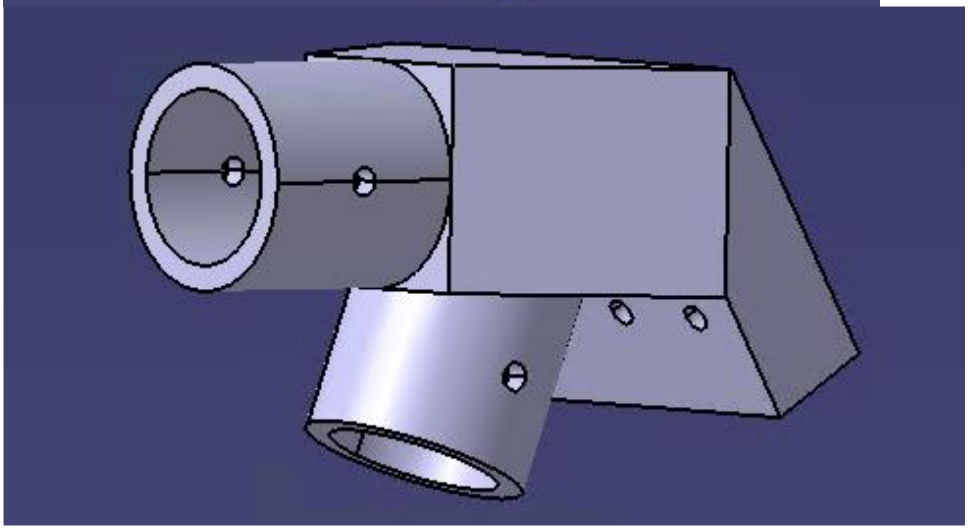
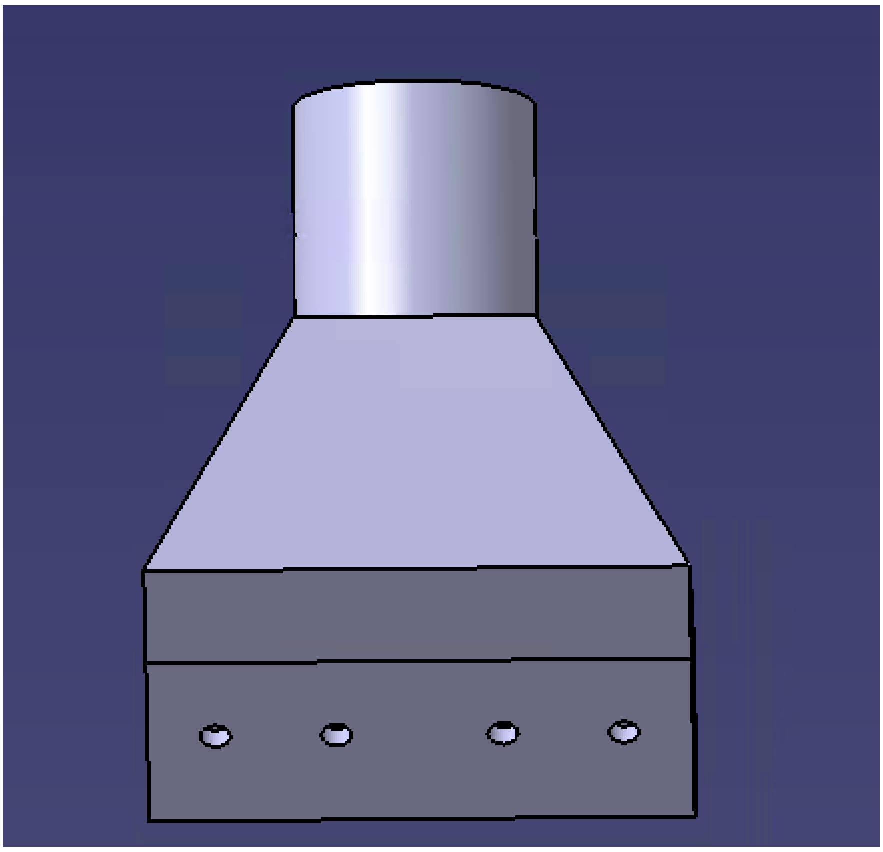


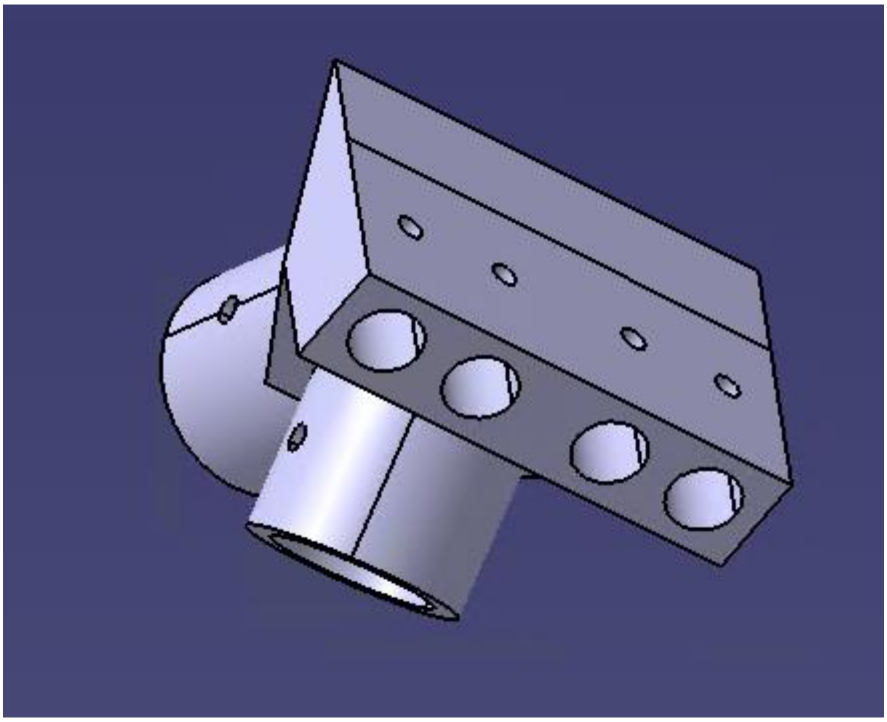


Back joint:

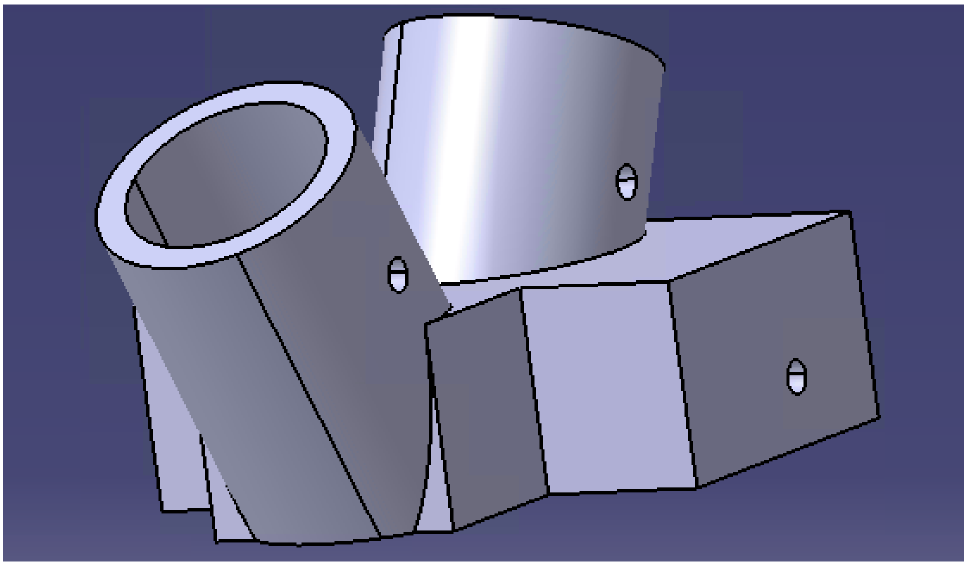


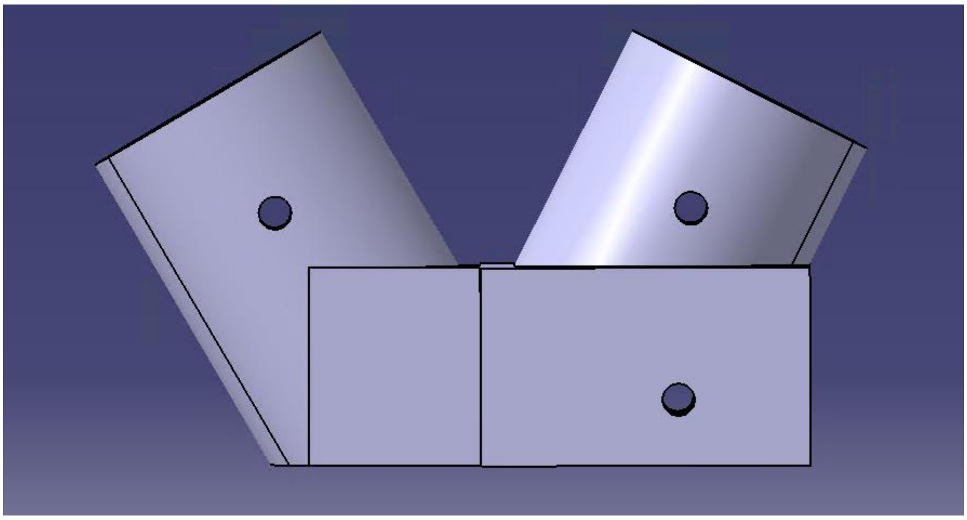


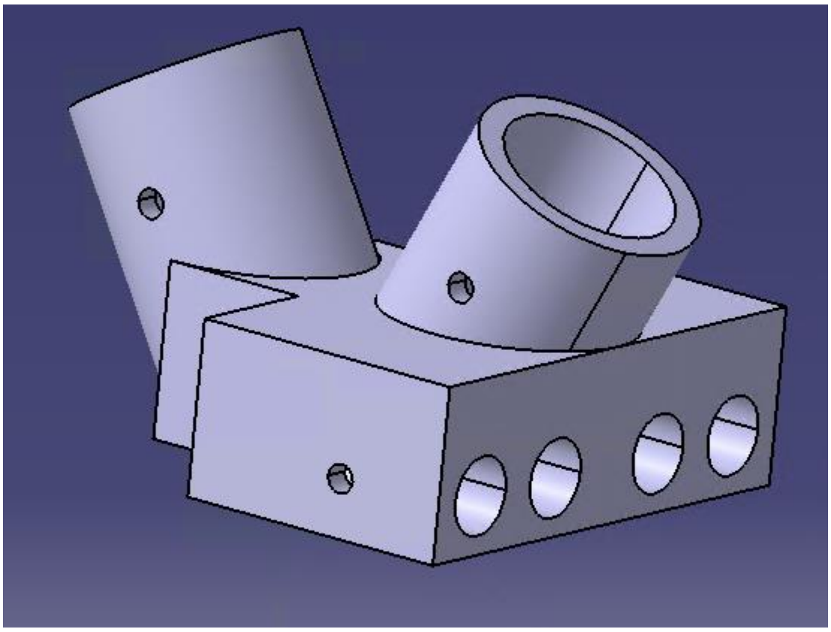




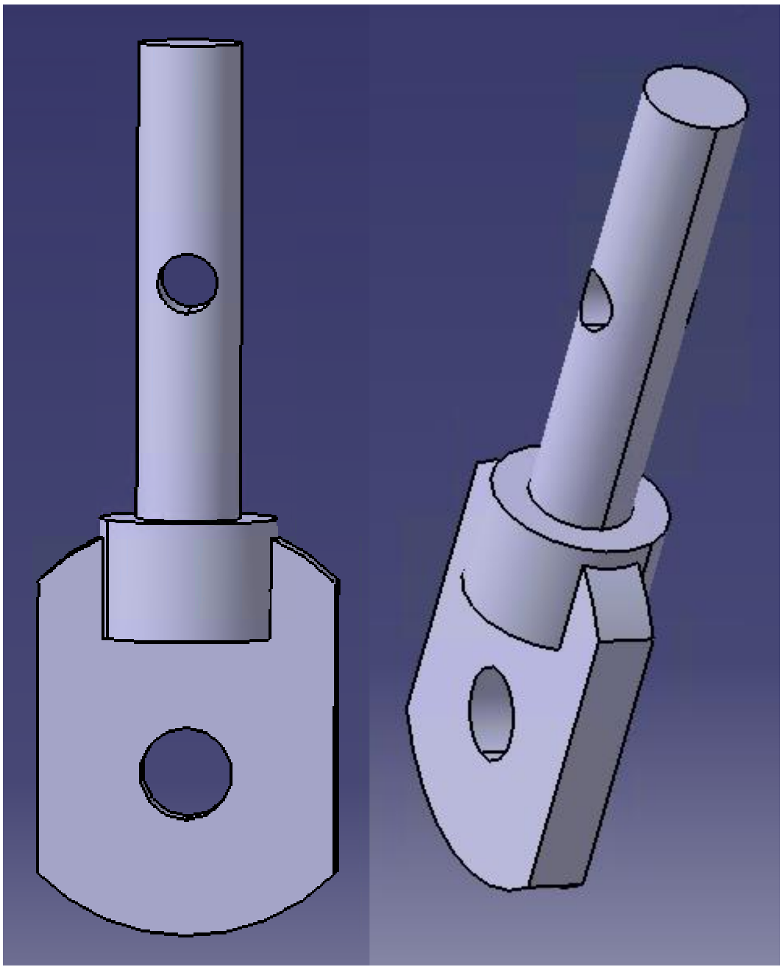
Pedal joint:







Front wheel:



Back wheel: