Engineering Design Report
Car Number 63
Norwegian University of Science and Technology

Overall Goal and Design

Revolve NTNU has a long term goal of becoming a stable top 5 FS team. To achieve this, the 2019 car needs to complete the acceleration event 0.34 s faster, and increase the average speed on autocross with 2.2 km/h compared to the 2018 car. Based on this we set two acceleration goals for the 2019 vehicle, increase the maximal lateral acceleration of the vehicle/driver on an FS track with 4% (Resulting in 2.8 g), and increase the positive longitudinal acceleration of the car with 8% (Resulting in 1.3 g).

To increase the traction circle for 2019, great effort has been put into understanding the 2018 car, having the best competition result to date, with a 2nd place overall in FSG. Through dynamic and static validation, analysis of the competition and thorough analysis of data gathered during the 2018 season, strengths and areas of improvement were identified. Three factors were found to contribute the most to reach the needed acceleration capabilities, available torque, total mass and downforce. Based on event simulations, these technical requirements were set to reach the acceleration goals:

- New powertrain yielding at least 1600 Nm of torque $\sim$ 22% increase
- Total mass of less than 165 kg $\sim$ 10% decrease
- 950 N of simulated downforce at 60 km/h $\sim$ 15% increase

To achieve this, the 2019 car has a redesigned powertrain, including motor, gearbox, inverter and vehicle control unit. The design of the monocoque is kept to facilitate iterations on the aerodynamic package and the suspension system as well as enabling early testing of the systems in the car. Considerable effort has also been put into weight optimization on every small part of the vehicle.

Powertrain

Gearbox and motor

Data gathered from competitions show that the 2018 car with 1310 Nm of torque was limited by torque on the rear wheels before reaching the power limit at 46 km/h. Analyzing tire test data combined with data from competition runs show that the rear wheels can utilize almost 800 Nm of torque (1600 Nm total on the car) before being limited by traction. The problem stated for the gearbox and motor was, therefore, to increase the total available torque to 1600 Nm without compromising top-speed, mass or volume.

A re-evaluation of motor options was done to achieve this. The previously used AMK DD5 motor was compared to a new semi-custom motor from Fischer elektromotoren. The new motor was chosen for the 28% increased torque, 8% decreased mass, identical rpm range, and 5% reduced diameter at a compromise of increased complexity.

Three different approaches have been used to evaluate the optimal gear ratio for the torque/rpm curve of the new motors. An event lap time comparison using a half-car acceleration simulation, a motor torque/rpm efficiency evaluation for the endurance event and an acceleration sensitivity analysis for track conditions. This evaluation gave the target gear ratio interval, 13.5:1 to 15.8:1. Using KissSys, several million gear combinations for a compound planetary, fixed ratio gearbox were found. The final gearbox configuration with a reduction of 14.4:1 was selected using an optimization algorithm, with a custom objective function weighing parameters like reduction ratio, efficiency, weight, and volume.

The resulting motor and gearbox have reached the torque goal with a total of 1682 Nm torque (31% increase). It has a top speed of 120 km/h (9% increase) and decreased its mass with 3.3 kg (-14.4%). Designing the mechanical parts of the motors makes a smaller input gear possible, giving the gearbox of 2019 64% higher reduction per volume. The gearbox is 5 mm smaller, together with a 5 mm smaller diameter motor gives more design space for the upper A-arms, that is utilized to achieve a desired higher camber gain in heave motion.

Inverter

The OEM inverters used by Revolve the previous years were heavy, did not easily integrate with the vehicle control unit and had poor maintainability. Due to the limited amount of commercial alternatives, the solution to implement a self-developed system was chosen. The system is a continuation of a four-year development of a SiC MOSFET-based inverter and controller.

Developing the inverter using SiC MOSFETs facilitates the use of smaller passive components by increasing the switching speed, effectively reducing system weight and volume. The inverter features discrete TO-247 transistors in parallel to reduce the conduction losses, while not compromising switching losses. Extensive double pulse testing was used to validate the parallel architecture. The in-house designed FOC-based motor control algorithm operates at a higher frequency than with the previously used OEM solutions. Allowing the speed controller to be run faster without compromising the decoupling between the controllers. This enables the slip ratio controller to better capture the fast tire dynamics.

The new inverter design has saved 4 kg (−41.7%) of its high placed mass and increased synergy with the slip ratio controller. Developing the inverter and controller in-house has also increased the maintainability of the system by eliminating "black box" OEM solutions, as well as increased the team knowledge in the field of power electronics and motor control.

Accumulator

After a thorough analysis of sensitivities and accumulator design of previous seasons, four key performance indicators were set: Temperature management, available energy, reliability of the electronic systems and weight. Thus, the problem stated for the accumulator system was having sufficient cooling and energy to last an Endurance with an average velocity of 55 km/h, while improving reliability of the AMS and saving 2 kg.

The required energy was determined by comparing simulations on different setups and analysing power consumption for our previous seasons, which concluded with a desired energy of 6.47 kWh for the TS and 0.23 kWh for the LVS. The chosen cell concept is $LiCoO_2$ pouch cells in a 144s2p configuration with a DCDC to supply the LVS. These cells were chosen as they suit our needs and have been thoroughly used and tested over multiple seasons. The stack-up were chosen as to meet the energy needs while having as high a voltage as possible, increasing efficiency of the TS, while being subject to rules and packaging constraints introduced by design space and the chosen cooling concept. General design improvements and the inclusion of a DCDC means the combined weight of the TS and LVS accumulator system is reduced by 2.5 kg.

This year's accumulator is air cooled; this solution has low complexity and is light while still providing adequate cooling, in compliance with the overall goals. To fully utilize the limited airflow, each cell is placed with the largest side along the longitudinal axis to expose 4.66 times more surface to the passing air than the 2018 stack up. Simulations indicate that the maximum temperature in the accumulator after a 20 min long Endurance run is reduced from 57°C to 48°C (15.8%,).

The AMS is in-house developed and its design has been iterated on for five years, featuring a centralised master-slave configuration communicating with a daisy chained isoSPI connection. This concept is chosen to let the team tailor the system for the accumulator topology. In order to facilitate reliability, the number of slaves for each segment is halved in addition to keeping the length of communication wiring to a minimum, decreasing the susceptibility to EMC.

Suspension

The 2018 suspension introduced a heave actuated third spring to increase the heave/pitch stability of the aerodynamics and keep a more constant rideheight at a compromise of added mass and increased CG height. Driver feedback from 2018 track testing pointed out excessively high steering torques. The problem statement for the suspension kinematics for 2019 is to benchmark the heave spring concept, reduce the steering torque of the car and increase the lateral tractive forces, contributing to the goal of a wider traction circle.

The heave actuated third spring, introduced in 2018, was dynamically bench-marked against the car without heave spring. Heave and pitch sensitivity analysis of the aerodynamics found it beneficial to keep the heave actuated third spring as it enhances the grip from aerodynamics in braking and turn-in situations. For 2019 the mechanical spring/damper has been replaced with an air shock, where the first 37% of the travel is un-actuated. The air shock gives a desired progressive rate in heave motion while reducing the mass by 484g in total (37% decrease).

The 13” Continental tire is chosen for its reduced unsprung/rotational mass and enlarged in-wheel design space compared to the 10” Hoosier tires. It is well known by Revolve, and our track data together with FSAE TTC data provides a lot of data useful for modelling and validation. Analyzing the available data indicated that higher camber gain would yield a better utilization of the lateral capabilities of the tires. To achieve this, a data-driven optimization approach was chosen. A full 3D model of the suspension kinematics has been implemented in Matlab, and an optimization procedure outputting suspension pick up points was written. The objective was to increase the lateral tractive forces during an AutoX event.

The most significant changes for the SLA double wishbone suspension yielded by the optimization are a shortening of the FVSAL to 1386 mm (14% shorter) front and 846 mm (25% shorter) rear. The front kingpin inclination was reduced to 3.6° while the caster remains at 4.2°. Simulations and evaluation of previous data indicate that these changes alone increase the average lateral forces by 1 % during cornering.

The steering torque contributions from self-aligning torque, mechanical trail, jacking forces, centrifugal caster and torque steering were analyzed. Reducing the kingpin offset 3 mm was found to be the best countermeasure with the least detriments to other areas of the kinematics. In combination with changes from the optimization, the static front mechanical trail was reduced from 8.9 mm to 4.9 mm. This reduction leads to a reduction of peak steering torques by 25% while the mean was reduced by 8.3%.

Control systems

Data showed that the 2018 torque allocation algorithm, running at 100 Hz, struggled to keep up with the tire dynamics thus traction was lost to excessive slip ratios. Dynamic testing showed that allocating rpm set points based on optimal slip ratio could increase the utilization of longitudinal grip on each wheel. Half-car acceleration simulations show that slip ratio based control could increase the positive longitudinal acceleration by 2%. The problem for the control system for 2019 has been to implement a slip ratio generating torque vectoring which can utilize the increased available torque.

The 2019 torque vectoring algorithm uses direct yaw-moment control, based on a single track bicycle model, to control the four motors, keeping the car neutrally steered. The previously used linearized tire model is replaced by the Pacejka MF 5.2 formula. The estimations allows for better utilization of available longitudinal traction. Utilizing a more precise estimate for available grip, the QP-solver generates slip references providing the required yaw moment and longitudinal acceleration. The new in-house developed inverters control the rpm on 1 kHz capturing the fast dynamics of the wheel.

Structural

Keeping the damper packaging concept, and only doing smaller iterations on the suspension geometry has allowed the structural suspension design to focus on load paths, load propagation, and improving the solutions from the 2018 car. The problem for the structural design of the 2019 suspension has been to reduce the weight of the system to reach the weight reduction goal, without an increase of compliance in the system.

Comparing the contact patch load case previously used, based on tire test data, to forces estimated during competition driving revealed an overestimation of the longitudinal and vertical forces. Based on the comparison, a two-fold design criterion was developed, a worst case based on steady-state tire potential and a performance load case based on data from competition driving. Based on the new performance load case for longitudinal forces, the brake system has been redesigned to a feature a much lighter rear brake caliper, and an in-house developed front brake caliper. The new calipers have saved 0.65 kg (43%), compared to OEM ones used previously, while keeping sufficient braking performance.

The single shear bellcrank and its attachments to the monocoque in the 2018 suspension were heavy. Creating a double shear bracket for the bellcranks, which transfer the load to the monocoque through coupled inserts, saved 0.4 kg of the suspension and monocoque. All the mechanical parts of the suspension system have been redesigned, reducing the weight of the suspension system by 20% compared to the 2018 suspension while keeping the same displacement in the performance load case.

Chassis

To reach the goal of a total car mass of 165 kg, the monocoque, without hoops, must weight no more than 18kg. Studying acceptable roll angle deviation between the front and rear axle, a needed torsional stiffness of 3000 Nm/deg roll (4x the total suspension roll stiffness) was found to be the point of diminishing returns for the connection between the front and rear suspension.

The layup was designed using FEA, a Monte Carlo optimization and a study evaluating every zone on the monocoque in terms of weight, influence on torsional stiffness and the competition regulations. The analysis showed that changing from the 2018 intermediate modulus fibre to a high modulus fibre could increase specific stiffness while maintaining the needed strength, at a compromise of added cost. Hardpoints are designed using theory from the ESA handbook of insert design combined with high focus physical testing to establish a reasonable safety factor.

Resources have been put into the production process and validation. Smart use of draping, laser cutting/milling of all core material and strict production planning has led to a reduction in planned vs actual weight deviation to 3%, compared to 8-12% from earlier years. The production deviation has been validated by laser scanning of all suspension pick up points, and the adhesive joints for the inserts are checked using x-ray scanning to ensure the desired quality of production.

The 2019 monocoque weighs 17.4 kg without hoops, a decrease of 2,4kg (13%) from 2018. Torsional stiffness of 3000 Nm/degree (17% increase) was tested hub-to-hub showing 15% deviation from the FEA model.

Ergonomics

Based on driver feedback and analysis of sensor data from the 2018 season, three main improvement areas on ergonomics where found; placement of driver interaction components in the chassis, brake feel during regenerative braking and reduction of steering torque (detailed in the section on vehicle dynamics).

Placement of the systems interacting directly with the drivers was decided in a new rig, having adjustable position and orientation of all significant components. The rig was used to mould the seat shape, find the position and reclining angle of the driver, as well as steering wheel position, pedal placements and angles.

The traction circle of the 2018 vehicle/driver combination revealed that drivers were not confident using braking during turn-in combined with regenerative braking. This led to a sub-optimal turn-in procedure with no help from the control system. The regenerative braking torque in 2018 was proportional to brake pedal travel in a soft range before hitting the hydraulic cylinders. To ensure maximum energy recuperation without compromising the brake feel for the driver, the 2019 brake pedal has incorporated a load cell that measures force on the brake pedal, such that the brake force on the vehicle is proportional to how hard the driver pushes the brake pedal, regardless of whether it is regenerative braking or mechanical braking.

Aerodynamics

With track validation from the 2018 car showing a lap time decrease of ∼10% when the vehicle was tested with an aerodynamic package vs without, we confirmed that aerodynamics is a major contribution to FSAE vehicle corner- and brake performance. The goal for the 2019 aerodynamics is to increase the CL by 15% without increasing drag, this to help reach the traction circle target.

In terms of downforce increase, the most substantial potential was found in the underbody devices, including the chassis floor. With this in mind, only smaller revisions to the front and rear wing have been made, in order to have more time to develop the undertray. The undertray, and partly the chassis floor, have been subject to a significant redesign. Using an iterative design process, initially, large design changes were simulated in STAR CCM+, with enforced symmetry along the vehicle XZ-plane, using a straight line domain. Changes were kept based on predetermined sensitivity relations for mass, downforce and drag. The iterations were periodically checked in cornering and different vehicle motion modes to ensure aerodynamic stability.

Careful attention to mass vs downforce combined with refined production methods and materials selection has led to the simulated performance parameters found in Table 1.

Parameter	2019	% Relative 2018
C_L	4.8	+14.3%
% DF rear	47	51%
C_D	1.5	−2.5%
Mass [kg]	8.55	−38%
A_{ref} $[m^2]$	1.17	+1%
F_L at 16.67 m/s [N]	940	16%

Table 1: Overall aerodynamic stats

From track- and wind tunnel experiments, the current CFD scheme was found to have a discrepancy of up to 15%. As test time and access to advanced test facilities are scarce, it was found beneficial to investigate different transient simulations to predict performance better. These include RANS, URANS and (ID)DES. Initial results suggest that transient simulations yield a satisfactory representation as an alternative means of validation.

Electronics

The success of the 2018 car was among other things due to a robust low voltage system. Therefore, it was decided to iterate on most systems without introducing significant changes. However, the computational power of the VCU was limiting the potential of the control system, as described in the control system section. The problem stated for the low voltage system is to maintain the level of robustness while allowing for increased performance of the VCU.

The VCU has been upgraded from featuring a single core microcontroller to a dual-core system on a chip, increasing computational power with a factor of five. The vehicle features a substantial sensor package that samples at a rate of 1 kHz. Sampling at this speed allows filtering to reduce the signal-to-noise ratio without introducing any significant delay.

To meet the requirements of the control system and improve data acquisition, the new low voltage system features two CAN-FD buses. This increases the data throughput by a factor of 3.3 compared to CAN 2.0, without introducing additional wiring. Further measures taken to ensure reliable electronic systems are keyed connectors, design standardization and a strict focus on EMC for the wire harness and PCB design. For instance, carefully placed casings with cobber mesh to inhibit EMI and extensive prototyping of our PCBs.

In-house analysis software

To efficiently analyze and post-process data from the sensor suite, a self-developed program, Revolve Analyze, was developed. Revolve Analyze receives live telemetry data and lets the team members inspect and plot the collected data in real-time. The data is stored and used for post-processing. It is an essential tool for understanding the vehicle and is heavily used for concept/design decisions and during validation. Revolve Analyze can also be used to set parameters in the car's electronics wirelessly and playback messages from the CAN-bus, helping streamline testing and verify embedded systems in a realistic environment.

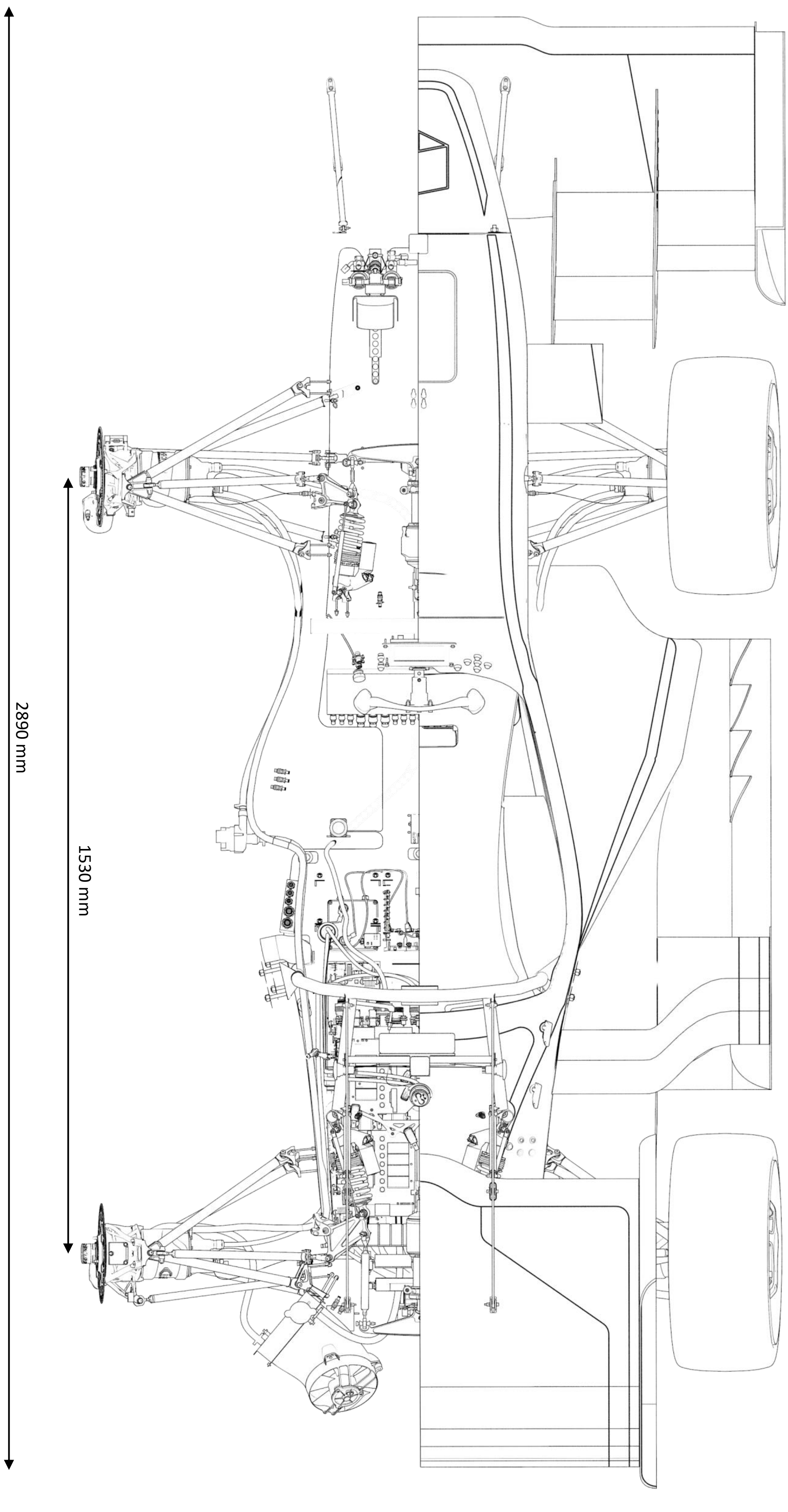
Summary

For the 2019 car, Revolve NTNU set the goals of increasing the lateral acceleration capabilities by 4% and increasing the longitudinal acceleration by 8% compared to the 2018 car. The technical requirements set to achieve this has been reached, as the 2019 car has $\sim$11% reduced mass (163 kg total mass), $\sim$ 28% increased torque and $\sim$15% increased aerodynamic downforce, which has resulted in an increased traction circle.

The increased torque is utilized through a new optimal slip ratio based rpm allocation algorithm, controlled by a 1 kHz algorithm on the inverter. Together with the decreased mass, comparative half-car acceleration simulation of 2018 car and the new 2019 car shows a potential increase of 5% in longitudinal acceleration.

Mass reduction, increased downforce and the optimization of suspension kinematics of the 2019 car gives an increase in high-speed cornering lateral acceleration during an autocross of 12 to 18 % in comparative simulations using ChassisSim.

Simulation with the changes increase the average speed on an autocross event with 3.1 km/h and decrease the time used on the acceleration event with 0.2 s. The increased performance during the dynamic events should give Revolve NTNU a good chance of reaching the overall goal of finishing among the top 5 teams.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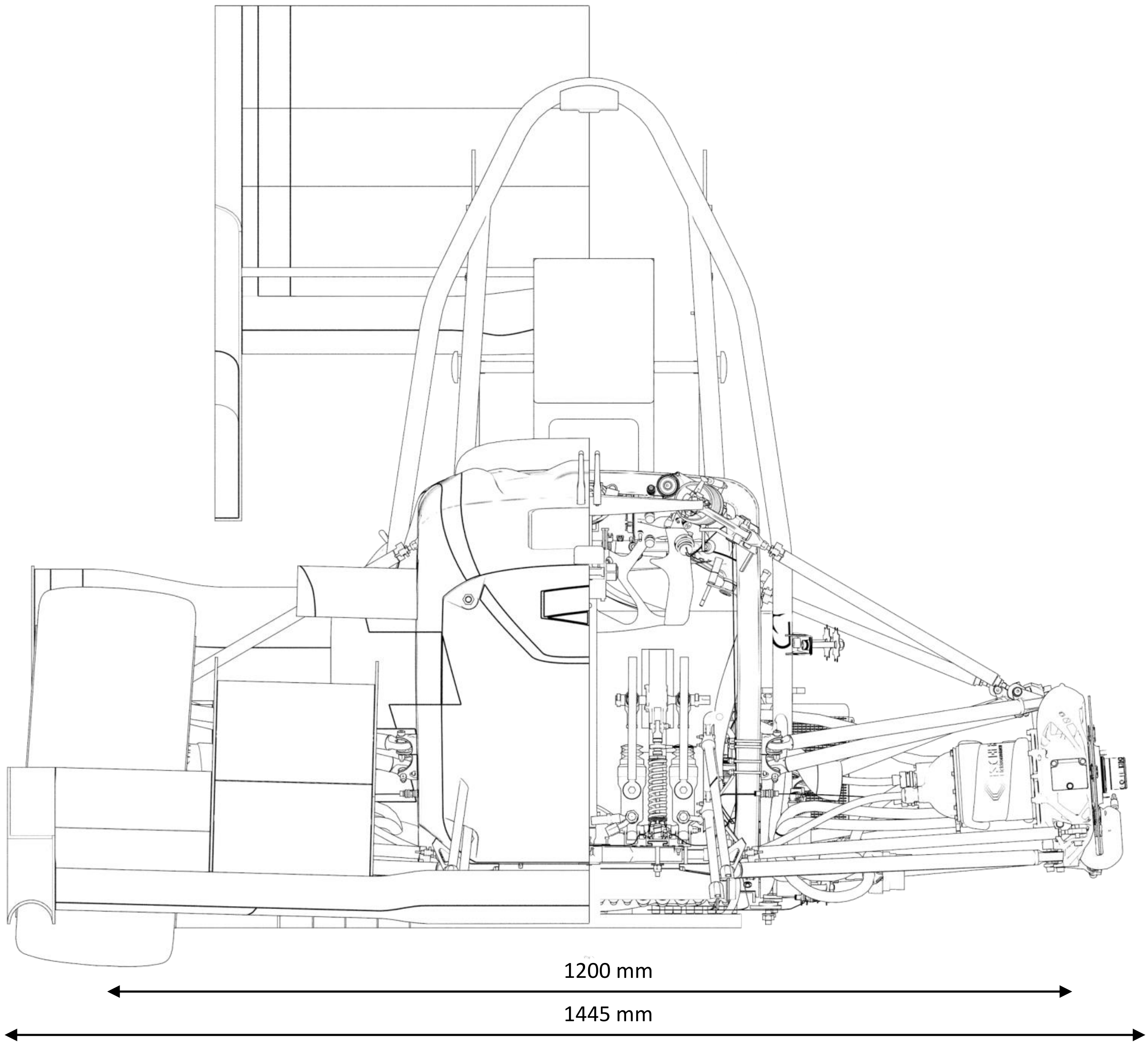
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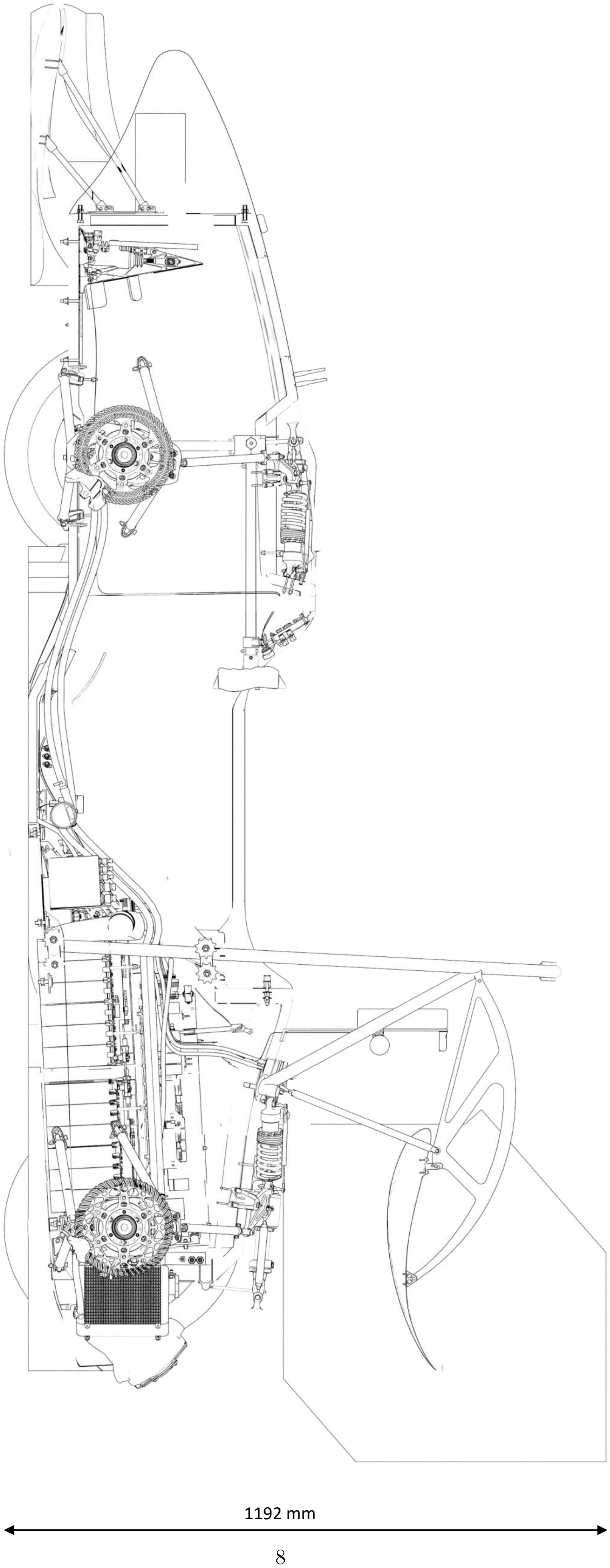
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