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FACULTY OF MECHANICAL ENGINEERING

INSTITUTE OF SOLID MECHANICS, MECHATRONICS AND BIOMECHANICS

KONSTRUKCE PODVOZKU EXPERIMENTÁLNÍHO VOZIDLA SE ČTYŘMI ŘÍZENÝMI KOLY

DESIGN OF EXPERIMENTAL VEHICLE UNDERCARRIAGE WITH FOUR WHEEL STEERING

BAKALÁŘSKÁ PRÁCE

BACHELOR'S THESIS

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ZADÁNÍ BAKALÁŘSKÉ PRÁCE

student(ka): Filip Vadlejch

který/která studuje v **bakalářském studijním programu**

obor: **Mechatronika (3906R001)**

Ředitel ústavu Vám v souladu se zákonem č.111/1998 o vysokých školách a se Studijním a zkušebním řádem VUT v Brně určuje následující téma bakalářské práce:

Konstrukce podvozku experimentálního vozidla se čtyřmi řízenými koly

v anglickém jazyce:

Design of experimental vehicle undercarriage with four wheel steering

Stručná charakteristika problematiky úkolu:

Práce se bude zabývat konstrukčním návrhem podvozku vozidla se čtyřmi řízenými a hnanými koly. Předpokládá se provoz ve vnitřním i vnějším prostředí.

Cíle bakalářské práce:

1) Proveďte literární rešerši, vyhledejte podobné konstrukce, zhodnoťte.
2) Vypracujte několik variant konstrukčního řešení v SW SolidWorks a popište jejich technické a ekonomické parametry a výhody a nevýhody. Uvažujte konkrétní motory pro pohon a natáčení kol vozidla. Do návrhu zahrňte i konstrukční řešení odpružení kol.
3) Detailně zpracujte vybranou variantu v SolidWorks včetně výběru konkrétních použitých komponent a cenové kalkulace.

Seznam odborné literatury:

1.Valášek, M.: Mechatronika, Vydavatelství ČVUT 1995
2.Kratochvíl: Mechanika těles - dynamika, skriptum FSI VUT v Brně
3.Grepl, R.: Kinematika a dynamika mechatronických systémů, skriptum FSI VUT v Brně, 2008

Vedoucí bakalářské práce: Ing. Robert Grepl, Ph.D.

Termín odevzdání bakalářské práce je stanoven časovým plánem akademického roku 2009/2010.

V Brně, dne

L.S.

prof. Ing. Jindřich Petruška, CSc.	doc. RNDr. Miroslav Doupovec, CSc.
Ředitel ústavu	Děkan fakulty

Anotace

Bakalářská práce se zabývá návrhem a realizací podvozku experimentálního čtyřkolého vozidla s nezávislým pohonem a řízením všech kol. Vozidlo je určeno jako učební a vývojová pomůcka pro testování konceptu řízení všech kol a systémů kontroly řízení, pohonu a brzdění. Práce obsahuje několik konceptů jak samotného vozidla, tak konstrukčních detailů, především uložení kol a distribuce hnacího momentu.

Klíčová slova:

řízení všech kol; pohon všech kol; kolový robot; experimentální vozidlo; podvozek; 4WS; 4WD

Annotation

This bachelor thesis covers design and manufacture of experimental four-wheeled vehicle undercarriage, with all-wheel steering and all-wheel drive. The vehicle is supposed to serve as a teaching aid or prototype for new system development. The vehicle is able to test all-wheel steering concept and systems for steering, drive and braking control. The thesis includes several concepts of vehicle design and also technical details, such as wheel mount and driving power distribution.

Keywords:

four wheel steering; four wheel drive; wheeled robot; experimental vehicle; undercarriage; 4WS; 4WD

Bibliographical citation of thesis:

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Announcement

I announce that I have produced this bachelor thesis on my own, with guidance of my supervisor and all used resources are listed at the end of the thesis.

Filip Vadlejch, Brno, 2010 Author’s signature

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Acknowledgements

I would like to thank, to all of those who contributed to realization of my bachelor thesis, especially to Ing. Robert Grepl Ph.D. for guidance and essential advices and Ing. Pavel Čoupek for brilliant ideas and patience. Many thanks belong also to all colleagues participating on Car4 project development, for their hints during designing and help with manufacturing and final completion, to employees of Truckcentrum Strakonice ltd. for inspiring discussion about technical solutions and also to all other companies, which assisted during manufacturing.

I appreciate support from my family within all the time of my studies.

Content

1. Introduction

Progress in automotive industry is to be seen in everyday life. In last few decades a huge rise in safety and reliability of produced cars was reached. Big credit on these successes have not only the past-accident safety elements such as airbags or crumple zones, but also (and more and more in last years) the active crash-avoidance systems, whose purpose is to prevent the accident to even happen. These elements are affecting car's stability, improving its behaviour in common or critical situation and reducing driver's workload and therefore his tiredness. Group of active safety systems includes well known anti-block system with its enriched versions designed to assure right braking force distribution, system for skid detection and prevention and, with advancements in four-wheel-drive automobiles, also driving force distribution systems. Although modern driver may consider these gadgets as a matter of course, they weren't here all the time. Their implementation in common vehicles was done after number of tests and prototypes.

The purpose of project called Car4, which this thesis is a part of, was to design and construct a model vehicle, which can be considered one of mentioned prototypes – a vehicle applicable to testing its behaviour in different modes. To ensure universality of this project and wide assertion, concept of four wheel drive vehicle was chosen. In addition to classic concept, four wheel steering was included. Outcome of this project (and bachelor and diploma theses made during the project) is thus a model of automobile's undercarriage with possibility to independently drive and steer all four wheels. Final product is ready to be instrumental as a teaching aid or prototype in new system development.

The undercarriage development itself was influenced by primary project specifications. The goal was to build a model vehicle for testing four wheel steering – four wheel drive concept. In addition the vehicle was supposed to have powerful engine (or engines), to be able to skid during acceleration and braking. This, together with efficient electronics and controllers, would lead to a very versatile base for developing or testing innovative, brand new or well known car control systems.

Assumption of using the model indoors and outdoors led to need of a sturdy structure, resistant to flexion and torsion deformation, capable of handling stress at any condition. Chassis had to be fully sprung by independent springs with absorbers at each wheel. The structure was supposed to be relatively light to make it easy to carry by only one person. The size of the model shouldn't require too much space of storing, but should be large enough, on the other hand, to keep results comparable to a real vehicle.

2. Background research

The concept of multiple steering wheels is not new. Many solutions are already used in regular duty, including not only four-wheeled cars, but also six-wheeled buses or even eight-wheeled military vehicles. In these cases is steering of multiple wheels inevitable. Compared to these examples seems all wheel steering on four-wheeled car unnecessary, even useless. But using this concept on small vehicles could conduce to a very manoeuvrable base. This is the reason why are similar systems applied on varietal runabouts, forklift stackers and mainly robots.

Four wheel drive, on the other hand, has quite a common application these days. Many off-road vehicles and other devices use the manoeuvrability, versatility and ability to conquer rough terrain given by multiple simultaneously driven wheels.

A background research was performed to gain an overview on similar vehicles, development projects or their parts, such as wheel mount, which could be used as inspiration in designing and developing our own version.

2.1. Fieldrobots

Many robots using all wheel drive and steering can be found at premises of universities. Number of different versions is being developed within various projects. Some of them are objectives of bachelor and diploma theses like ours, some of them are supposed to participate on a competition. Several interesting robots can be found among annual FieldRobot competition [1] participants. Event, taking place alternately in Holland and Germany, is focused at agricultural robots. Parts of the contest are situated in ordinary field, therefore must the robots fulfil design requirements allowing them to work in outdoor surroundings and challenging terrain.

2.1.1. EasyWheels robot

Robot was developed specially for FieldRobot event at Helsinki University of Technology, Faculty of Electronics, Communications and Automation [2]. It’s an autonomous four-wheeled robot with four wheel drive and steering, composed from modules, which can be easily changed in case of any defect. One of modules is a block containing two wheels’ mounts. Wheels are connected together by a differential unit and therefore driven by only one electrical motor. A servomotor handles the steering. Wheel mounts are not individually sprung, but whole block is connected to frame by a joint enabling itself to rotate among direct axis. This solution guarantees permanent contact between wheels and road and uninterrupted motion as well, even in field terrain.

Fig. 1: EasyWheels robot during FieldRobot competition. [3]

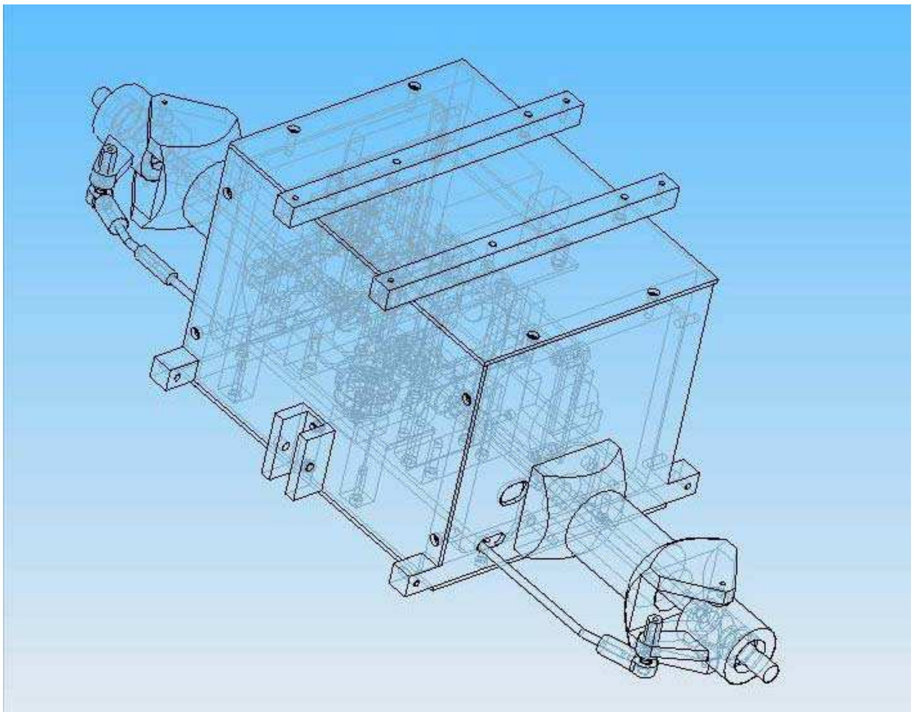

Fig. 2: EasyWheels robot's wheel mount block. [3]

2.1.2. Demeter robot

Demeter [4] is the ancestor of EasyWheels robot. Its framework is similar to radio controlled model trucks. Wheel mount is however devoid of most of the springs and placed again into two blocks. Block suspension is done by a joint similar to EasyWheels robot. Most alike is the mechanical differential dividing power to both wheels in block.

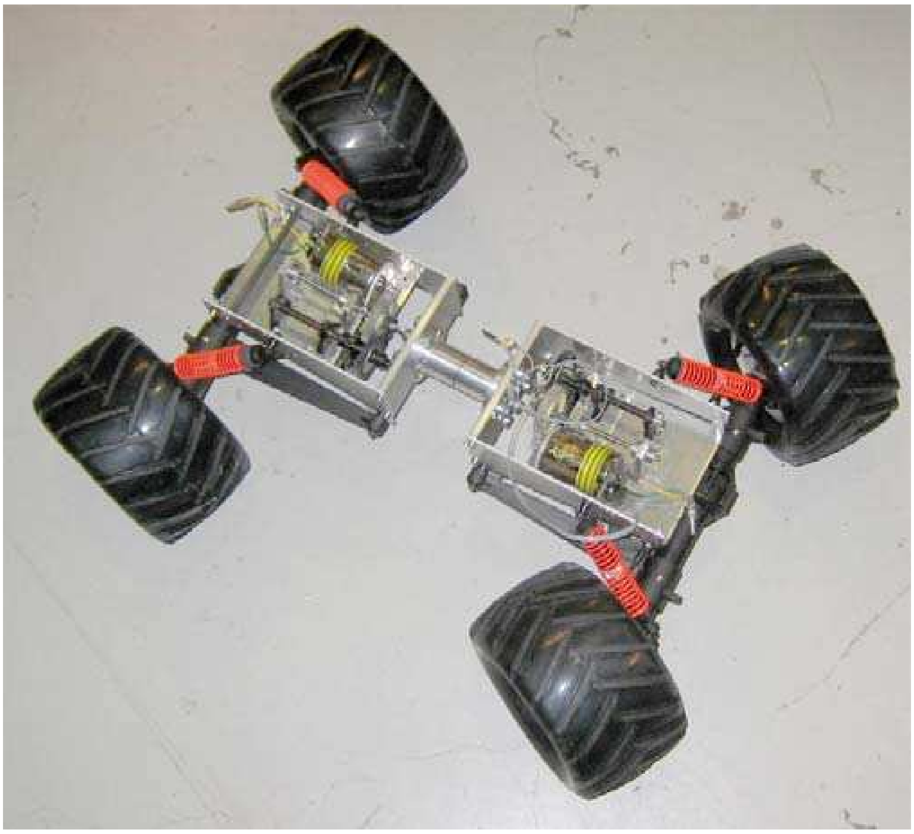

Fig. 3: Demeter robot's undercarriage. [4]

2.2. Seekur robot

Seekur [5] is a commercial platform from company Mobile Robots. The company is developing and selling robots and their undercarriages intended as bases for extensions and adjustments executed or specified by the customer. The type called Seekur is a sturdy, four-wheeled undercarriage with all wheel drive and steering. Thanks to its proportions and well designed suspension is suitable to use in arduous terrain. All wheels are mounted, steered, driven and sprung independently, making Seekur very universal product.

Fig. 4: Seekur platform. [5]

2.3. Spider slope mower

At first look is Spider [6], from Czech producer Dvořák – svahové sekačky ltd, very similar to the Seekur robot. It is a four wheeled undercarriage with all wheel drive and all wheel steering as well. However wheels are not independent in steering. They are all turned together and the body remains in unchanged direction, moving in a yawing motion. Suspension matches assumptive driving conditions. It’s tailored to movement in grass-grown terrain, but firm enough to provide mowing function and keep the trimmed grass at constant level.

Interesting on this type are also bulky wheels, guarantying high terrain mobility, and low laid centre of gravity, enabling the mower to climb and drive steep slopes. Modified undercarriage, supplemented by proper electronics, was also used in FieldRobot competition.

Fig. 5: Spider slope mower, mark 02. [6]

2.4. SuperDroid dSPACE robot

This robot [7] was developed by SuperDroid Robots Inc. according to dSPACE Inc. company specifications. Whole device is a low frame four wheel steering, four wheel drive construction build around dSPACE's control unit called AutoBox [8]. This unit is also available in Mechatronics Laboratory at Faculty of Mechanical Engineering, and was considered in early stages of development to be possible way to control our vehicle. This robot is mentioned here mainly as an example of placing the Autobox unit in the body.

Fig. 6: SuperDroid robot developed for dSPACE. [7]

2.5. Omnirota robot

Another participant of FieldRobot event was robot called Omnirota [9] created by students at University of Aarhus in Denmark. Contrary to other mentioned project has Omnirota three wheels and only one of them is driven and steered. The aim of whole development was to produce this very wheel and its universal mount. The outcome is a wheel mount capable of 360° rotation, with big wheel to excel in every terrain. Whole mount’s suspension is implemented inside the leg, hidden and covered, but still very effective.

Fig. 7: Visualization of Omnirota robot. [9]

Fig. 8: Omnirota’s universal wheel mount. [9]

2.6. High Trek baby-coach

Interesting wheel mount which can be seen on baby-coach BéBé Confort High Trek [10] brings a proof that inspiration is not to be found at similar projects only.

Wheel is obviously nor driven, nor steered, just freely revolving. On the other hand, the spring's emplacement is very sophisticated, but simple and effectively made. It neither magnifies the mount, nor reduces the turning possibility.

Fig. 9: BéBé Confort High Trek baby-coach and its front wheel suspension. [10]

2.7. Radio controlled models

The most alike undercarriage as the real cars have is clearly used in car's miniatures. Models are manufactured in almost every scaling with corresponding details. Many of them are created as mobile miniatures and are operated by remote radio-connected controllers. Some off-road versions [11] are equipped with four wheel drive. Although nearly none serial product is performed as four wheel steering vehicle, the front axle can be used as a representative part. Desired four wheel steering undercarriage would be constructed if two front axles were used.

Wheel turning angle of this solution is significantly worse than in previous cases, but similar to real cars' one and therefore still satisfactory. Wheels can be independently sprung, steered and driven so a huge variability in further development is still assured and vehicle's body can be customized to match other requirements. Various pars are available in specialized shops allowing the manufacturing price and effort to be reduced.

Fig. 10: RC model car Baja Buggy from FG Modellsport company. [11]

2.8. Overview

Mentioned variants served well while designing own concepts of wheel mount. Although the priority during designing was the best functionality, manufactory demands and overall cost were also considered. These and more requests are summed up in following chapter as detailed variants are.

3. Wheel mount

The main part of undercarriage development lay in proper wheel mount solution. After research, discussions and clarifying the requirements, several concepts were made. All concepts include one wheel mount only because the whole undercarriage design presumed using the same mount for all wheels.

3.1. Mount requirements

At the beginning, the possibility to steer the wheel (in best case) in any direction was priority. Considering real car's implementation, it was decided to give up on this demand, because it was not necessary to be able to move the car in any direction, or turn on the spot. Requirements about low price and manufacturing simplicity on the other hand, remained.

Other considered issue was required turning moment. Moment would be reduced by mounting the wheel as close to vertical axle of the wheel as possible. If done so, mathematical model describing steering of the wheel would be simpler and less demanding on controlling processor. In other words the mathematical model should be preferably linear. Likewise linear should be the relation between actuator's deflection and steered angle.

Not a bit less important is supplying driving force from the engine to the wheel. There had to be enough space in the mount, where a shaft, belt or roller chain, or even a whole engine could be placed. This requirement was closely associated with wheel steering. Attached engine or shaft could rapidly reduce turning angle of the wheel.

The wheel mount's parts which would be inclinable to be soiled or damaged in outdoor conditions shall be covered or located at a safe place. The chassis should be sprung to allow outdoor operation.

3.2. Mount variants

3.2.1. Baby-coach

Concept, especially the spring placement, is inspired by mount of rotatable wheel of High Trek pushchair. Extension spring is used to absorb roughness of terrain. Turning axel can be placed exactly in the middle of the wheel, so the required steering moment will be reduced. Wheel can be steered in every direction.

Inconveniently connected is the engine. Placing it directly at the wheel makes it vulnerable and the whole unit is oversized in width.

This variant can be well performed with a special flat engine, which would be placed inside the wheel itself. Otherwise working environment without danger of damaging the engine would be required.

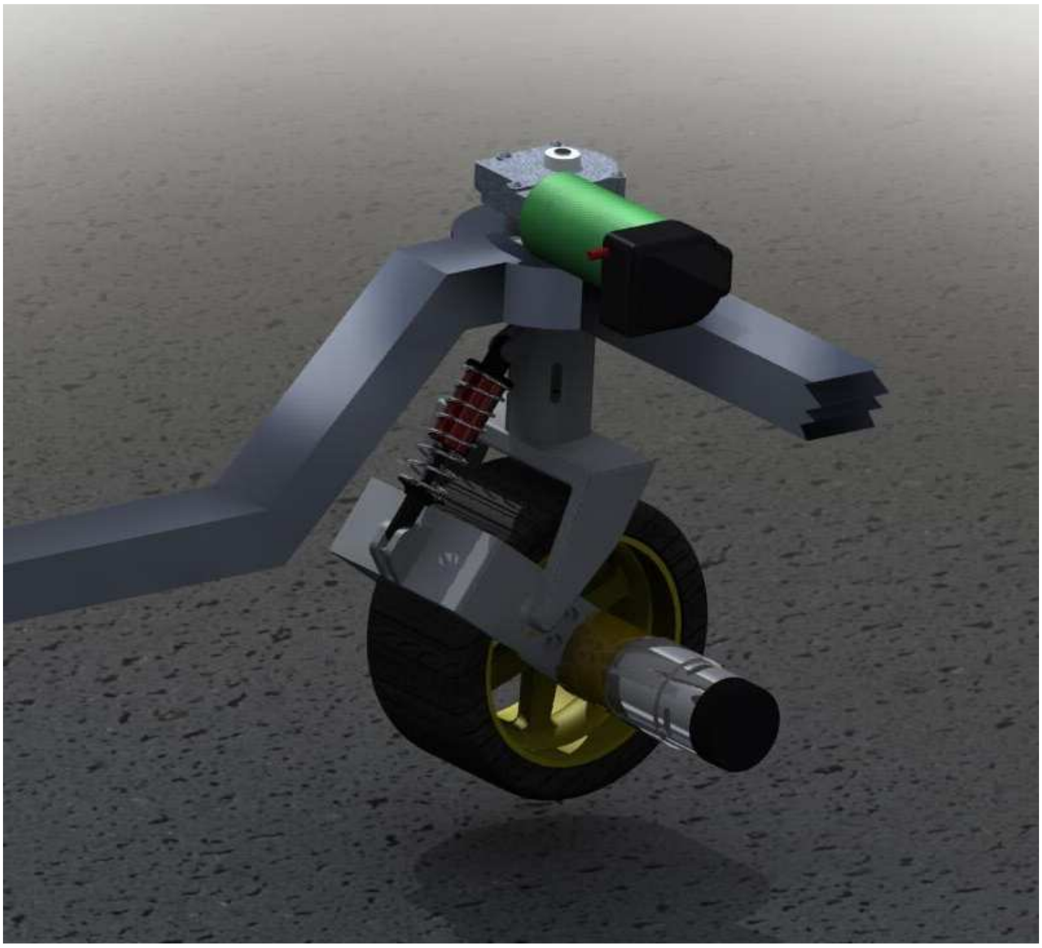

Fig. 11: Wheel mount design inspired by baby-coach suspension, with engine connected directly to the wheel.

Other possible variant of this wheel mount have the engine mounted on the unsprung part of the leg, which would be safe a spot even for outdoor driving. The engine's output moment is transmitted to the wheel by a synchronous belt. The distance between wheel's and engine's axle is constant, therefore the belt would remain properly tensioned even during springing.

Downside of this mount is big unsprung weight at the wheel. The weight of the engine (approximately 1 kilogram), respective it's inertia and produced forces during springing would be too big for current mount dimensioning. Proper function would be assured by enlarging the leg's dimensions, but this would also raise the manufacturing effort and overall price.

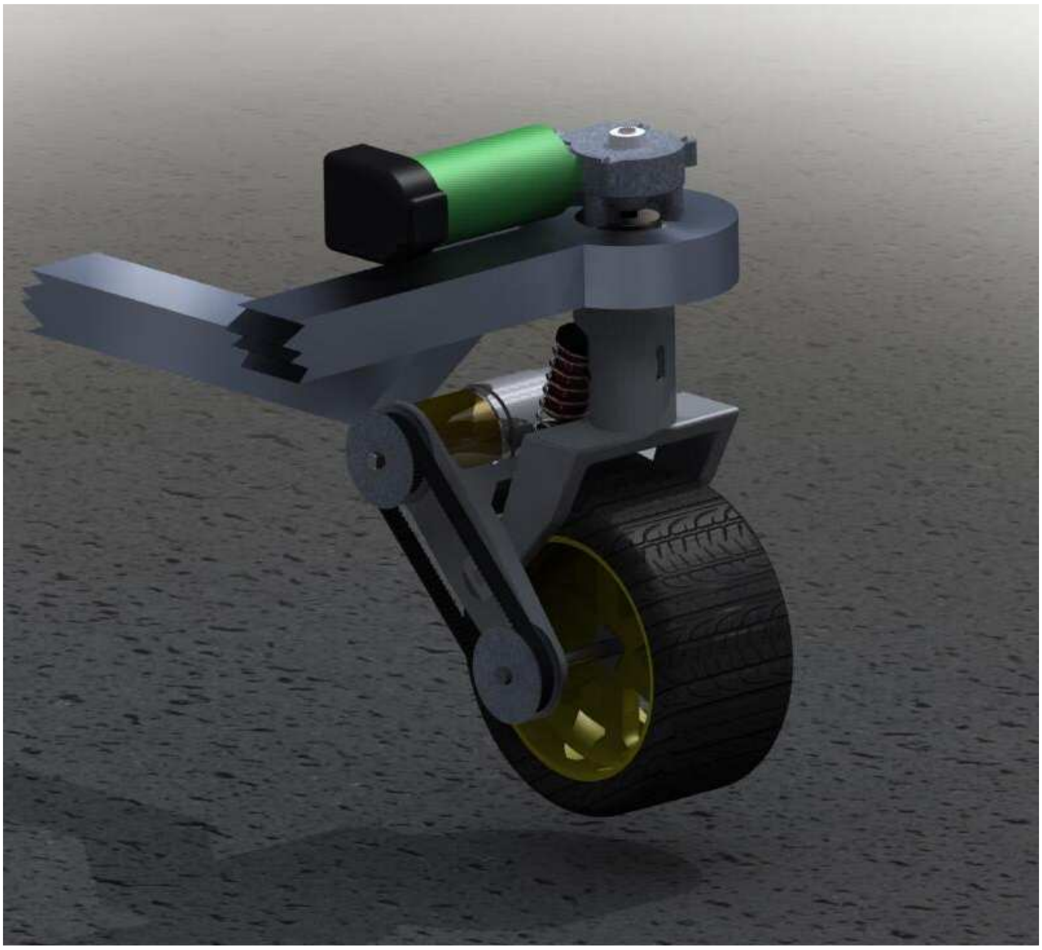

Fig. 12: Wheel mount design inspired by baby-coach suspension, with engine placed at the mount leg.

3.2.2. Seekur

This variant arises from wheel mounts on Seekur or SuperDroid robots and Spider mower. Engine is well protected and full steering angle is still preserved. Turning axle can be again led through the centre of the wheel. Concept is easier and therefore cheaper to produce and not demanding on material.

Height of the mount, on the other hand, can’t be listed as a pro. Worse is the absence of suspension. In case of placing it at the top of turning leg, the height would be enormous. Other possibility is to spring whole mount unit against the chassis, as is done on Spider mower. This can be applied on heavy machines (the mower most certainly belongs to this group) which have major part of their mass placed in the body and the unsprung weight at every mount is low, compared to the mass of the rest of the vehicle. Our vehicle shall be quite light and engines and wheel mounts would be the main part of its mass, therefore this kind of suspension would be ineffective.

Despite of that is this concept very elegant and could be recommended for vehicles operating indoors and not requiring springing, or bigger and heavier vehicles for outdoor use.

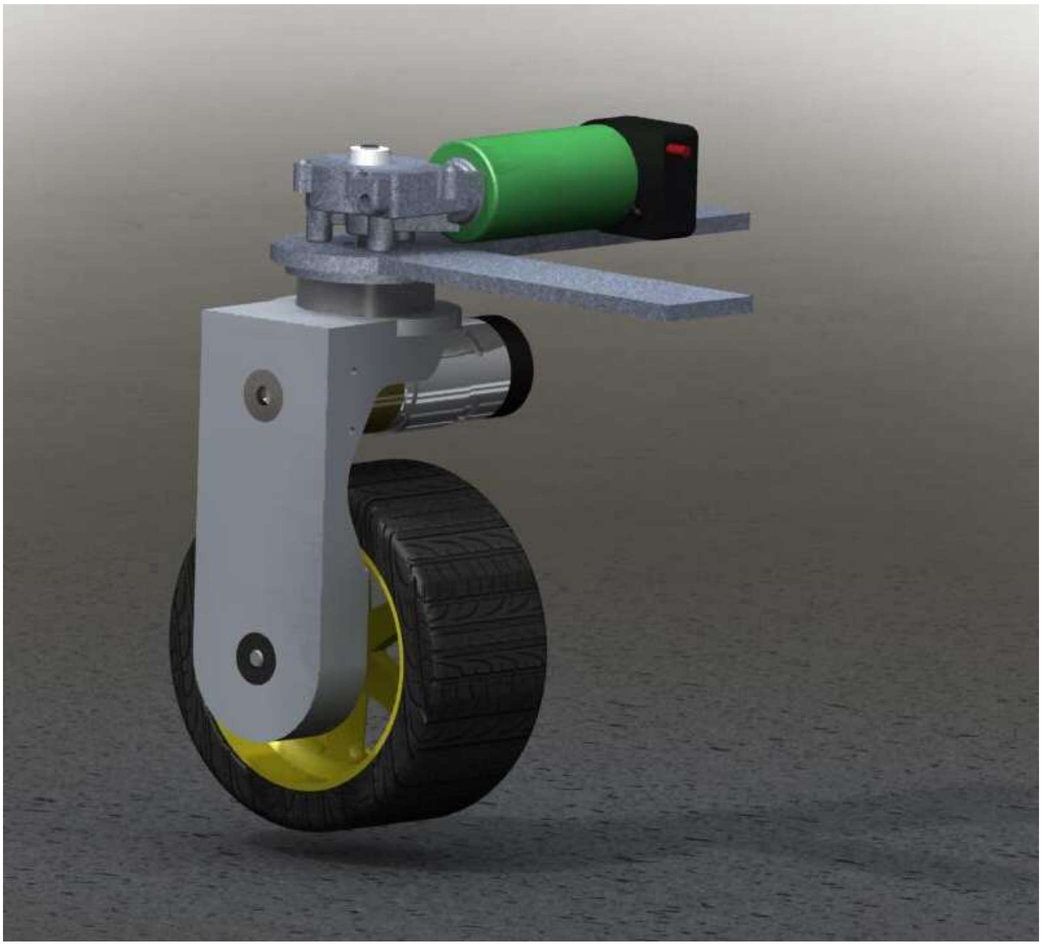

Fig. 13: Wheel mount design inspired by Seekur robot.

3.2.3. Omnirota

Effective solution of suspension placement brings the Omnirota's universal leg. Springs and absorbers are integrated in the leg itself. Due to this, the engine and wheel change their mutual position while springing. This issue can be compensated by transferring the power by a length-changing shaft or a belt with continual tensioning (by an extra pulley as shown in picture bellow).

This solution may be a bit too sturdy for smaller vehicles, but even so can be useful, if the compensation of axels' distance differentiation is well thought-out.

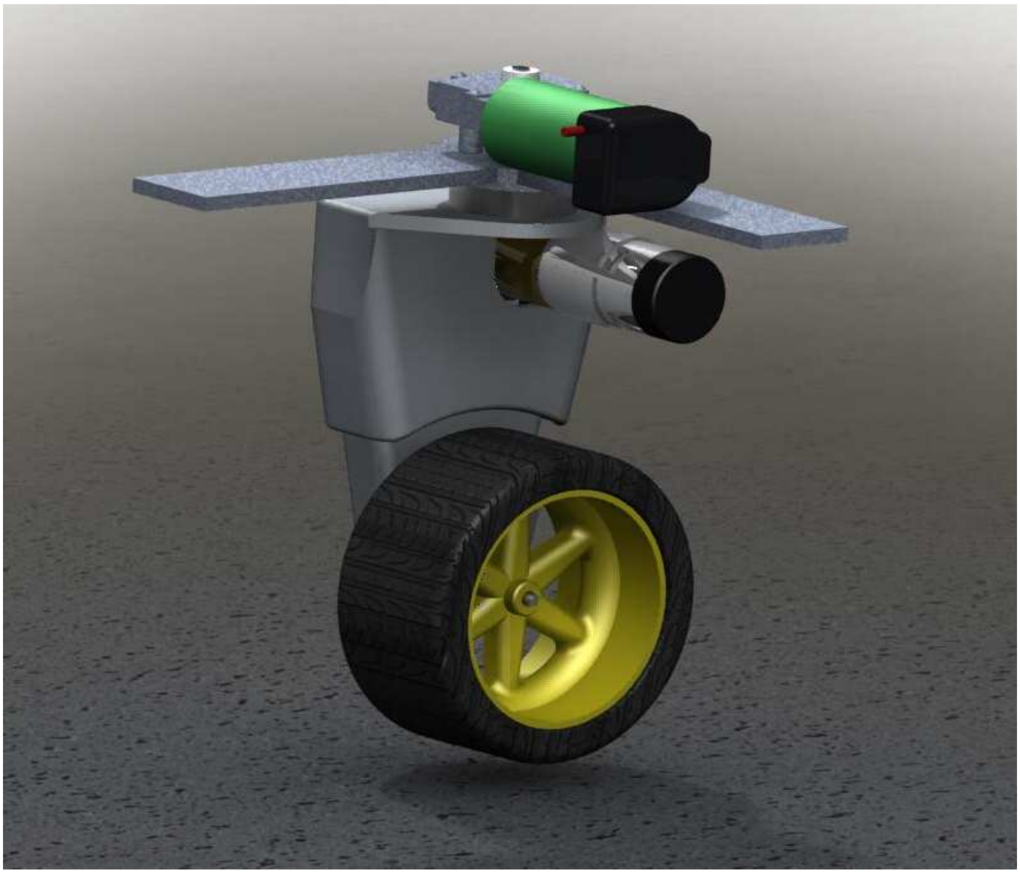

Fig. 14: Visualization of a wheel mount similar to Omnirota's universal leg.

Fig. 15: Detail of belt tensioning system inside the leg.

3.2.4. Cone gear unit

At first glance more difficult variant is using cone transmission. The engine is placed vertically in mount's leg which is also engine's protective case and sliding surface for compressive spring. Axle of turning does not intersect the wheel but steering to every angle is still possible.

Engine is connected to the wheel via cone gear unit. Proper choice of this unit would be essential for mount size. In addition the gears would be very sensitive to dirt and would require a cover of some sort.

Placing engine into the turning leg could cause difficult servicing. Also adequate ventilation should be covered in design. Contact surfaces between the leg and the frame shall be lubricated and manufactured in highest possible precision to prevent them from seizing and jamming. This is the main problem of the concept. Increasing manufacturing precision would raise the price rapidly, lowering it could cause fault liability.

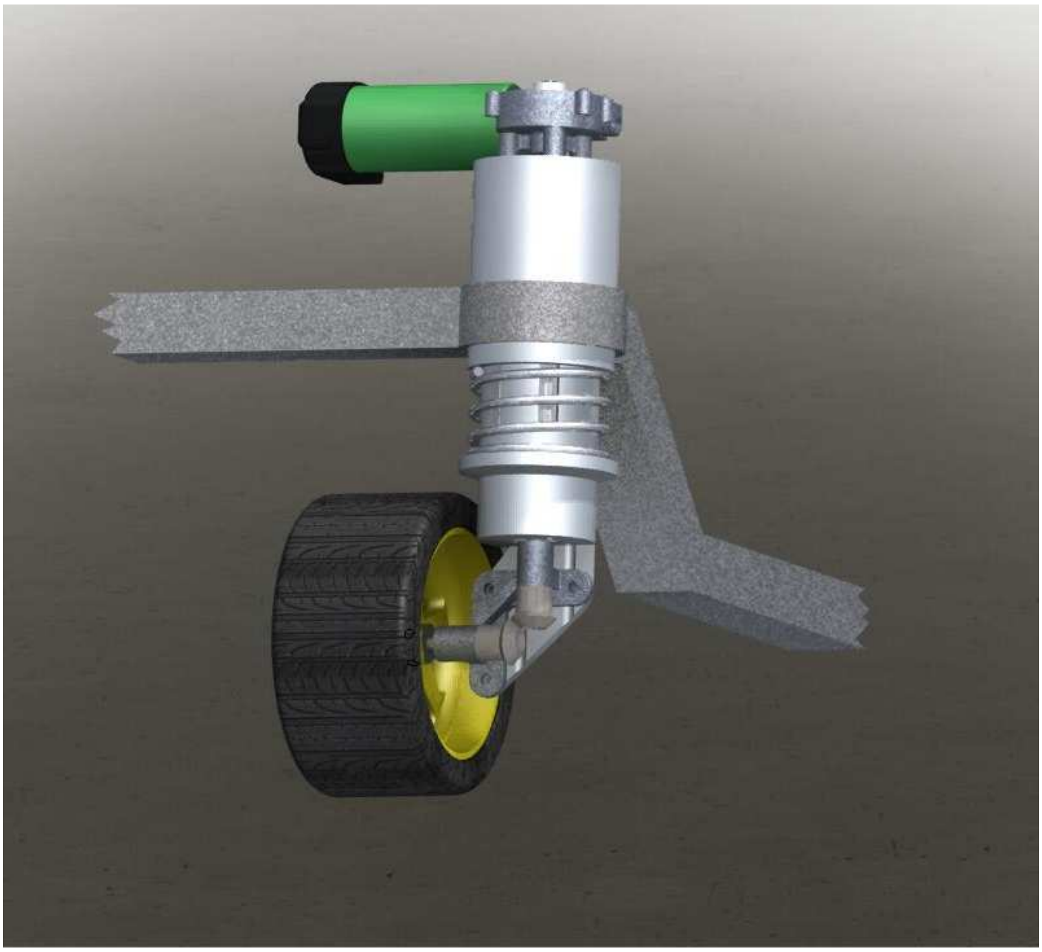

Fig. 16: Wheel mount using the cone gear unit.

3.2.5. RC cars

Closest to desired model of real automobile is the idea to use parts from RC model cars. Similar parts in proper size are used in real cars from the very beginning of automobile industry, therefore is this concept verified and reliable. Driving force can be brought to the wheel in multiple ways, from mounting the engine into the wheel to placing it inside the chassis and distributing force remotely. Compared to other variants, this is the only flexible in number of engines. Four, two or even only one engine could be used for all wheels. The engine placement and driving force distribution extremely depends on engine choice and therefore a separate chapter is dedicated to it.

Suspension on this concept is independent for each wheel, which makes it ideal for rough terrain. The mount allows changing the position of the springs with absorbers, so the spring rate can be adjusted variously for different terrain.

This concept is basically a copy of real car's wheel mount and thus could be preferred. Using available parts from radio controlled models will reduce manufacturing effort to minimum and enable variability during engine selection. Wheel mount will not affect the frame and whole layout can head for functionality and simplicity.

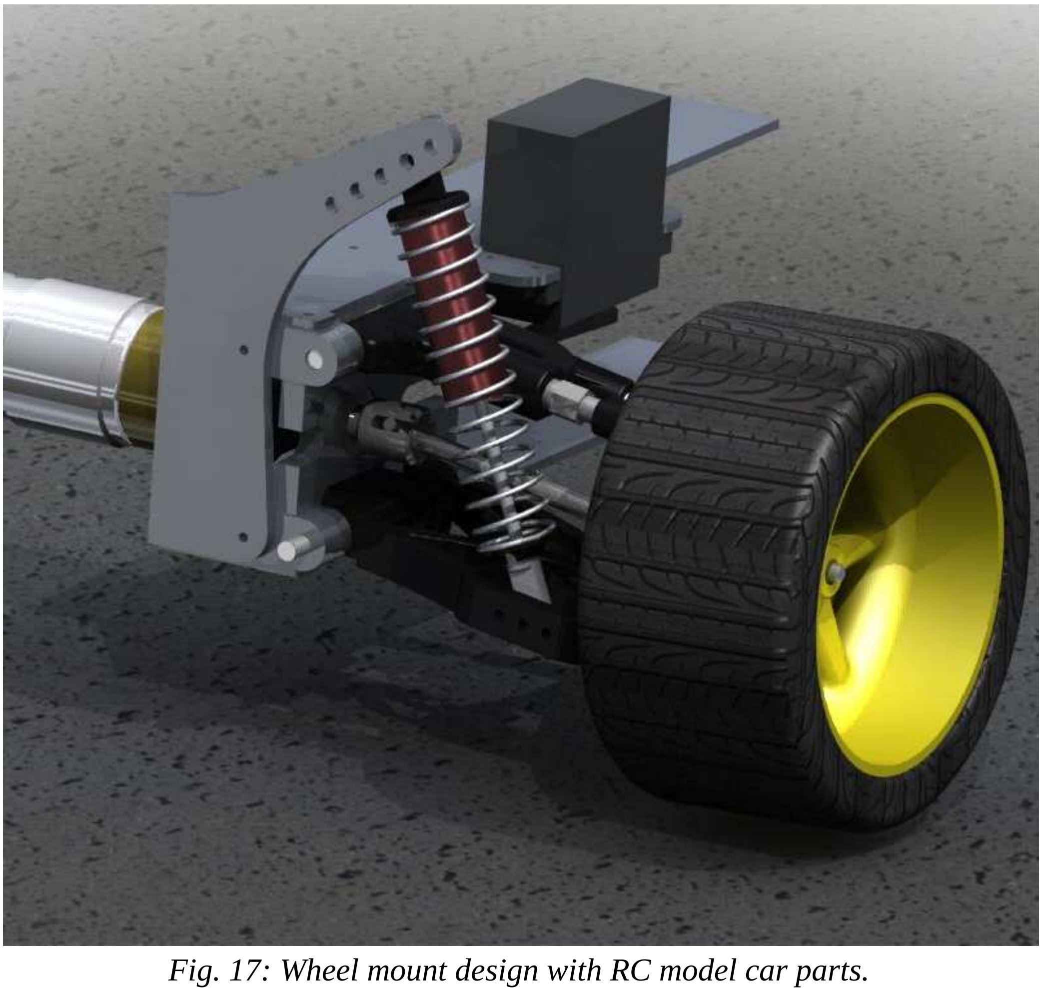

Fig. 17: Wheel mount design with RC model car parts.

3.3. Overview

Some essential requirements on wheel mount were mentioned during variant listing. Remaining step is to sum them up and exclude concepts which do not meet some of them.

Priority is the flawless function. Design should be simple, but effective. Correct uninterrupted power distribution is required. Proper functionality of steering needs to be assured. The mount shall be sprung, preferably by a spring with a shock absorber. Whole mount should be easily producible, low on used material and reasonably on price.

Some wheel mounts provide very high steering angle. Although this attribute can be appreciated, it is not essential. Keeping in mind the basic concept similar to car, the steering angle about +20/-20 degrees is satisfactory.

Variants which are not suitable for use in outdoor environment can be excluded. Variants which lacks suspension, or which would be oversized with it, can be left as well.

The number of remaining variants is now reduced and can the final variant can be chosen according to the engine’s choice.

Solution provided by using RC car’s parts seems to be the leading variant through its universality. Mount inspired by the baby coach, as well as the one with cone gear unit, can be used if a proper-sized engine is found.

4. Choosing specific components

Before the final variant of wheel mount could be chosen and implemented into the frame, all components of developed vehicle had to be defined. In this chapter there are listed all the parts used in undercarriage design.

4.1. Frame

The shape of the frame is to be profiled according to all chosen components' size, placing and mass. Despite of that some of the frame's characteristics are already defined:

The size and mass of the vehicle should not exceed the given limits. The mass of the rest of components is a given value and can't be changed, because other parts are chosen by different priorities. The only variable mass is the frame's one. Therefore aluminium was picked as the main material, because it is lightweight but yet durable. The frame made of aluminium would be sturdy enough to handle all possible stress, but still light and subtle to ease manipulation and storing. The material is ductile and can be easily machined, which reduces the manufacturing effort and price. Several aluminium alloys with different characteristics are available at suppliers. Also their price is acceptable.

Besides the frame itself, the vehicle should have some bumpers to protect the wheels and important parts of the frame in case of accident or collision sensor failure.

4.2. Drive engines

Electric motors were chosen almost immediately due to theirs characteristics. They are very light compared to other engines of the same power. The output moment, respective velocity can be easily controlled through input voltage and current.

Several motors were considered. The main criterion was their output moment and ability to reach it without overloading, or to handle the overloading at least during the acceleration. The needed moment can be also gained by using a gear box, but it must be considered if the velocity would remain sufficient. There needs to be mentioned that the number of engines was not strictly determined. If the moment from one engine would be big enough to ride all wheels, there is no need to have more than just one engine.

Some basic calculations were performed to state the needed moment. The vehicle of approximate weight of 20 kilograms with wheels of 170 millimetres in diameter should be able to skid during acceleration. This means that the engine's output moment, respectively the force it produces at the wheel, had to be bigger than friction between wheel and terrain. Considering equation for friction force [equation 1] and input values, the friction force is approximately 40 N per one wheel, if the acceleration is performed on clean concrete. For used diameter of the wheel is necessary moment 3.4 Nm at each wheel [equation 2]. To be able to skid the wheel during acceleration, the engine's output moment has to be at least equal to this value, if one engine per wheel is used. If less than four engines are used, their output moment would have to be equally bigger. For example, if only one engine drives the vehicle, its moment would have to handle all four wheels and hence it would have to be at least 13.6 Nm.

The demanded moment could be decreased by lowering the coefficient of friction, or in other words, testing the vehicle on tarmac, wet or dusty concrete or even ice.

$$F_t = m \times g \times f$$

[equation 1]

F_t ... friction force
m ... weight of vehicle
g ... gravitational acceleration
f ... coefficient of friction

$$M_t = F_t \times r$$

[equation 2]

M_t ... friction moment
r ... the wheel's diameter

Other important thing was the motor's size. Choosing the smallest possible motors is essential to preserve the freedom of design, because large engine would have special space and mount demands.

4.2.1. MX3035 motors

The MX3035 motors were the first choice, because they were available in Mechatronics Laboratory. If two motors were used, their moment would be slightly under the demanded value to skid the vehicle on concrete road. Using four motors would not be easy due to their size. The motors, although not equipped with encoder, were still possible to use in two-engine concept.

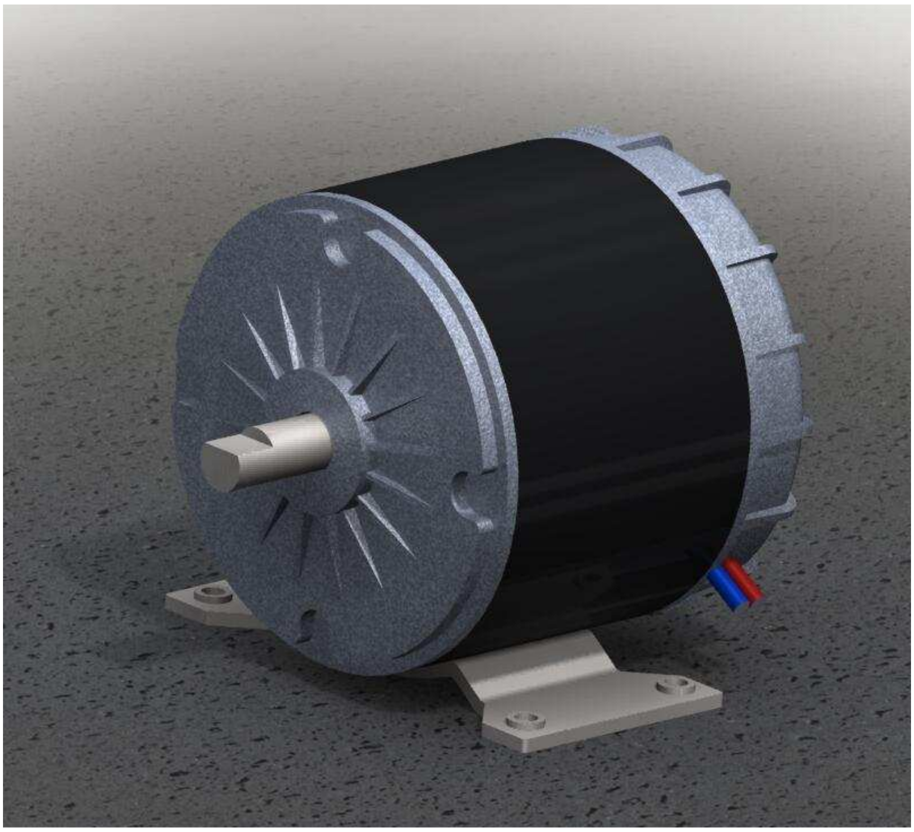

Fig. 18: The MX3035 motor visualization.

4.2.2. PD52103 motors

Other motors available in laboratory were the Transmotec PD52103 motors [12]. They were supposed to be used for Car4 project according the preliminary specifications. Two different types were considered to use. Motors equipped with encoder (letters OE in their marking) or with brake (letter B), both types with 1:39 epicyclic (or planetary) gearing. The brake is not intended for braking during normal duty, but more for locking the motor's position when it stops. Besides that, electric motors can brake by reversed current and don't really need an additional brake; therefore motors with encoders were preferred.

The output moment, even with 1:39 gear box, was still too small for our vehicle and PD52103 motors were put aside.

Fig. 19: The PD52103 motor with gearing. [12]

4.2.3. Transmotec motors

After checking all motors already available in laboratory it was considered to buy new motors. Good characteristic of PD52103 motors and comprehensive and complete datasheets led to choosing other Transmotec Sweden AB company product. After comparing the moment/velocity ratio of many types, motors PD4266 were chosen. It was decided to use the 24 V variant instead of 12 V, because the motor's current demands during eventual overloading would be smaller and batteries would last longer.

The gear box ratio was chosen from output break torque estimation [equation 3].

$$T_B = \frac{T_S}{T_R} \times T_{S_G}$$

[equation 3]

T_B ... break torque

T_S ... stall torque of the motor

T_R ... rated torque of the motor
T_{SG} ... stall torque with the gearbox

Required break torque of 3.4 Nm is satisfied by 1:14 gearbox's estimated torque of approximately 3.7 Nm. According to the datasheet information [13], the vehicle's speed would reach 10 kilometres per hour, which is even more than required.

The variant with encoder was again preferred so the PD4266-24V-14gearOE motors were chosen.

Fig. 20: The PD4266 motor with encoder and gearing. [13]

4.3. Steering motors

Choosing the motors used to turn the wheels was not as easy as it may seem. The motors need to handle quite a big turning moment and be able to keep requested angle no matter of the force which occurs at the wheel. This can be done in two ways. The first is in using motor with included brake, which will lock the angle after changing. The downside of this method is absence of any monitor controlling the correct angle. The second way is obviously in using motor with an encoder, which monitors deviation from desired angle. The problem of this solution can be a need to continuous electric power supply, because the encoder is always correcting the wheel angle while outer force is present. Due to these issues using of ordinary motor would be troubling. Originally it was intended to use Transmotec WLD4383 motors [14] equipped with encoders for proper deflection measurement and 1:31 worm gear unit to gain needed steering moment. However their output rotational speed is too low compared to possible travelling velocity. Therefore it was decided to use servomotors for steering the wheels. Servos are specially developed motors with inbuilt gearbox and accurate encoder. The gearbox gives them a great output moment and makes them stiff, and the encoder can precisely detect the smallest change of the angle.

The steering could be performed by four servos, if all wheel need to be steered independently. Two servos would be enough if proper angle of both at once steered wheels would match the Ackermann geometry condition (of two wheels needing to trace out circles of different radii). Therefore should be the frame prepared for mounting two or four servos according to the chosen variant.

Proper size of chosen servos is also essential. They shouldn't be too big and occupy large space in the undercarriage. Smaller servos, on the other hand, couldn't handle the moment present at wheels during steering at big speeds. Probably best choice would be large scale servos, which are designed for steering RC cars of similar size as our vehicle would be.

The final choice was two or four Scanner SSV 9960MG servos [15], due to their characteristics and convenient price. These servos have durable metal gears, dual ball bearings and strong engine, which allows them handle a torque of 24 kg-cm at speed 0.13 seconds per 60°.

Fig. 21: Scanner SSV 9960MG servomotor with mount parts and horns. [15]

4.4. Batteries

The electric motors, servomotors and controlling electronics require an electric power supply. During the first tests it is supposed to supply electricity to the vehicle through a cable from laboratory power supply. After basic tests are done, the vehicle shall have its own power supply to be autonomous and able to be tested outdoors.

The time of one test, enabled by batteries' endurance, should be at least 20 minutes. The discharge load on batteries is 24 volts at 13 amperes to each PD4266 engine, plus power needed by electronics. Considering momentarily overloading of the engines during acceleration, it was decided to use battery supply for 24 volts and at least 100 amperes. Usual batteries are not capable of giving such values, therefore special batteries were needed. Demanded power can be provided by accumulators used commonly by modellers. After data about number of types were compared, the A123 cells [16] were chosen. One battery can give 3.3 volts at 70 amperes with charge of 2.3 ampere-hours. Positive is also the weight of 70 grams. These batteries are sold either separately or soldered in packs.

For required voltage 8 batteries would be needed. With given characteristics they would be able to keep vehicle driving for demanded 20 minutes. Charging of batteries would be possible by one of chargers available in laboratory.

Fig. 22: Pack of A123 batteries. [16]

5. Driving power distribution

During choosing the engines, their size and proportions were already considered. Engines which are more compact were preferred as the wheel mount concept was still not clear. This turned out well during solving the driving power distribution, because smaller engines offered bigger variability.

5.1. Engine in the wheel

Placing engine directly into the wheel is very convenient, because not other shafts, gears or connections have to be used. On the other hand the length of chosen engine would cause problems as the engines' body would collide with other parts of the mount while springing or turning.

This variant is mentioned here to make list of possible engine placing complete and can be used if proper mount concept would be chosen.

Fig. 23: Engine placed in the wheel.

5.2. Using elastic shaft

Elastic shaft would solve problems with insufficient space for engine at the wheel. In this case engine is placed in the frame and connected to the wheel by a shaft capable of flexion, therefore the turning and springing would be possible.

After searching devices with elastic shaft and available shafts, it was found that for given length of the shaft and transmitted moment would be the shaft's flexion angle too small and more important, the price would be enormous. Moreover the elastic shaft is more suitable as an alternative to gear transmission between two fixed intersecting shafts than for moment transmission between axels changing their mutual position.

Fig. 24: Motor connected by elastic shaft.

5.3. Using double cardan shaft

The elastic shaft had to be replaced in other variants by more reliable part, which would still be able to continuously transmit the driving moment. Following concept is based on a shaft with two cardan joints (also called universal joints). These allow the rigid shaft to bend and transmit rotary motion between two position-changing axels, so the engine could be placed inside the frame, covered and protected from the environment.

Engines would be placed in frame next to or upon each other, because the track would be enormous when with engines placed behind each other in a row. By slightly offsetting the engines' axels the cardan joint could be placed symmetrically at both sides of vehicle. On the other hand, high angle of offset would negatively affect the joint's function. In other words, the joint can handle only a limited angle between the axels (about 30 degrees). If the offset was too small and joints placing not symmetrical, the shaft between the two joints would not be collinear with not-turned wheel's axel, causing the maximal turning angle to be smaller in one direction than in the other.

The basic idea of using cardan shaft in this variant is used in all the following ones, with a demand on placing the joint in one line, symmetrically on both sides.

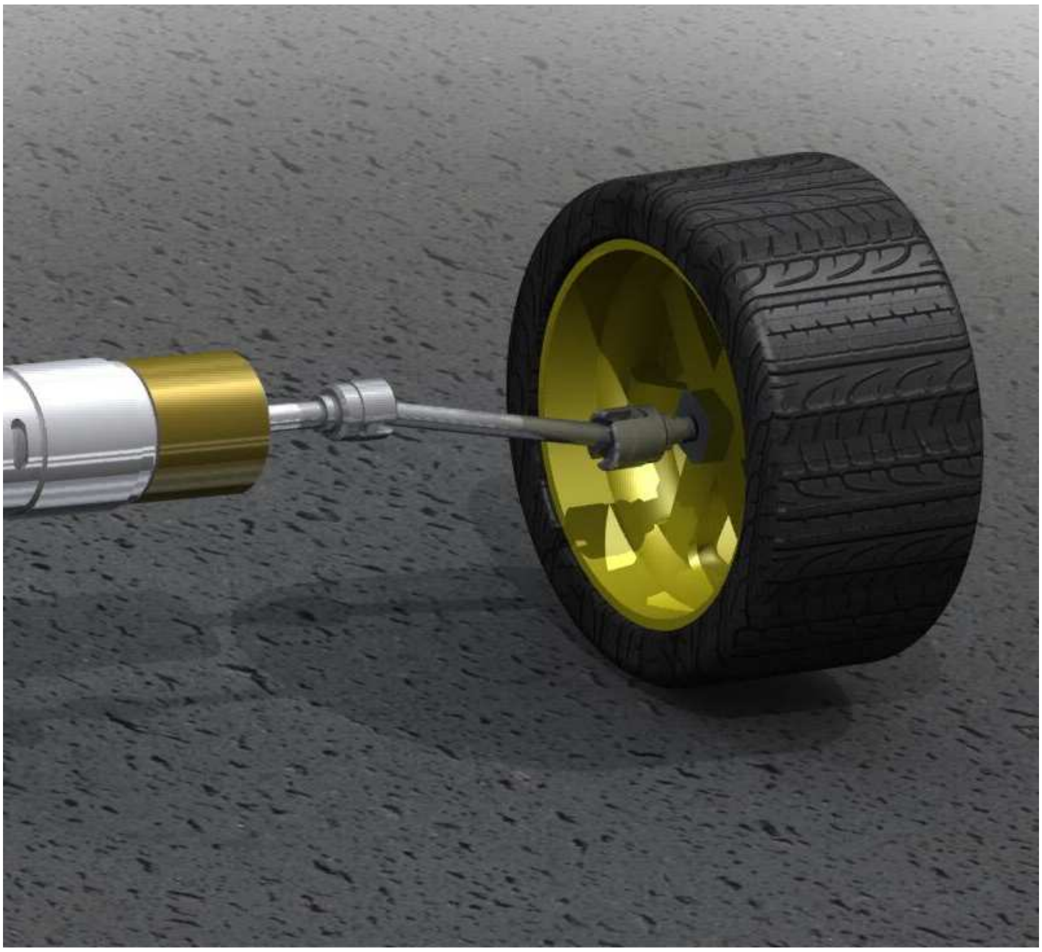

Fig. 25: Shaft with two cardan joints.

5.4. Using cone gear unit

After difficulties caused by placing the engines crosswise in the body, possibility to mount them lengthwise was checked. The engine would be connected to the cardan shaft by a cone gear unit, so the engine's axel and the shaft would be perpendicular. Vehicle's width would be comparable to variant with engines lying next to each other.

Fig. 26: Moment transmitting using cone gear unit.

5.5. Using differential unit

This mount is designed for two engines for the whole car (one engine per axel). It is very similar to front axle of front wheel drive vehicle. Hyperbolically speaking, two front axels with separate power supply would be placed mirrored behind each other.

Although the concept seemed to be very plain and easy to build, it raised more problems than any other one. While driving two wheels with one engine, there is no simple way to measure the movement of the wheels separately because the encoder, placed at the engine, is shared by both wheels. This measurement is necessary to test the anti-blocking systems or to avoid the wheel from skidding. Placing the encoder at wheel would be problematic as would be calculating the wheel movement from a mathematic equation of some sort. Also brakes would need to be placed at each wheel.

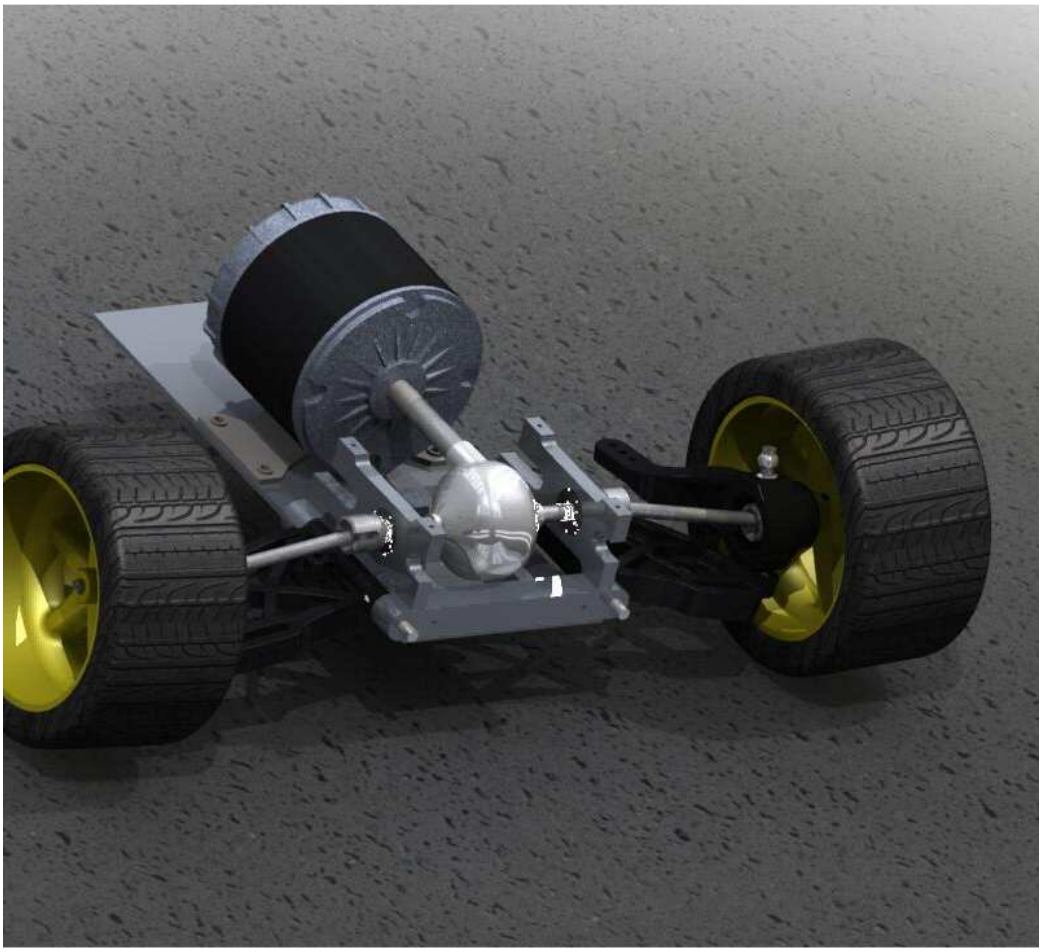

Fig. 27: Two wheels driven by one motor through differential.

5.6. Using belt

After discussion about advantages and disadvantages of previous variants, following requirements were states: there shall be four driving engines, each for one wheel; the moment will be transmitted from the frame to the wheel by cardan shaft; the engines would be placed outside the axel itself to reduce its track's width (possibly in the centre of car to assure right weight displacement); engines need to be connected to wheels in way that will prevent different rotary speeds on wheel and engine to occur, so the engine can be used as a brake and its encoder will measure the wheel motion as well.

The driving moment would need to be transmitted at a long distance because of placing the engines out of the axel. A belt was therefore used to link engine with cardan shaft. To prevent the belt to slip during high moment transmitting the synchronous belt would be used, thus the encoder would give proper value.

Also the efficiency of this moment transmission is sufficient (about 95%) and would not worse the engine's characteristics.

The only problems raised by this solution were strictly demands on design. The width of pulleys needed to fit in narrow space of the engine's shaft. The belt itself has to be constantly tensed to prevent its slipping. These factors were considered during implementing the drive mechanism into the frame.

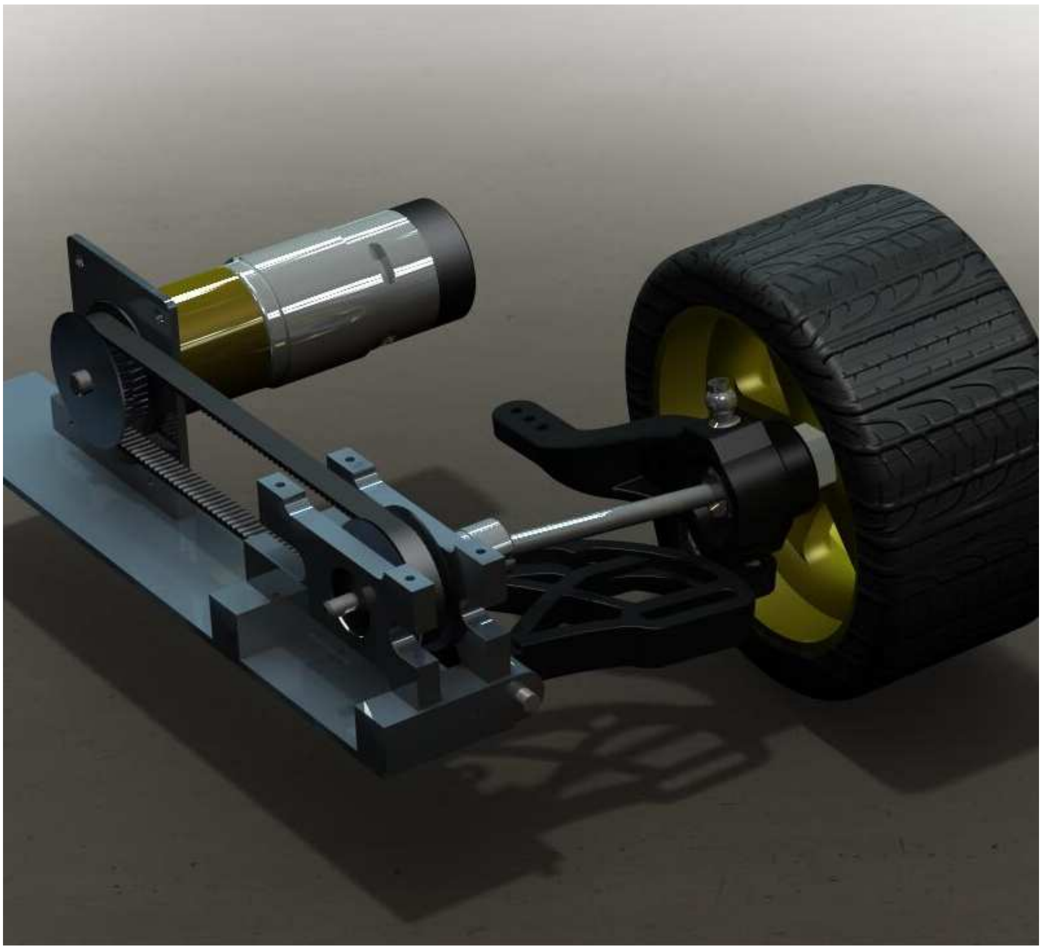

Fig. 28: Motor connected to the wheel by synchronous belt.

6. Undercarriage design

All what remained after choosing proper components for the vehicle was to compose them and mount them into the frame of the vehicle to be. According to many possible parts, there were again several concepts.

This chapter presents these variants and summarizes all their pros and cons. In the end there is the final variant, its development and also the manufacturing mentioned.

6.1. Requirements

Some of the requirements which are concerned with wheel mount or component choosing are already listed upwards. Let's mention them again and add some new requests, concerning the framework itself. After that the whole concept shall get specific contours.

The size of the vehicle is highly affected by used wheel mount, engines and power distribution system. The dimensions are conformed to the vehicle's weight. Enough room for placing circuit boards shall be left at a safe spot inside the main body, as well as room for placing necessary sensors (collision, thermal, gyroscope, etc). Evident is a need to place batteries into covered, but accessible place to ease manipulation during charging.

Material of frame is already chosen, the shape, on the other hand, is to be defined according to the used parts and power distribution concept. If the belt is used, it would be necessary to resolve its tensioning already during designing.

6.2. Variants

6.2.1. Two engines and differential

This concept uses two MX3035 engines connected to wheel by a differential. Frame itself is an aluminium plate reinforced at the bottom to prevent its flexion. RC car's parts are used in wheel mount in this and all following concepts.

Disadvantages of using only one engine per axel and a differential unit are already mentioned in the mount variants' list. Because of the required concept of model vehicle, capable of testing different control systems, this variant was not used.

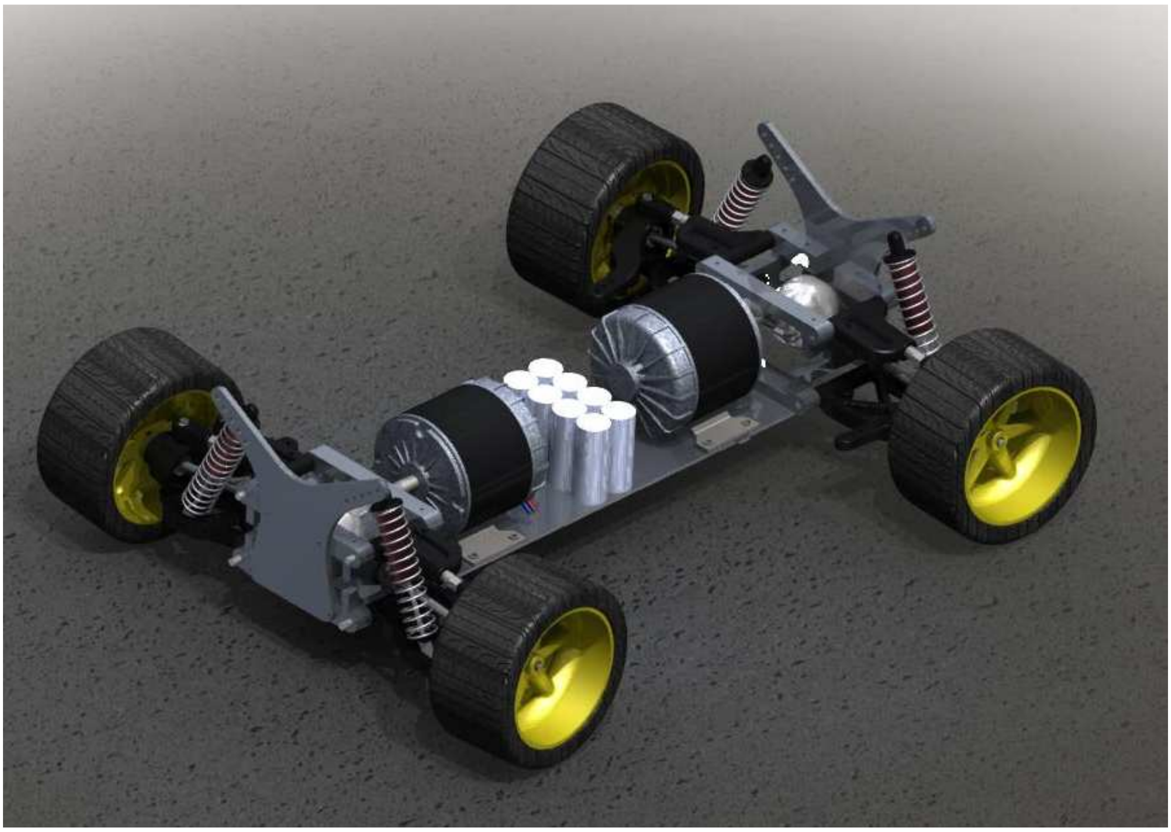

Fig. 29: Variant with two MX3035 motors and differential units.

6.2.2. Four offset engines

The variants with four drive engines fulfil requirements of universal testing vehicle. Variant with offset engines was modelled to check if cardan joints would be placed correctly in one row to assure correct function. The frame is therefore similar to previous one.

Placing engines into the axel makes the vehicles width enormous. In addition, the weight is concentrated at the ends of frame and the space in middle section is wasted.

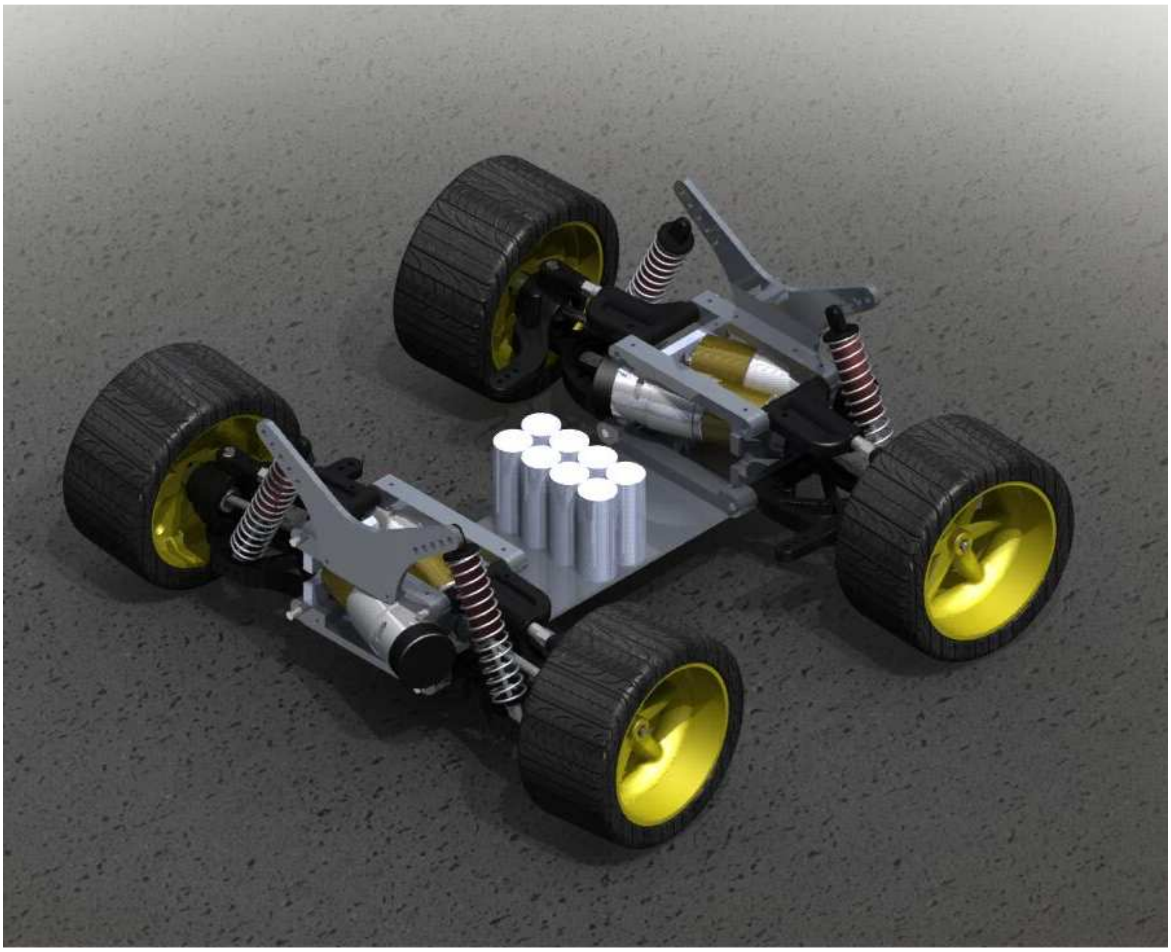

Fig. 30: Variant with four PD4266 offset motors

6.2.3. Four engines and belt

Using a belt to transmit the driving force enable the engines to be placed in free space near the centre of gravity of the vehicle. Thus the characteristics of the vehicle are similar to real car ones. Belt is tensioned already during assemblage by an adjustable engine mount and doesn't require extra pulley to keep its tension.

This variant, although with major structural changes, was used in further development.

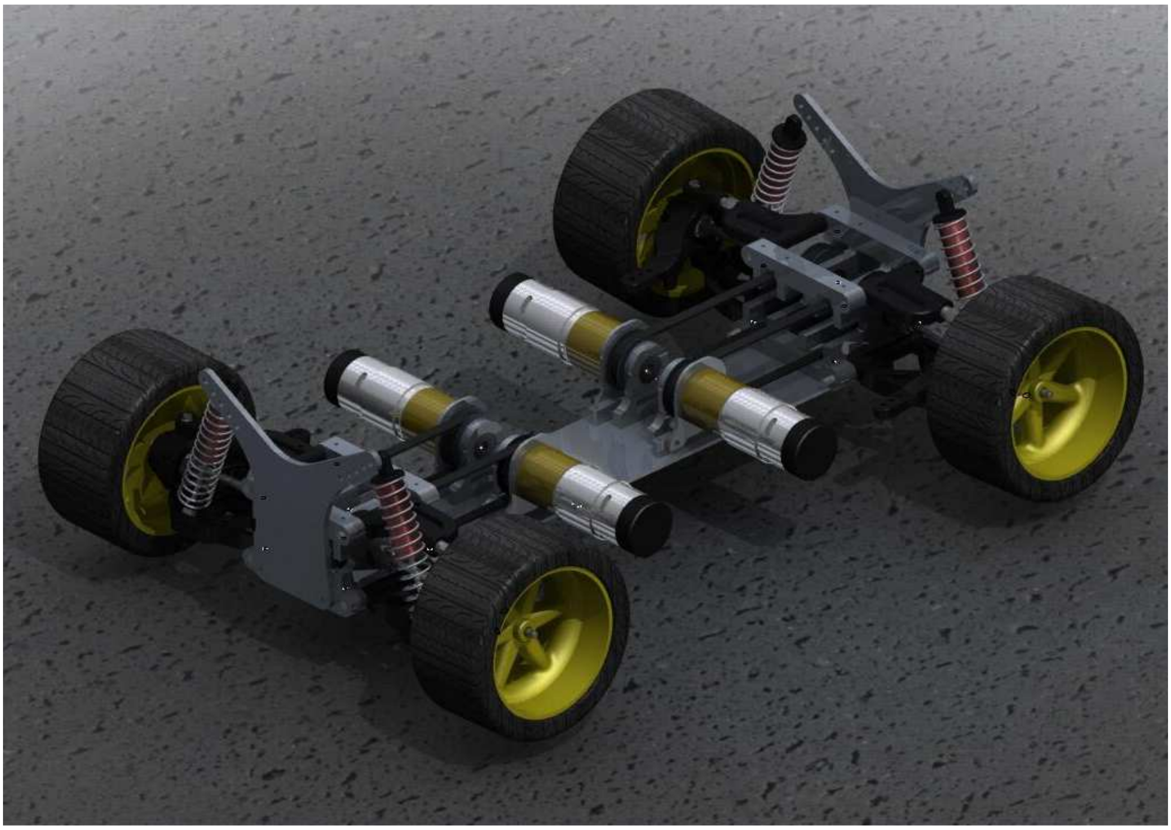

Fig. 31: Variant with four PD4266 motors, moment transmitted to wheels by belts.

6.3. Development of chosen variant

First changes were applied on the frame. A second plate was added to make it more rigid and flexion and torsion-resistant. Its whole shape became more compact, elegant and proportionally similar to a real car.

The limited space inside the frame and especially the length of the engine's shaft required special pulleys to be used. The shaft had a length of approximately 20 millimetres. Engine is assumed to mount upon its front side and due to high transmitted moment also a bearing at the end of the shaft is required. These formal demands left a space with width about 16 millimetres for mounting the pulley. Therefore the pulleys were narrowed by removing redundant material using a lathe. They were attached to the shaft by a grub screw led vertically thought pulley's body.

The number of steering engines or servomotors was variable, depending on decision if each wheel would be steered independently.

6.4. Final version

The final design was adapted according to the wheel mount after its parts were bought. Parts from two front axels of RC car "Baja Buggy" by company FG Modellsport were used, thanks to help and advices from the sellers, Mr. Dušan Bayer and his son Martin. This buggy is a four wheel drive outdoor vehicle in scale of 1:6, hence the parts were ideal for intended concept and size.

The frame shape and dimensions were corrected to match the real mount's parts. Proper belts and pulleys were chosen with patient help of technicians from companies Mateza ltd and UZIMEX PRAHA ltd. All pulleys are the same size, because there was no need to add other gearing. Chosen pulleys 40-3MR-09, designed for the used belt, are one of the narrowest available, but still not narrow enough to fit in the space given by engine's shaft length and therefore were adjusted as listed upwards (section 6.3). Used belt is a Gates PowerGrip synchronous belt with HTD 3M profile and 9 millimetre width. In conditions occurring at our vehicle (given engine's output moment, rotational speed and pulley's diameter) is capable to transmit permanently a maximal moment of 3.06 Nm for a lifetime of 10,000 hours. Exceeding continuously the maximal moment will shorten the lifetime approximately ten times, but commonly used moment is assumed to be under this value. The pulleys' mount and belt placement are designed to ease eventual change of the belt. The belt is tensioned by adjustable engine mount. Each engine can be slid forwards and backwards and locked independently to assure the correct tension for every belt.

During designing it was intended to make parts universal and easy to assemble. Almost all screws and nuts are the same size to reduce number of needed tools.

Ball bearings were used at the end of the engine's shaft (1 per engine) and at the driven pulley shaft mount (2 per shaft). The 608-2Z ball bearings were chosen because of their resistance and endurance. They are overlarge to extend their life cycle and prevent failures.

Different thicknesses of aluminium plates were used. Plates with thickness of 8 millimetres were used for vertical parts to enable bearing mounting. Plates thick 3 millimetres were used for the main upper and bottom parts connecting all the vertical ones, and for the bumpers, because they're light and can be easily manufactured. Also 5 millimetres thick plate is used for the suspension mount. All vertical parts are connected to main frame plates by hardened metric thread screws with hexagonal socket and M3 diameter.

The upper main plate is also supposed for electronics to be placed, for it's the safest spot of whole vehicle.

Four Scanner servos were used for bigger variability and accurate steering, but the concept is also ready for two-servo steering. Switching servos can be easily done by unscrewing the present servos, changing the steering arm for a longer one and placing the two servos into the prepared gap. Proper implementation of Ackermann condition is assured by multiple possible variants of connecting the servo to the arm of the steering hub.

The frame is prepared for a future installation of a plastic chassis which will cover the engines and the belt from below and the electronic at the top.

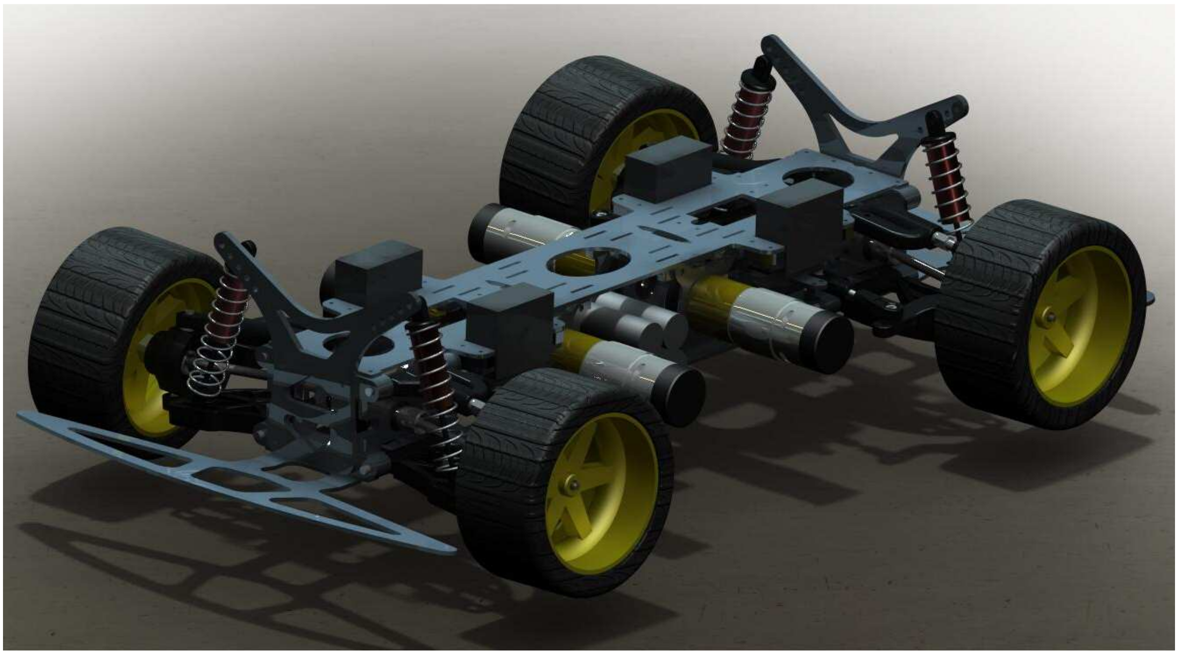

Fig. 32: Final variant.

6.5. Manufacture and assemblage

All manufactured parts (all aluminium plates of all thicknesses) were cut according to our drawings by professional metal processing companies with laser (3 and 5 mm thick parts) or water (8 mm parts) and then finished at Institute of Machine and Industrial Design’s workshop, where threads were drilled and holes with high geometrical accuracy for bearings were made. After these preparations, cleaning and manual adjustments, the undercarriage was prepared to be assembled.

Except minor upgrades and alternations the assemblage did not cause any problem and was easily done by one person. This proved that the design was well prepared for manual assemblage and generally well thought.

The minor problems were caused by insufficient place around pulleys at engine’s shaft. Additional space was gained by using countersunk screws in affected area and pulleys proper position was locked by washers.

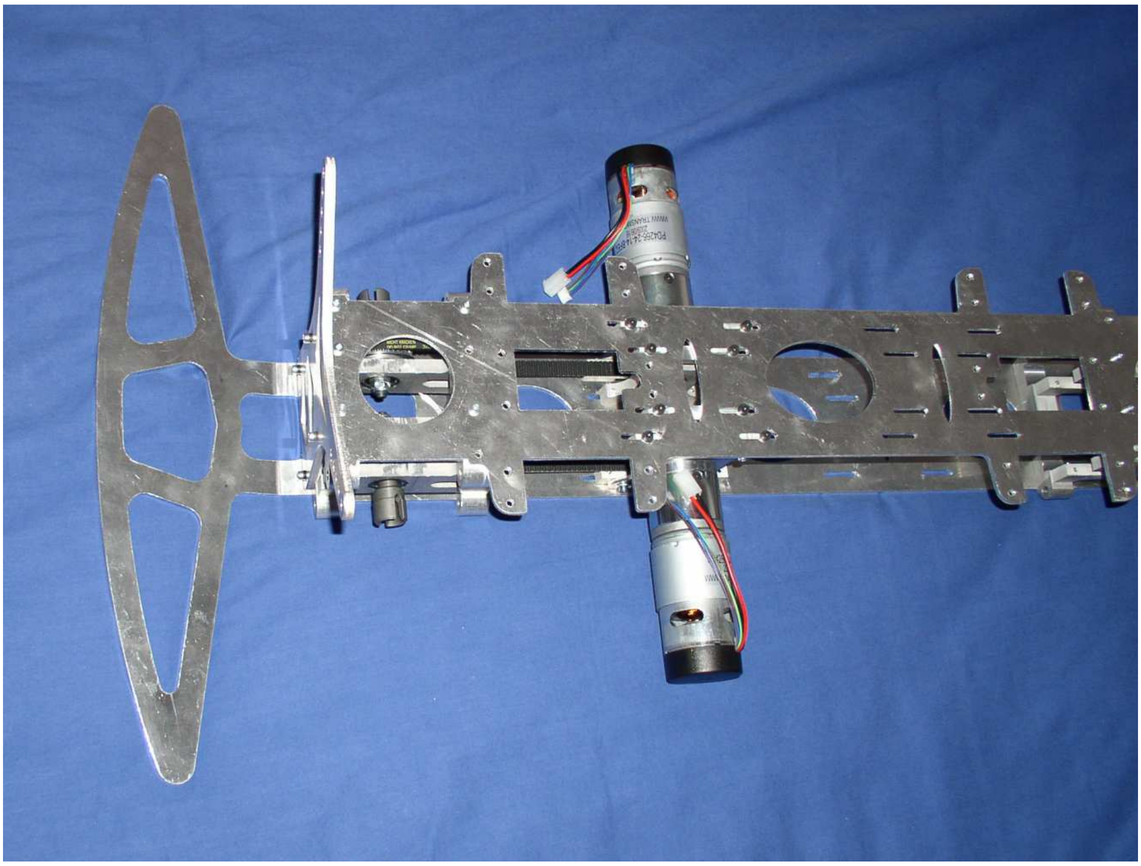

Fig. 33: Undercarriage during assembly.

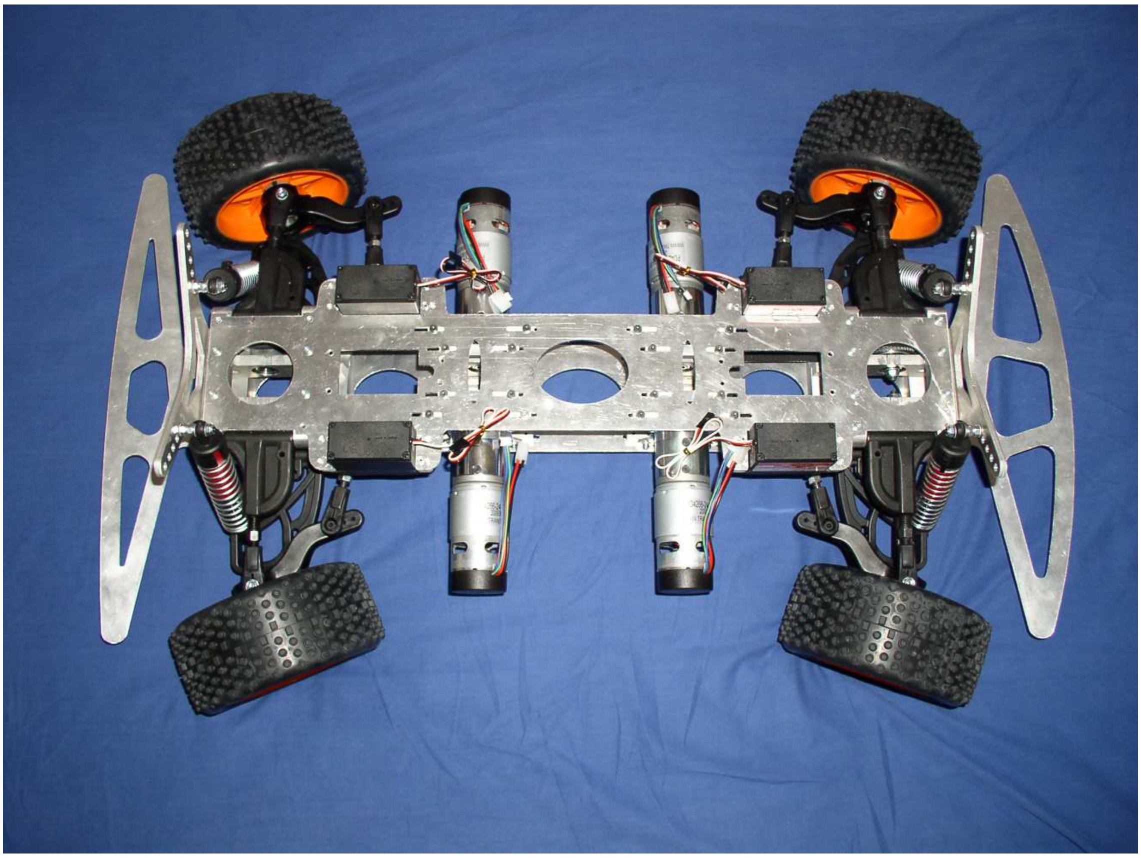

Fig. 34: Completed mechanical part of vehicle (without electronics).

7. Conclusion

The material outcome of this thesis is an undercarriage of a model car ready for controlling electronics to be implemented. The vehicle is in its way unique four wheel drive, four wheel steering model of real car in a scale of approximately 1:5, and can be used as a teaching aid or a base for other theses and projects. Theses about electronic development, state estimation and mathematical model of the vehicle were parts of Car4 project development.

The goal of project was fulfilled and final manufactured version meets all requirements stated at the beginning of the project. The vehicle has powerful independently controlled motor with accurate encoder at each wheel and many supporting sensors (a gyroscope for example) therefore can test any kind of intelligent and innovative vehicle driving or safety system. All motors can be easily mechanically disconnected from the wheel so the vehicle can be front-, rear- or all-wheel-driven as demanded by current testing procedure. Also steering servomotors can be blocked, for example for testing with conventional front wheel steering.

However, the more important outcome is the experience of team work and development of an ambitious project.

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