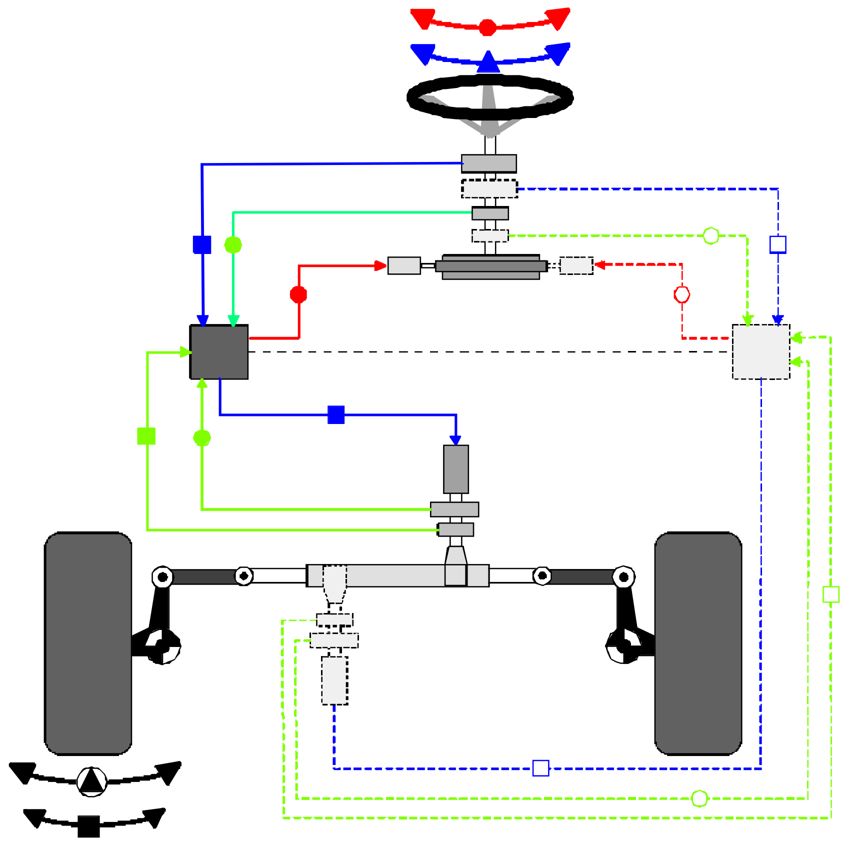

Working Principle

Steer-By-Wire System
for cars

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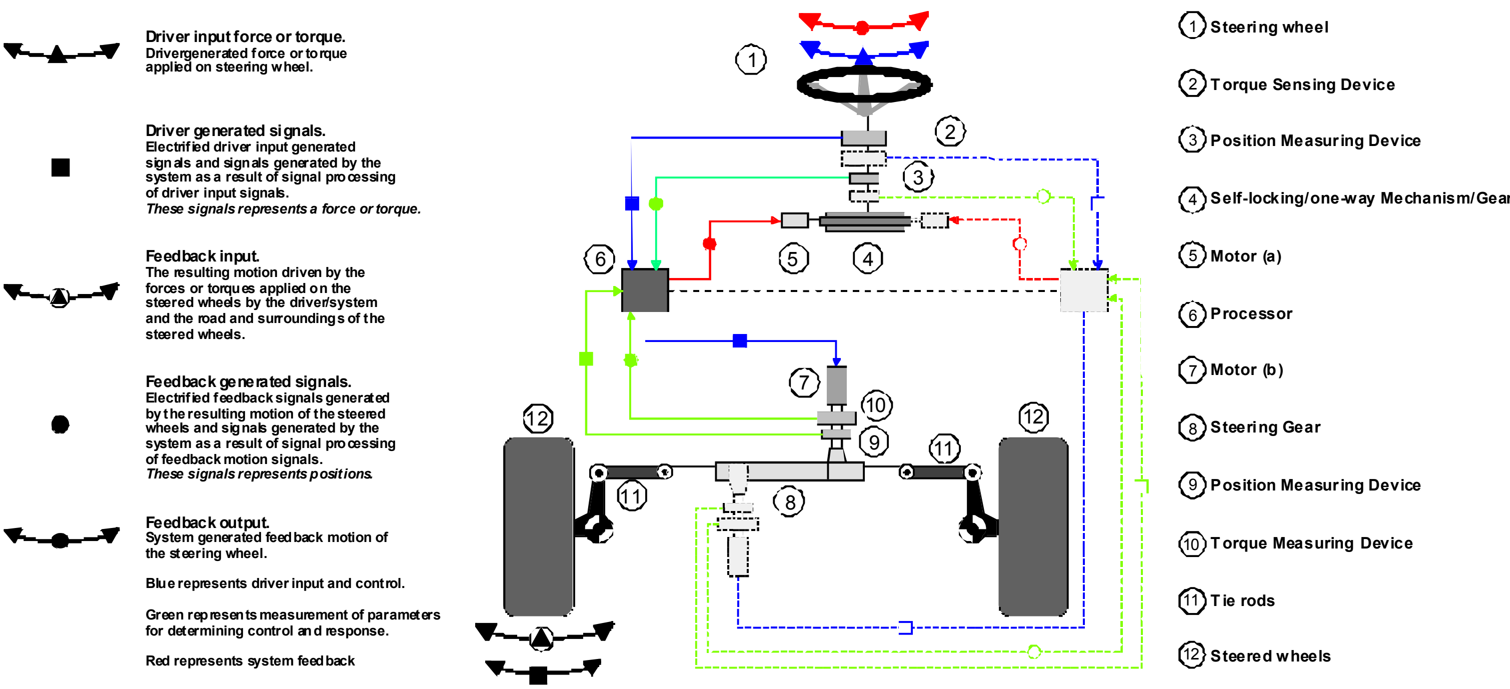
Description of Working Principle

The system basically consists of two separate systems; a control system that enables the driver to control the steerable wheels of the car and a feedback system that allows the driver to sense the reaction of the steerable wheels in the steering wheel.

The torque applied by the driver on the steering wheel is measured by a torque measuring device and transmitted to a processing unit. The processing unit controls a motor (b) to produce a torque corresponding to the torque applied by the driver on the steering wheel. If the torque applied by the motor (b) to the steering gear is sufficient to overcome friction and road forces, the wheels will begin to move. The steering gear can be a traditional rack-and-pinion drive connected to the steered wheels by tie rods.

If external forces acting on the steered wheels exceed the force applied by the tie rods from the torque provided by motor (b) through the steering gear, the wheels will move as well.



The position of the wheels is measured by a position measuring device. Trough the processing unit, the motor (a) is controlled to move the steering wheel through a self-locking mechanism/gear to a position corresponding to the position of the wheels.

The position of the steering wheel is measured by a position measuring device, to provide input information to the processing unit for determining how to control the motor (a) to bring the steering wheel in the correct position.

Basic Controller Algorithm

The driver applies a torque T_1 on the steering wheel (1). The steering wheel is firmly connected to the one-way working gear (4) and can therefore not be moved by the driver. The torque T_1 applied by the driver is measured by the torque measuring device (2) and is represented by a voltage V_1.

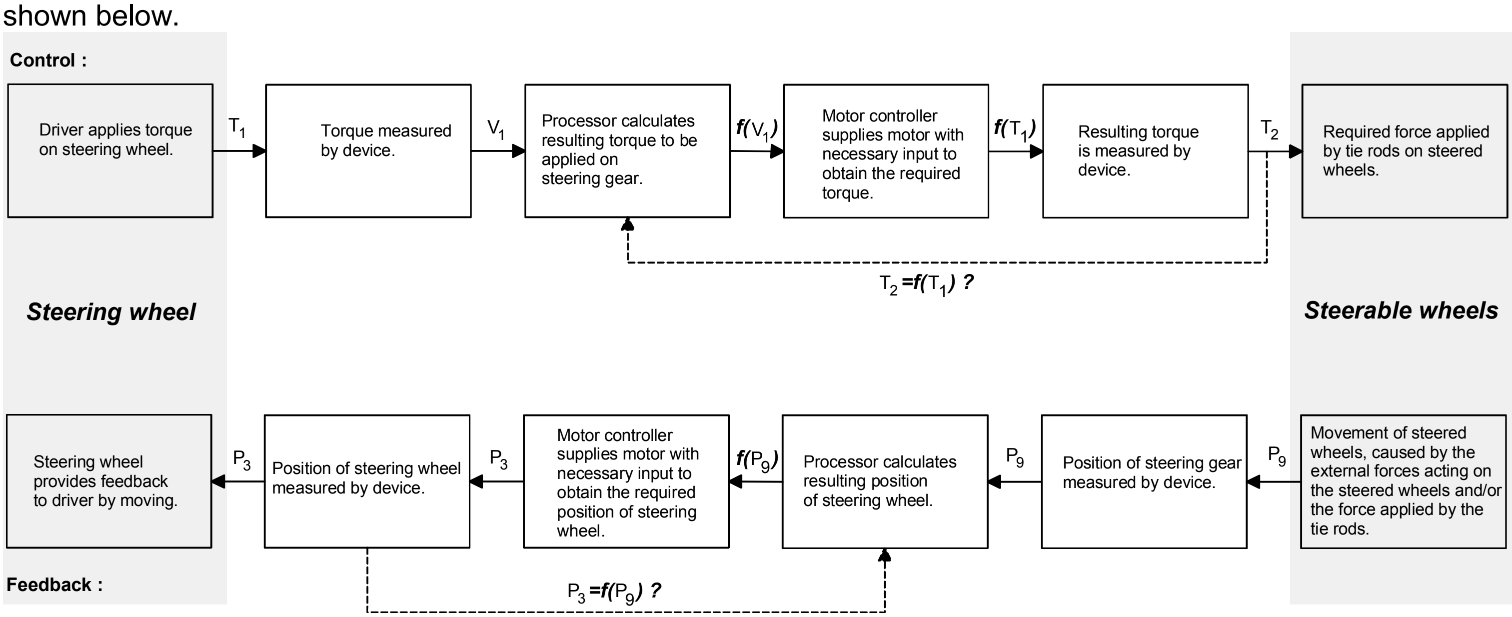
The voltage V_1 is transmitted to the processor (6) and a voltage $\boldsymbol{f}(V_1)$ is applied by the processor (6) to the electrical motor (7). The voltage $\boldsymbol{f}(V_1)$ is a function of the voltage V_1 and can be dependant on defined rules concerning, for instance, vehicle speed and/or operator defined characteristics which is desired to influence the handling. By applying a voltage $\boldsymbol{f}(V_1)$ to it the motor (7) will apply a torque T_2 on the steering gear (8). The torque T_2 is thus a function of the torque T_1 applied on the steering wheel by the operator, $T_2 = \boldsymbol{f}(T_1)$.

Obtaining the required output torque T_2 from the motor (7) can be done by either relying on known characteristics of the motor so a given input gives a given output, or by refining the system by adding an additional torque measuring device (10) between the motor (7) and the steering gear (8). By adding an additional torque sensor (10) the voltage applied on the motor (7) can be fine-tuned to achieve the target value torque T_2.

Friction between the mechanical parts in the steering gear (8) and the tie rod steering connections (11) between the steering gear (8) and the controlled wheels (12), as well as the friction between the road surface and the controlled wheels (12), requires a torque T_3 to be overcome.

As long as the torque $T_2 = \boldsymbol{f}(T_1) < T_3$ none of the parts move. If the torque T_2 gets larger than the torque T_3 the controlled wheels (12) start to move. The acceleration, and thus the speed by which the controlled wheels (12) begin to move, is determined by the resulting torque $T_{Resulting} = T_2 - T_3$, being the difference between the torques T_2 and T_3.

The motor (7) shall keep up and maintain the torque $T_2 = \boldsymbol{f}(T_1)$ which means that the current to the motor must be increased. This part of the system, the control part, is represented in the upper row in the information flow chart shown below.



The lower row in the information flow chart above represents the feedback part of the system.

The position measuring device (9) measures the position P_9 of the steering gear (8) and the position is represented electrically and constantly (or very frequently) transmitted to the processor (6). As long as the controlled wheels (12) do not move the readings from the position measuring device will not cause anything to happen.

As soon as the controlled wheels (12) move the readings P_9 of the position measuring device (9) change. The processor (6) will control the motor (5) in such a way that the position P_3 of the steering wheel (1) as quickly as possible is made to correspond with the position P_9 measured by the position measuring device (9) and thus $P_3=\boldsymbol{f}(P_9)$.

The position P_3 of the steering wheel (1) is measured by the position measuring device (3)

It is evident that all signals between the units, both in the control part and in the feedback part of the system, can be represented as electrical voltages or currents or as digital values. The latter would be obvious with today's electronics and especially in combination with the FlexRay™ bus-system.

In an analogue system, voltages and currents are regulated continuously and controlled by operation amplifiers.

In modern digitalised computer based systems the all-important motor controllers can operate with by fixed time intervals. By measuring the positions P_3 of the steering wheel (1) and the position P_9 of the steering gear (8) by fixed time intervals of Δt the processor (6) can determine a target value position $P_{3Target}$ of the steering wheel (1) for each timeframe of Δt. The processor (6) controls the motor (5) through a motor controller by adjusting the speed of the motor (5) so that the desired position $P_{3Target}$ of the steering wheel (1) can be obtained within a timeframe of Δt.

If at the time Δt a position P_{91} of the steering gear (8) is measured by the position measuring device (9) and the position measuring device (3) measures a position $P_{31}=\boldsymbol{f}(P_{91})$ of the steering wheel (1) no adjustment is required so the motor (5) does not move.

At the time $2\Delta t$ the position measuring device (9) measures the position P_{92} of the steering gear (8) where the position P_{92} is different from the previously measured position P_{91} measured at the time Δt. This means that the steering gear (8), and thus the controlled wheels (12), has started to move. The position measuring device (3) is still measuring the position P_{31} of the steering wheel (1), since the operator can not move the steering wheel (1) due to the one-way working gear (4). The motor (5) shall then drive the steering wheel with a speed $S_1=(P_{32}-P_{31})/\Delta t$, where P_{32} is the desired position of the steering wheel determined by the processor (6) as $P_{32}=\boldsymbol{f}(P_{92})$.

At the time $3\Delta t$ the position measuring device (9) measures a position P_{93} of the steering gear (8) and a position P'_{32} (which is somewhere between P_{31} and P_{32}) is measured by the position measuring device (3). Motor (5) now changes speed to $S_2=(P_{33}- P'_{32})/\Delta t$ where P_{33} is the by now desired position of the steering wheel determined by the processor (6) as $P_{33}=\boldsymbol{f}(P_{93})$.

If Δt is made adequately small it will in practical use appear as if the positions measured by the position measuring devices (3) and (9) change simultaneously. Using modern digital electronics frequencies of 100Hz or more should be achievable.

Additional Features

In the simplest and purest form, the system provides a steering system, that works and feels like a simple rack and pinion steering system with power steering. However, by introducing a steer-by-wire system, some additional features are made available by the system and by adding input and communication with other electronic systems in the car, even more features become available.

Built-in Multi-functional Power Steering

The torque provided by motor (b) is a function of the torque applied by the driver on the steering wheel. In the very simple shape the function is simply that the torque provided by motor (b) is equal to the torque applied by the driver on the steering wheel. This corresponds to a traditional rack and pinion steering system where the steer-by-wire system simply simulates the steering column. By introducing a function that multiplies the torque applied by the driver on the steering wheel by a factor the steering can be made lighter or heavier than “direct” steering.

If the factor is made a function of the steered wheels’ position, the steering can also be made lighter or heavier depending on the steered wheels’ position. By adding input from the cars’ speedometer, the steering resistance can be made step-less variable depending on speed.

Since the position of the steering wheel is controlled by the system as a function of the position of the steered wheels, similar function can also be applied between the steered wheels’ position and the position of the steering wheel. Thus, not only can the steering resistance be made dependant on speed but also the gear-ratio between the steering wheel and the steered wheels. That way, steering can be made light and aggressive at low speeds and at high speeds firmer and less aggressive. The system can even be made to change characteristics if the car is driven in reverse or selectable by the driver.

Since this system relies on the system to only move the steering wheel, the steering wheel has built-in end-of-travel-stops and therefore the gear-ratio can be varied without having to consider conflicting end-of-travel-stops of steering wheel and steered wheels. The end-of-travel-stops of the steering wheel will always automatically adjust to those of the steered wheels.

Automated Parking System

A lot of hardware necessary for automated parking systems is already in the car when the steering system is integrated and the system can move both the steered wheels and the steering wheel. In automated park mode, the system can control the steerable wheel by controlling the steering motor (b) to produce torque in the amount and direction necessary to obtain the desired steering. The parking system can determine the desired steering from distance sensors, cameras and information of vehicle speed and measure the actual steering from the steer-by-wire system’s position measuring device at the steering gear.

If the driver should have to intervene or quickly interrupt the automated parking system, the driver can simply apply force on the steering wheel to correct or modify the automated parking system’s steering. As soon as the driver starts to try to turn the steering wheel, a torque will be applied and detected by the torque measuring device on the steering wheel and the system can react accordingly.

Vehicle Stability System

When equipped by a steer-by-wire system the car is steered by electronics, and as for automated parking systems the steer-by-wire system can also contribute to increased performance of the cars' electronic stability control system. Present stability control systems work by utilising the anti-locking brake system to brake each wheel individually to maintain vehicle stability in critical situations. With a steer-by-wire system like this all the motors and sensors necessary for correctional steering to the stability program are already present in the car. Furthermore, this system enables the driver to override the stability program, if desired, simply by applying force on the steering wheel. The stability system can then react accordingly. Adding steering to the vehicle's stability system will benefit both skid avoidance and so-called second collision avoidance.

Lane Departure Warning System

Combined by a lane departure warning system the steer-by-wire system can automatically correct steering to keep the vehicle in lane which the driver would be made aware of since the steering wheel would move accordingly. It could also make steering resulting in further lane departure significantly heavier and steering resulting in correction significantly lighter than normal. If indicators are turned on the system will not perform any corrections since lane departure seems intentional.

Collision Avoidance System

Combined with distance- and speed measuring devices used in adaptive cruise-control and overtake-warnings a collision avoidance system can be made. If an object is detected in the vehicle's moving direction, a collision avoidance system can apply the brakes automatically and simultaneously use sensors to check for other cars overtaking or approaching in the opposite direction in the other side of the road and for obstacles, like fences, people or buildings, in the surroundings. If the actual deceleration obtained by applying the brakes (depending on road surface and tire conditions) can be calculated to result in a collision with the suddenly appeared object, evasive steering can be applied by the steer-by-wire system, without comprising the stability of the vehicle (taken care of by the stability system) and without resulting in a collision with an overtaking vehicle or a head-on collision with a car going in the other direction.

With this system, the driver can always be enabled to override the systems (if desired by the car manufacturer) by simply applying force on the steering wheel which will then be detected by the torque sensor at the steering wheel. By allowing the driver to override the automated safety systems the driver has the opportunity to compensate for situations not foreseen or detected by the automated system. Furthermore the driver is ultimately still the legally responsible operator of the vehicle.