Two Brains, One Car—Actively Controlled Steering

Benson Tongue

One of the primary reasons for the continued popularity of cars over mass transit systems is the car's ability to travel wherever (within limits) and whenever the driver wishes. Key to this capability is a user-controlled steering system. As sensor and microprocessor capabilities continue to improve, however, control engineers have begun to investigate the move toward vehicle autonomy through the use of actively controlled steering (ACS) systems. Employing an on-board microprocessor, ACS is both a necessary enabler for fully autonomous vehicular operations and a functional element that can improve a car's operational envelope independent of autonomous operation.

Examples of ACS

ACS has already been implemented in a variety of settings. For example, ACS is widely used for autonomously operating forklifts and similar factory-floor vehicles. Magnetic guides and lasers are used as reference signals for the vehicle's steering system. No operator is needed for these vehicles.

The PATH program in California was originally designed to relieve traffic congestion through the creation of autonomous vehicles. One outcome of this work is car-mounted magnetometers that sense magnets embedded in the roadway. The car's controller can use this information, together with global positioning system (GPS) signal data, to determine the instantaneous position of the car. Servoactuators can then steer the vehicle to maintain a given trajectory. Three guided buses using this technology were successfully demonstrated in San Diego, California, in 2003, and work is ongoing among transit agencies for commercial deployment in the United States. The magnetic guidance system has already been deployed in Japan and The Netherlands.

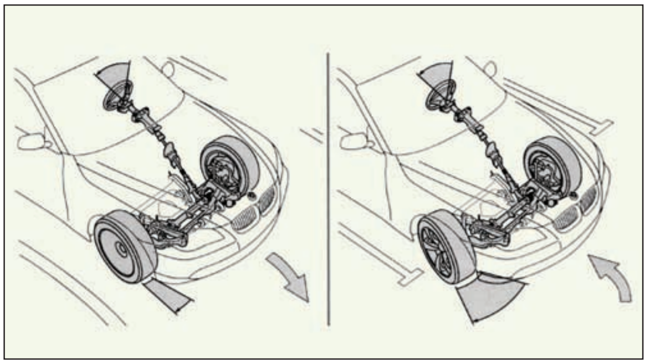

Figure 1. *A comparison of low- and high-gain wheel rotation angles as controlled by BMW's active steering system. This system changes the steering ratio as a function of vehicle forward speed. (Image courtesy of BMW NA.)*

With regard to personal automobiles, Toyota recently demonstrated an intelligent parking assist option for Priuses sold in Japan. Developed as an aid for urban city driving, the system is designed to automatically parallel park a vehicle. After guiding the car ahead of a potential parking spot, the driver shifts into reverse, keeps a foot lightly on the brake, and then allows the car to park itself. As in the PATH implementation, control of the steering wheel comes through the use of actuators that completely remove the need for driver input. Although limited in scope as a parking aid due to the restricted types of parking maneuvers it can accomplish, the system demonstrates completely active steering in which the driver provides no independent steering inputs.

BMW's Active Steering System

The systems described above are examples of "either/or ACS," that is, either a person is driving or electronically controlled actuators are driving. In contrast, BMW's active steering system is an all-mechanical steering linkage that accepts, and at all times utilizes, two separate steering inputs—one from the driver and one from the car's steering algorithm. At its most basic level, BMW's system can modify the gain between the steering wheel input and the front wheels' rotation angle (Figure 1), where the steering ratio is determined as a function of vehicle speed. During low-speed operation, the gain is moved to a high value, leading small rotation angles of the steering wheel to induce large rotation angles of the wheels (10:1 steering ratio of driver input to wheel output, which corresponds to a high gain and thus low ratio). This ratio allows the driver to maneuver the car with small steering inputs, removing the need for arm-over-arm turning of the steering wheel.

High sensitivity to driver inputs, however, is undesirable during high-speed driving since minor, inadvertent steering wheel disturbances can induce large lateral movements of the vehicle. To avoid this problem, the steering ratio is increased (and thus gain and sensitivity are decreased) as speed increases, up to a maximum ratio of 20:1. Standard steering systems, or cars without active steering systems, have a fixed ratio of 14.1:1, which represents a compromise between the needs of low- and high-speed operation.

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Description of the BMW Active Steering System

Unlike a traditional steering system in which the steering wheel directly controls the vehicle's steering rack, in BMW's active steering system the steering column is only one part of the total input to the wheels. By turning the steering wheel, the driver controls an input sun gear within a dual planetary gear assembly (Figure 2). The output sun gear connects to the steering rack. The BMW active steering system then controls the vehicle through the ring gear, which also serves as a planetary carrier. The ring gear is driven by a worm gear, which is controlled by an electric motor. The input sun/planetary gearset have radii that are different from the output sun/planetary gearset, which is key to enabling a variable steering ratio. By including the electrically controlled ring gear/planetary carrier, the system combines the rotational steering wheel rate ω_{sw} from the driver with the rotational motion ω_{ring} generated through the worm gear to produce the rotational speed ω_{os} of the output shaft. The resulting input/output relationship has the form

$$\omega_{\text{os}} = \alpha_1\omega_{\text{sw}} + \alpha_2\omega_{\text{ring}},$$

where the coefficients α_1, α_2 are determined by the physical details of the system. A single integration with respect to time (from known initial angles) provides the angular position of the output shaft as a function of the steering angle and planetary carrier angle.

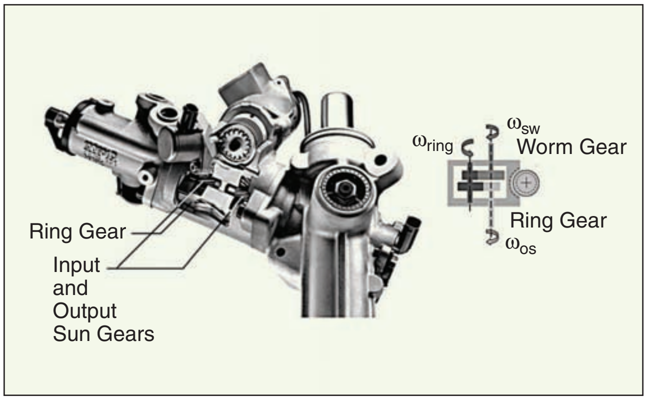

Figure 2. *Cutaway of the BMW Active Steering system showing the input and output shafts, input and output sun gears, planetary gears, and carrier and worm gear. The rotation of the input shaft (controlled by the driver) and the planetary carrier are summed to produce an overall rotational output that acts on the vehicle's steering gear. (Picture courtesy of BMW NA.)*

Stability Controllers Based on ACS Systems

The guiding rationale for allowing an ACS system to take control from the driver is that there may be instances when the driver loses, or is on the verge of losing, control. For example, a slippery road condition may be encountered during a turn, or a driver may enter a turn at a speed that is too high for the tires to maintain sufficient lateral force, which can occur if an unexpected obstacle is encountered on the road. In each case the driver, due to insufficient training and experience, may apply too much steering input or actually steer in the wrong direction (wrong in the sense of what is needed to stabilize the vehicle). With sufficient sophistication to determine the correct steering input, the stability algorithm can act to override the driver's destabilizing input.

The equations of motion governing the car's response characteristics define an internal reference model of the vehicle. The output of this reference model, based on the vehicle's known input conditions, is then used to determine whether the vehicle is responding acceptably to the driver's commands. For instance, suppose that the driver is rounding a corner. The stability control algorithm checks to see whether, based on the tire's slip angle, steering angle, and longitudinal speed, the yaw rate matches the rate required to negotiate the turn in a nominal manner. A yaw rate that is too high implies an oversteering condition, while an even more extreme yaw rate indicates that the car is in a spin. If the yaw rate is beyond the acceptable limits predefined by the algorithm, the brakes are activated at individual wheels and the throttle is modulated. The aim of these actions is to bring the car back on track, if possible.

Stability controllers are widely offered and come under a variety of names, such as BMW's dynamic stability control and Cadillac's stabilitrak. In all cases, the computer assist, which allows the driver to provide the steering inputs, intervenes only when the driver inputs lead to vehicle instability. The intervention of these controls is easily discerned by the driver. Most obvious is the throttle control, which gives a feeling of the engine abruptly losing power.

An ACS system works in concert with the car's stability control algorithm. As discussed above, a conventional stability control program takes action only after the driver's inputs have induced a problem condition. With an ACS system, the stability algorithm does not accept the driver's destabilizing inputs. For instance, the driver, surprised by an obstacle in the road ahead, may try to jerk the steering wheel too quickly, which could destabilize the vehicle. In this case, the ACS system applies a countersteer input (steering in a direction that is opposite direction to the driver's input) to the steering linkage, limiting the steering input to an acceptable range. Thus, by altering the resultant steering inputs to the wheels, the car can be kept from entering an unstable operational regime, obviating the need for computer-controlled brake/throttle inputs. When the ACS system inputs prove insufficient for maintaining stability, the control algorithm also applies the more intrusive brake/throttle control.

An ACS system can also be used for disturbance rejection. Lateral wind gusts that act on a car tend to push the car off its course. An ACS system can sense these disturbances from the nominal path and thus steer into the wind to cancel the force of the wind. These minor steering corrections can take place without the driver being aware of them. This feature is not currently available, however.

The Big Picture of ACS Systems

ACS systems represent a new paradigm for automobile steering. Beyond stabilizing the vehicle when the unexpected occurs, ACS can remove the driver from primacy in the control system, relegating the driver (at least momentarily) to passenger status. The control-design viewpoint shifts from "help the driver retain control" to "take over control from the driver when needed." As these systems develop and as ACS gains user acceptance, the steering authority of the car is expected to increase.

A reduced level of driver control isn't fundamentally new since people have long ceded vehicle control, trusting the pilot of an airplane or a bus driver to transport them to their destinations. The new twist is that now it's not mass transportation that's reducing the autonomy of drivers but rather the car itself. Whether or not continued development of vehicle autonomy is viewed positively will depend greatly on liability concerns; specifically, who is at fault if an accident occurs when the car is operating in an autonomous mode, the manufacturer or the driver? People's views about personal freedom and independence in their cars will also play a key role.

A layer of technology between the driver and the car can be problematic, especially in early development and deployment. For example, real-world experience with the only widely available ACS system, the BMW active steering system, has uncovered an interesting problem. As currently designed, the system alters the steering ratio as a function of the vehicle's speed, which makes sense for steady-state vehicle operation at a fixed or slowly varying speed. In general, this quasi-static approach is acceptable for normal street driving. Yet when applied in a more demanding venue such as racing, the system can cause difficulties due to fast transitions from high-speed to low-speed operation, which typically occur on a track. When the driver approaches a sharp turn, for example, the normal action of the driver is to approach the turn at a high speed, wait until the last possible moment, and then apply the brakes firmly. Once through the turn, the driver quickly accelerates the car back to speed. The response of the active steering system, which considers only the current speed, is to sharply reduce the steering ratio as the vehicle's speed drops. This change in ratio can be disconcerting to the driver, who is steering based on a different steering ratio. The difficulty is that the highly transient nature of the task parameters is not well served by the more steady-state assumption of the active steering system.

Automotive enthusiast magazines show that vehicle evaluation often focuses on high-performance driving. In fact, many manufacturers have in-house performance divisions, such as BMW's M cars, Cadillac's V cars, Audi's S cars, and Ion's Redline cars. Many customers expect electronic aids, such as the BMW active steering system, to enhance their driving experience, not detract from it, even in situations that "normal" drivers would never encounter. The challenge for the control designer is to create a control system that satisfies "normal" drivers as well as enthusiasts.

One way to mitigate the effect of a steering ratio change is to introduce a delay in its onset. Alternatively, steering ratio changes can be permitted only when the acceleration magnitude is above a specified level. The main point is that the range of dynamic behaviors in human-piloted vehicles is large, and there clearly will be opportunities for continued improvement in the car's stability control systems in the foreseeable future.

Conclusions

ACS systems enable vehicle autonomy and facilitate the trend in active stabilization and control that has been developing steadily over the last decade. These systems can improve the overall driving experience, and it seems likely that ACS systems will find wider use as control sophistication increases and the cost of manufacturing drops due to economies of scale.

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