

Drive-By-Wire for an Autonomous Formula SAE Car

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Abstract: The automotive industry is increasingly using electrical control systems in order to assist the driver of a vehicle or to automate certain maneuvers. This paper describes the conversion of a Formula SAE car into a vehicle with autonomous drive capability. The setup of the low-level controller and actuators are discussed. The systems used to convert the vehicle to drive-by-wire acceleration, braking and steering are documented along with details of the low-level controller and safety systems.

1. INTRODUCTION

With advances in electronic technology the automotive industry has been moving away from mechanical systems to electrically controlled subsystems. This move to automate the function of a vehicle has created the opportunity for computer-controlled systems to increase the effectiveness of a vehicle's systems. Further technologies such as self-parking functions allow electronic systems to take control of certain functions of the vehicle and use sensor feedback to control action taken by electronic control systems. The Renewable Energy Vehicle Project (REV) at UWA designed a fully autonomous vehicle for research into high-level control systems. This extends previous research into driver-assistance technologies undertaken by the REV Project.

In 2010/11 the REV Project implemented modifications to a BMW X5 in order to add electronically controlled actuators to the vehicle. The purpose of these systems was to enable the development of driver assistance aids such as obstacle avoidance and collision mitigation. In order to do this, actuation of both steering angle and brake force was required. When considering the best techniques in order to develop drive-by-wire systems, the reliability of the added system and the system's implications on safety to both the vehicle's occupants and its existing systems are the highest priority. It was found that in order to preserve occupant safety and to reduce the impact of drive-by-wire modifications to the X5, the addition of a DC motor (with inbuilt gear box) located in the engine bay was the most appropriate solution to actuate the steering angle of the vehicle (Webster 2011).

In order to determine the steering wheel position and hence the heading of the X5, a Vishay 601HE Hall Effect sensor was coupled to the steering column via a gear drive enabled accurate steering position feedback to an on-board controller. Actuation of the brake pedal in order to engage the brakes of the X5 was desirable, as this did not interfere with the original systems of the vehicle, deemed reliable and was reasonably easy to implement. An SSPS-105 servomotor was installed in the interior of the vehicle above the brake pedal.

A bracket couples the servomotor to the brake function by applying a force to the upper arm that the brake pedal is attached to. For safety reasons, this design allows the brake to be further engaged by the driver if necessary.

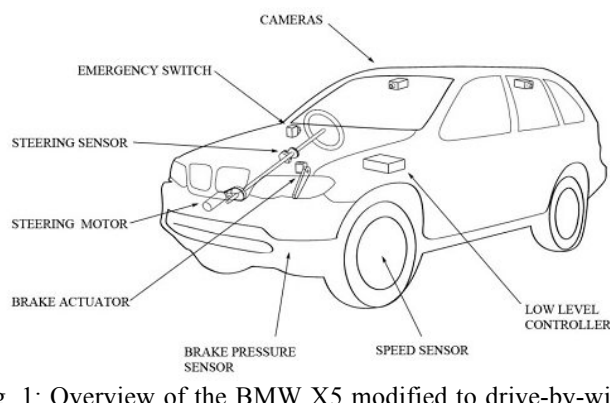


Fig. 1: Overview of the BMW X5 modified to drive-by-wire (Webster 2011).

To coordinate the drive-by-wire components, an Arduino Uno microcontroller system was installed. This microcontroller communicates with a high-level control system in order to receive steer and brake-by-wire commands. The high-level system provides decision making capabilities and has the processing power to interface with and process data from sensors that detect if a collision is imminent.

2. OUTLINE OF DRIVE-BY-WIRE SYSTEM

The next step in automation systems for the REV Project involved full control of all three driver tasks (acceleration, steering and braking). The inspiration for a fully autonomous vehicle is based in the idea that automation technologies may provide assistance to drivers or take over full control in dangerous situations.

A test bed for such a driverless system was implemented using a Formula SAE-Electric vehicle as shown in Fig. 2. The electric drive simplified the integration of new drive-by-wire systems through direct access to the electronic throttle as

well as existing batteries in the vehicle providing a suitable power source for the new actuators.



Fig. 2: Formula SAE-Electric frame.

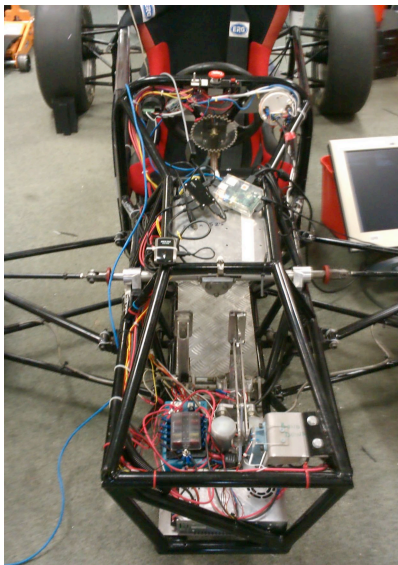


Fig. 3: Formula SAE vehicle with drive-by-wire components installed.

In order to perform automated steering, a 12V DC gear-motor was installed. This was coupled to the steering column of the SAE-Electric vehicle using a belt and pulley drivetrain. Feedback of the steering angle was achieved using a rotary hall effect sensor. This sensor was mounted in an adjustable bracket above the steering column. Gears were used to couple the sensor to the steering column. In comparison to an encoder built into the motor itself, this method has the advantage that a true sensor reading proportional to the steering angle will be returned regardless of any belt slippage.

The brake pedal used in the SAE-Electric vehicle directly drives a hydraulic reservoir which applies a force to engage the front brakes of the vehicle. In order to apply a force to the brake pedal, it was evident that the pedal would have to be pulled backwards. Any space on the driver's side of the pedal had to remain clear, in order for the driver to access the pedal. An SSPS-105 servomotor was used to pull the brake pedal backwards. Fig. 4 and 5 shows how this was achieved.

Acceleration of the vehicle is normally controlled by hall effect sensors mounted near the accelerator pedal. These sensors output an analogue voltage proportional to the amount the accelerator pedal is pressed. In autonomous mode, a

choice of retaining this control signal is present for manual acceleration with automated steering and braking systems. This allows high-level tuning of control loops at safe speeds. In full autonomous mode, the hall sensor signal is disconnected from the motor controllers and the low-level autonomous control system mimics the voltages that the hall sensor would produce to control acceleration.

The low-level control system uses a standard Arduino Uno microcontroller to control all three drive-by-wire functions of the vehicle. A PID control loop is used to control the DC motor to alter the steering angle using feedback from the hall effect sensor coupled to the steering column. The microcontroller accepts serial commands from a high-level system that determines what the best course of action is to take. The high-level system uses sensors such as radar, GPS and IMU (Inertial Measurement Unit) to enable the SAE vehicle to autonomously complete laps around a racecourse. The low-level system also checks for numerous fault conditions in its subsystems and will communicate any errors to the high-level system. Many of these errors will trigger an emergency brake condition without any user intervention required.

Finally, solid-state safety circuits that do not rely on the microcontroller were implemented. These additional circuits allow a passenger in the vehicle to overpower and consequently shut off the autonomous steering function.

3. COMMERCIAL DRIVE-BY-WIRE SYSTEMS

As manufacturers in the automotive industry continue to take advantage of new technologies, the various functions of a vehicle tend to become increasingly automated (Claudia et al, 2010). With the introduction of electric steering assistance, manufacturers have taken one step closer to completely decoupling driver input from physically actuating a vehicle's systems. While hydraulic systems are typically used to assist a driver to steer, electric assistance is becoming more popular in order to take advantage of characteristics such as lower power consumption (Azubir et al 2012). Currently, different mounting positions of the electric assist motor include coupling the motor to the steering column, pinion or rack (Azubir et al 2012). To determine the level of assistance required, the control system must collect feedback from torque applied to the steering wheel and speed sensors that take measurements of the vehicle's current travelling speed (Baharom et al 2013). Electronic control systems also enable manufacturers to implement additional safety features to a vehicle. Control algorithms that provide capabilities such as keeping a vehicle inside a lane when there is no driver input, aim to increase road safety (Marino et al 2012). Legal concerns still prevent a full steer-by-wire implementation (Baharom et al 2013), (Marino et al 2012). While this could reduce driver steering effort considerably, a failure in a full steer-by-wire steering system would prevent the driver from manually controlling the vehicle's direction.

Commercial application of brake-by-wire systems have allowed reduced effort in applying braking forces. Brake control systems use feedback from multiple sensors such as hall-effect sensors that convert brake pedal displacement into

an electronic signal (Coombs et al, 2005). These sensors provide feedback into a brake control unit and also provide sensor fault/error checking capabilities. Brake-by-wire improves braking performance as electronic control systems can be used to adapt the application of a vehicle's brakes. Factors such as current wheel speed can be measured from sensors and various control methods (such as new control algorithms, ABS and electronic stability programs) can be developed (Gunzert and Nägele 1999), (Sartori et al 2007) for use by electronic control systems. Resistance on the brake pedal is still felt by the driver and failure of the brake control unit deactivates electronic control systems while still allowing manual hydraulic forces to be applied to the brakes (Gunzert and Nägele 1999).

Throttle-by-wire systems use a similar method to that of brake-by-wire systems. A sensor that outputs an analogue voltage proportional to the amount that the accelerator pedal is depressed is used as feedback for throttle control. The accelerator pedal is not mechanically linked to throttle control as in earlier mechanical designs (Rossi et al 2000). Instead, an electric motor acts upon a throttle valve to allow alteration of acceleration rate. Electronic control of engine throttle allows more efficient operation of the motor through the use of electronic control systems (Rossi et al 2000). Furthermore, sensor failure does not result in a runaway vehicle: upon detection of throttle sensor failure, the output from the vehicle's motor is limited via a mechanical mechanism (Chwan-Hsen et al 2010).

4. MECHANICAL SYSTEMS

4.1 Brake-by-Wire

Before designing the braking mechanism it was necessary to determine how the brake pedal could be actuated without being intrusive to the driver. As a SSPS-105 servomotor was already available it was decided to focus on designs involving this component. From the geometry of the SAE vehicle it was clear that installing anything on the driver's side of the pedals risked intruding on either leg space or the ability of the driver to actuate the pedal.

The brake pedal on the SAE vehicle directly drives a hydraulic reservoir which applies front disc brakes. There are no existing electronics that assist braking similar to that in a commercial vehicle. In response to the application of the brakes, a constant force acts on the brake pedal, attempting to return the pedal to its original, disengaged position. As a consequence the force required to keep the pedal down would have to conform to the continuous ratings of the servomotor.

In order to convert the rotary movement of the servomotor into movement appropriate to pull back the brake pedal, brackets were designed to turn the servomotor's rotary movement into an arc. The result of the design process ended with numerous brackets, which can be seen assembled in Fig. 4. The bracket mounted on the rear of the brake pedal has a slot for coupling to the rest of the linkage. This slot allows the driver/passenger to apply the brake further than the autonomous system has engaged them if necessary. It also

decouples the linkage from manually driving the servomotor when the vehicle is being driven manually and the driver actuates the brake. Additionally, the linkage can never become misaligned or miss-engaging by design.

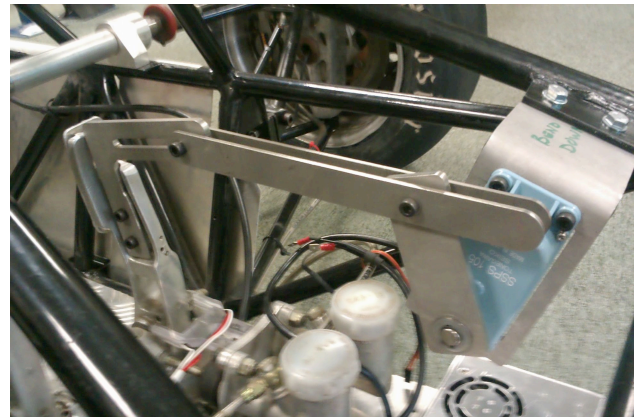


Fig. 4: The assembled brake linkage.

While the servomotor requires a 12V power supply, the control signal requires a standard 5V Pulse Width Modulation (PWM) signal. Since the servomotor contains considerable internal capacitance on its power rail, a PWM signal had to be applied after the microcontroller was turned off to prevent any erratic behaviour. The output of a 555-timer reset circuit is connected to the signal line of the servomotor through a relay, ensuring that the reset signal can never be applied when the autonomous system is functioning.



Fig. 5: CAD drawing of the mechanism used to provide autonomous control to the SAE vehicle's brakes.

4.2 Steer-by-Wire

To perform actuation of the steering function of the car, a Z5D120-12GU 12V electric motor with a 5GU40KB gearbox was installed. Since the maximum torque required to steer a vehicle is at stationary (R. Granger and R. S. Sharp, 2003), this combination met requirements to steer the vehicle when not in motion. Using a DC motor and avoiding the use of a worm gear driven system allows the driver of the vehicle to steer in emergency situations while the autonomous system is functioning. This setup also allows the vehicle to be driven normally (with the need for extra steering effort) without decoupling the DC motor from the steering column.

A mild steel plate was designed to mount the motor and

gearbox combination to the vehicle. To ensure that the car could still be driven manually, the motor was mounted above the driver's leg room next to the steering column. Shown in Fig. 7, the motor mounting bracket also provides belt tensioning capabilities as the bracket itself is slotted. This allows the belt to be tensioned as required.

For steering-angle feedback a Honeywell HRS100SSAB-090 rotary hall sensor was used. Being cost effective, accurate and having a long lifespan, as it does not rely on a mechanical wiper were key factors in its selection. Gears attached to both the steering column of the vehicle and the sensor were used to create a direct mapping of steering position to sensor output voltage. The result is that on startup, the autonomous system can tell exactly where the steering position is. This negates the use of a startup sequence and additional sensors when using incremental encoders instead. Fig. 6 shows the hall sensor attached to the steering column by gear drive. Since the force required to rotate such a sensor is minimal, gears were laser-cut from acrylic. Receiving feedback of steering position from the steering column ensures that the low-level system has accurate data on the steering of the vehicle. This overcomes issues of inaccurate data from encoders built into motors, as these cannot detect a possible belt slip. The sensor's feedback is used to control the DC motor via a PID loop.

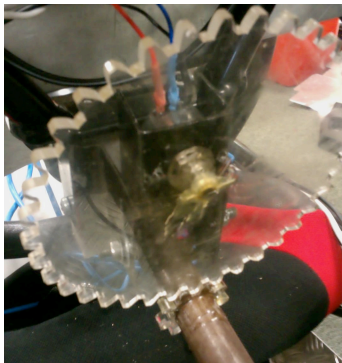


Fig. 6: The installed steering sensor assembly.

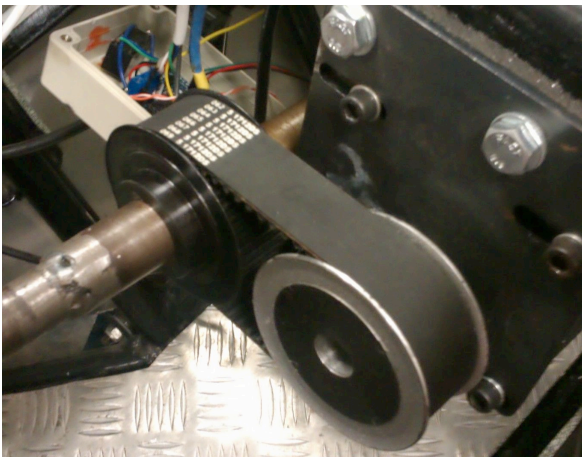


Fig. 7: DC motor and drivetrain.

To power the installed DC motor a VN2SP30 Motor Driver Carrier MD01B motor controller was used. To ensure that the motor controller does not overheat, the motor controller was

thermally attached inside a protective metal case. Since the motor controller is capable of delivering such high currents it is housed in a separate enclosure so that no other components such as the microcontroller will be damaged in the event of a possible severe failure. Feedback from the motor controller allows reporting of errors to the Arduino microcontroller.

5. ACCELERATE-BY-WIRE

All autonomous drive systems installed in the SAE-Electric vehicle are powered from a 48V-to-12V DC-DC converter, which isolates the system from the drive battery pack and drive motors. A consequence of this is that throttle control cannot be achieved by simply switch over the hall-effect sensor line via a relay. Instead, a Burr-Brown ISO124 isolation amplifier with a unity gain setup was sourced for this task. With a single sided 15V power supply, an output range of -2V to 5V can be achieved. As a 15V supply was not present on the vehicle a Maxim MAX680 was used either side of the ISO124 to boost existing 5V supplies available on either side of the device to $\pm 10V$. With increasing current draw, the voltage output of the MAXIM680 begins to drop. Using quiescent current loads for I_{L+} and I_{L-} and the positive source resistance, R_{S+} of the MAXIM680, the worst-case quiescent voltage output was 7.7V was calculated using (1). This left adequate capacity to provide the required 4V output. The circuit diagram of this configuration is shown in Fig. 8.

$$V_{Drop+} = (I_{L+} + I_{L-}) \times R_{S+} \tag{1}$$

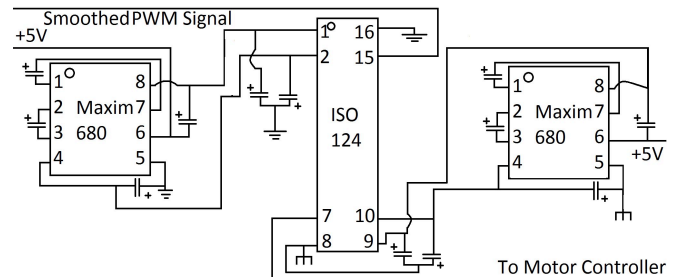


Fig. 8: Isolating circuit used to pass accelerator output from drive-by-wire controller to vehicle's drive motors.

As the Arduino Uno does not have a true Digital to Analogue Converter, the default analogue output of the Uno is a PWM signal at 490Hz. To convert this to an analogue voltage a low-pass filter was constructed. Using ORCAD PSpice simulations, filter parameters were selected to ensure that excessive delay was not added by the low pass filter, ripple was small with respect to the output signal and that the 40mA source/sink capability of the microcontroller pin was not exceeded. In order to improve transient response, the frequency of the PWM fed into this filter was increased to 7.8kHz by altering the PWM's timer frequency.

6. SAFETY SYSTEMS

To increase driver safety when the autonomous system is controlling the vehicle, additional circuits and sensors were introduced. Being separate from the microcontroller, these will continue functioning regardless of the software run on the system or if the microcontroller develops a fault. Using

hall-effect sensors near the brake pedal and voltage feedback from the VNH2SP30, combinational logic was used to perform numerous functions dependent on driver action:

- If the driver attempts to steer in a different direction to the autonomous system, a relay cuts power to the steering motor, allowing the driver to control the direction of steering. An emergency brake command is sent as well.
- If the driver applies the brake when the autonomous system is not braking, control of the steering motor is returned to the driver and an emergency stop command is sent to the low-level controller. In addition, with the brake applied, the autonomous system is unable to accelerate the vehicle.

7. SOFTWARE SYSTEMS

7.1 Communication System

The Arduino Uno comes with a USB B-type connector for communication to computer devices. Using the *serialEvent* function, a routine accepting bytes of data commences, whenever new data is received. Table 1 summarizes the types of valid commands and the respective range of allowable values.

Command Identifier	Minimum Value	Maximum Value
B (Brake)	0	255
A (Accelerate)	0	255
S (Steer)	-128	127

Table 1: Valid commands for the drive-by-wire controller via USB communication.

A watchdog on the microcontroller limits the system wait time for serial data by triggering an emergency brake. Additionally, the microcontroller checks whether new serial data has been received every 300ms. If a new command has not been received from the high-level system, an emergency brake condition is set. Both of these features ensure that if unreliable communication between the low-level and high-level system occurs, action is taken to prevent the autonomous system causing undesired behavior. Additionally, any received commands are echoed back to the high-level system for verification.

7.2 Software Safety

As inconsistent behavior can possibly result from software errors or other instabilities. The drive-by-wire software uses a watchdog timer to ensure that the low-level controller does not lock up or become unresponsive. In addition to standard communication over USB with the high-level system, an interrupt line on the Arduino allows the high-level system and additional safety circuits on the vehicle to trigger an emergency brake. The low-level controller software supports the checking of multiple values for consistency. In most cases an emergency brake condition is met if any error is detected. Table 2 documents all possible error codes and the action that the low-level controller takes when the error occurs. Errors

are communicated to the high-level controller via ASCII characters over the USB link to inform the system if a fault or loss of control has occurred.

Low-level Error Code	Description of Error	Action Taken
ER0	Serial array overflow error. Command received too long.	Command ignored.
ER1	Emergency brake condition currently present.	(Emergency braking already in progress)
ER2	Watchdog timeout occurred.	Emergency brake engaged.
ER3	Brake servomotor on for too long.	Brake disengaged to prevent servomotor pole burnout.
ER4	Steering motor controller reports a fault.	Emergency brake engaged, steering motor set to coast.
ER5	No new commands received within 300ms.	Emergency brake engaged.
ER6	Steering sensor out of bounds.	Emergency brake engaged, steering motor set to coast.

Table 2: Summary of drive-by-wire controller error codes.

8. MEASUREMENTS AND RESULTS

Testing of the steering system required the speed at which the DC motor can turn the steering column, the ability of the system to return to the same position given the same input command and the linearity of the low-level controller input to vehicle steering angle. Video footage of the system turning the vehicle from full left or full right to the straight position was used to determine the speed that the system operates. With no driver in the seat, the best-case speed corresponded to an average of 190°/second.

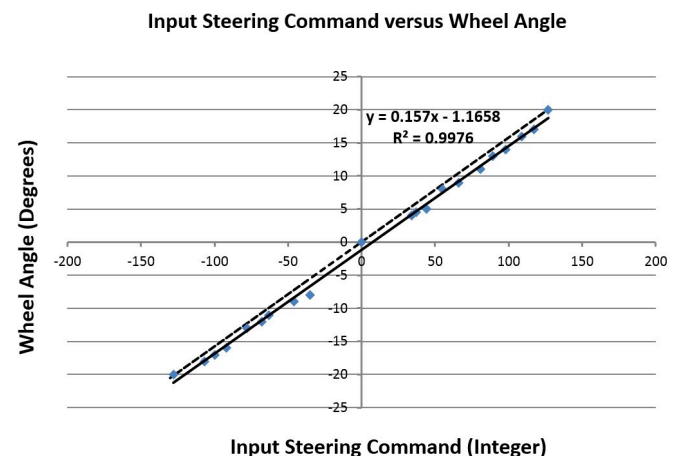


Fig. 9: Measuring linearity of autonomous steering system and vehicle heading (dashed line shows ideal, linear case).

Linearity of the system was measured by recording the angle that the wheels of the vehicle were facing with 90 degrees being the position where the wheels point straight. With an

R^2 value of 0.9976, a linear line of best fit appropriately describes the relationship between input steering integer commands and the angle that the wheels turn.

Target Steering Angle (Degrees)	Average Autonomous Steering Angle Error (Degrees)
15	0.86
0	0.93
-15	1.26

Table 3: Average autonomous steering angle error for various steering targets.

In order to measure the worst-case error of the steering system the steering system was tested without a driver in the vehicle. The system's ability to steer the vehicle to numerous positions was measured, with the results presented in Table 3 and Fig. 10. An error of this magnitude agrees with the results presented in Fig. 9.

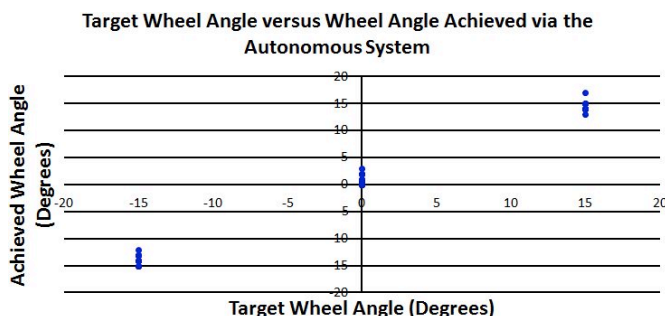


Fig. 10: Graphical spread of the autonomous system's steering repeatability.

By analyzing video footage of the servomotor applying the brake from disengaged to fully engaged, the servomotor required an average time of 0.29 seconds to complete the task. Measurement of the repeatability of the brake to engage to the same position was measured by the angle in which the servomotor rotated from a referenced angle to the full brake position. This was done with the vehicle at stationary with no driver in the seat of the vehicle. An average error of 0.6° was measured.

Using a multi-meter the acceleration signal after the isolated output circuit was measured. The signal fed back to the drive motors was incremented by 0.02V for every increment in the drive-by-wire software. This trend was valid within the original hall sensor voltage range.

SUMMARY

A drive-by-wire system for a fully autonomous Formula SAE-Electric car was presented and its performance evaluated. The system comprises throttle, brake and steering control and incorporates a number of independent safety systems.

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