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From Sensor to Street – Intelligent Vehicle Control Systems

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Acknowledgments
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From Sensor to Street: Intelligent Vehicle Control Systems

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Intelligent vehicle technology is the next major frontier of automotive engineering. For the past century, automobile operator interface has evolved slowly. Driver controls function in very much the same manner long after mechanical systems have evolved past the original design constraints.

A new wave of intelligent vehicle technologies will enable automakers to challenge the status-quo of automotive operator interface, and eventually enable driverless transportation. While driverless vehicles may eventually increase occupant safety and reduce operator stress, the greatest benefits lie in vastly increased infrastructure capacity and reduced energy consumption (Curley, 2008; Sauck, 2009).

The main source of traffic congestion is not a lack of capacity, but the cumulative effects of localized traffic density (Bertini, 2005). These are exacerbated by the cognitive delay present in each driver's reaction to changing conditions. An intelligent vehicle's ability to communicate with infrastructure will enable rapid traffic routing adjustments, and eliminate the localized traffic slowdowns that most contribute to wasted fuel and travel (Geller, 2015).

This research focuses on the challenge of fusing multiple sensor inputs to create a coherent strategy for dynamic vehicle control, which will either serve to aid a human driver or to control a vehicle intelligently. The inputs from these myriad of sensors must then be fused together to form a virtual representation of the terrain surrounding the vehicle, creating a model from which to draw guidance information. This can vary from simple highway lane guidance assistance, to autonomous off-road navigation.

By leveraging the strengths of individual sensors, the vehicle central computing system will fuse the raw data into a series of points and lines, which can be used to infer the optimal path ahead. Once this path is determined, a reverse kinematics approach can be used to actuate the steering, brake, and motor controls. These will enable active management of vehicle dynamics, preventing unnecessary lane wandering, and providing rapid recovery of unexpected movement due to un-sensed road conditions (Demirci and Metin, 2013).

When a human driver chooses to control the vehicle, the sensor-driven virtual world construct can provide collision warning, active avoidance, adaptive cruise control, and lane guidance.

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Nomenclature

ABS: Anti-lock Brake System
RADAR: Radio Detection and Ranging
LiDAR: Light Detection and Ranging
IMU: Inertial Measurement Unit
Reverse Kinematics: a mechanical approach to controlling actuator inputs based on actual vehicle position and attitude

Intelligent Vehicle Dynamic Situational Awareness

Intelligent vehicle subsystems have been part of consumer vehicles for decades. The first electromechanical cruise control systems began a long slide toward removing physical control of the vehicle from the human driver. Ever since, intelligent systems have provided enhancements in both convenience and safety. Anti-lock brakes can take control of braking when wheel lock-up is detected. These systems enable a panicked driver to both brake and steer at the same time, an impossibility with locked brakes (Jing et al., 2014). Back up and blind spot sensors, initially features of luxury brands, are now ubiquitous on cars at even basic trim levels. They provide situational awareness and warning to drivers of nearby objects or imminent collisions. The logical next generation of this technology lies in backup cameras, which enable drivers to totally rely on the car's sensors, driving in reverse using only an image on a dashboard screen for guidance.

Adaptive cruise control now keeps a constant following distance despite other vehicle's varying speeds. Satellite navigation and communication systems enable some vehicles to transmit and receive accurate location and other telemetry information. Near field sensors in select vehicles enable automatic parallel parking, completely hands free.

The combination of all of the above systems means that some vehicles already possess the ability to navigate, accelerate, steer, and brake, all without direct driver input. The greatest barrier to full intelligent control, virtual autonomy, is accurate lane guidance, and replicating the driver sense, necessary to navigate busy highways and inconsistent infrastructure.

Intelligent lane guidance, via image processing or infrastructure cues, is advancing rapidly, but replicating driver sense still presents a challenge. Human drivers can best process challenging conditions, and make decisions based on information not immediately apparent to a sensor array. One aspect of human driver sense, which computers can effectively substitute for, is slip recovery. This is an aspect not heavily explored by previous research into intelligent

Figure 1. A visual reprresentation of sensor fusion (Staszewski, and Estl, 2013)

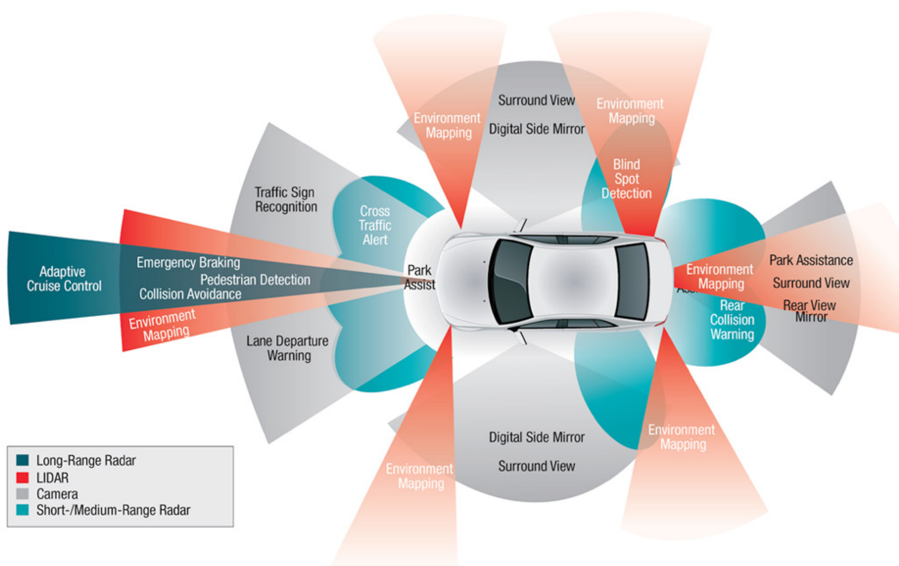
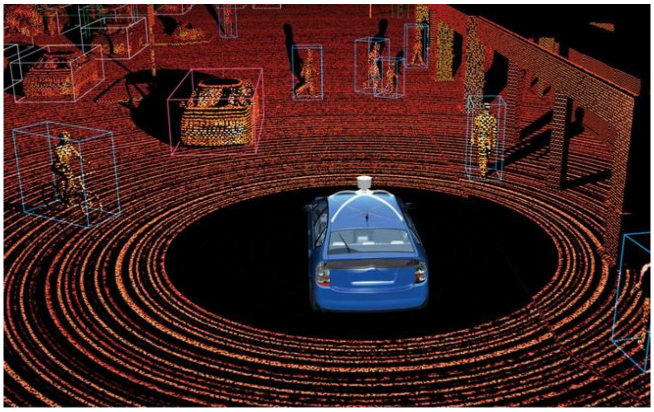


Figure 2. LiDAR Virtual world (ODYSSEUS LiDAR, 2015)



vehicle navigation (Curley, 2008).

Sensors

Intelligent vehicles rely on an overlapping group of sensors, which together fuse to create a virtual operating environment. For the purpose of this research, sensors fall into two categories: external and internal.

External sensors provide information about the world around the vehicle, enabling the computation of a safe and efficient trajectory toward a destination. They primarily include RADAR, LiDAR, ultrasonic, GPS, and a day camera. Figure 1 shows all of these systems fused together and each sensors' strengths and weaknesses.

RADAR sensors, currently used in some adaptive cruise control systems, provide the greatest clarity for relative speed. Utilizing the Doppler Effect, they can determine the relative speed of objects around the vehicle. Depending on model and placement, their wide field of view can detect objects of interest both in and around the vehicle's planned path. The main drawback of RADAR is the clarity of the data received. Because of the broad beam, RADAR cannot adequately discern the shape and contour of smaller objects. Its best use on an intelligent vehicle is rapid determination of rate of closure and long-distance object sensing (Lundquist and Schön, 2009).

LiDAR (Figure 2) provides a more precise virtual image of the world immediately around the vehicle. Due to the narrow beam width of the laser, a mechanical scanner is necessary to cover the target area. This results in some latency compared to RADAR, but together, they provide a fused image of a vehicle's surroundings. Precision, range, cost, and speed are all tradeoffs with LiDAR. An intelligent vehicle may incorporate multiple LiDAR sensors to enhance the quality of the virtual world model.

Ultrasonic sensors are currently in use in most reverse detection systems. They provide accurate, low cost, range detection of near obstacles, and will inform the fused virtual image of near obstacles around the entire vehicle. This will enable lane changes and emergency swerve maneuvers without unintentionally impacting near objects.

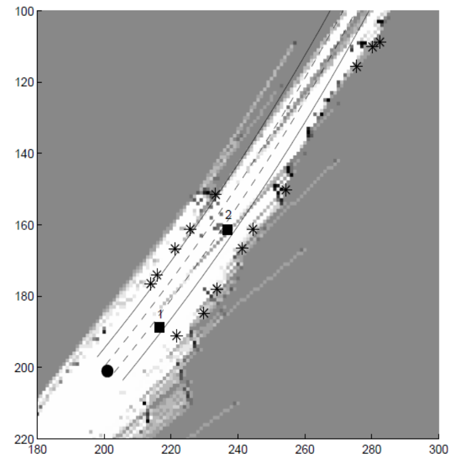
GPS provides an absolute position, navigation, and speed reference. It will enable macro-scale acceleration and speed calculations based on map data and road models, as well as provide continuous calibration of the Inertial Measurement Unit (IMU) and speed sensors. It does not however, provide the accuracy necessary to maintain lane guidance.

Internal sensors include the host of vehicle sensors, which inform the vehicle computers of the operating state of various subsystems. The key sensors related to intelligent vehicle operation are: wheel speed, steering angle, yaw rate, and acceleration.

Wheel speed and steering angle are used in concert to provide closed loop feedback to the vehicle controller. When a trajectory is commanded, the steering wheels will turn, and differential torque will be applied to the drive wheels. Sensor feedback will aid in preventing wheel slip and allow the virtual model to compute absolute vehicle position.

Finally, the yaw and acceleration sensors, combined into an IMU, provide a measure of error correction to the above speed and angle sensors. Under load, the dynamic performance of a rubber-tired vehicle will not exactly match simple kinematic models. This inertial measurement will enable closed loop feedback to correct for slip, and prevent loss of control. Doing so is critical because the inertial sensors provide a much faster feedback loop than the refresh time of the virtual fused model (Jing et al. and Liu, 2014).

Figure 3. A representative fused guidance model
(Lundquist and Schön, 2009)



Current Intelligent Operating Concept

The majority of research on intelligent vehicles focuses on either the sensors necessary to enable autonomous driving, or the infrastructure network required for large scale implementation (Curley, 2008; Sauck, 2009). This research focuses on the logical process and implementation of multiple sensor inputs, to ultimately control a four-wheeled vehicle. An intelligent vehicle with real-time control of steering, braking, and individual wheel power can provide an unprecedented level of safety and performance through varying conditions. This is accomplished by fusing sensor inputs, determining optimal trajectories, and maintaining closed-loop control of vehicle dynamics.

Various sensors provide the inputs necessary for the vehicle's computer to construct a virtual image of the world around it. Current production road-going vehicles already contain accurate vehicle speed sensors to control the automatic transmission and individual wheel speed sensors to enable the ABS system. Many also include ultrasonic or camera-based backup warning/guidance systems, and similar side blind-spot detection systems. Acting independently, these sensors provide the driver directly, or indirectly, with information on their specific measurements. An intelligent vehicle with sensor fusion will combine these inputs with longer range forward looking speed and distance sensors to create a virtual model of the objects around a vehicle (Lundquist, and Schön, 2009). Rather than individually warn the driver of impending collision hazards, fused together, these sensors will provide the constraints necessary to form a solution vector, which will either steer the vehicle autonomously or provide tactile sensory assistance (similar to a "stick shaker" in modern aircraft) to alert and assist the driver in immediate evasive action.

Active lane guidance, as part of sensor fusion, will enable the vehicle to maintain a center position between lanes based on image analysis of the lane markers and input from the rest of the vehicle's fused sensors. From this input, optimal trajectories will be computed, either to follow road curvature or avoid hazards within the road. Figure 3 shows a model developed by Lundquist and Schon, which infers a safe path between lane markers, with obstacle overlays.

The squares represent other vehicles, with the other icons indicating various sensor returns. The dark areas represent areas of uncertainty, while the white path is determined clear.

By reacting to a consolidated virtual model, the vehicle will continuously update its optimal trajectory with minimal computing overhead (Zhenhai and Bing, 2009). Under ideal conditions, the vehicle's color day camera, informs an image processor of the positions of the lane markers. These are overlaid on the virtual model, with a recommended trajectory directly down the center. As the lanes curve, the trajectory also curves. Vehicle speed is modulated so as not to exceed a safe stopping distance within the plotted clear trajectory.

If an obstacle were to appear in front of the vehicle, the obstacle detection sensors would provide its size and location to the virtual model. Development of this model is a key element of this research. If this obstacle impinges on the planned trajectory, a new course is plotted to avoid it with minimal course deflection (left or right). If such a deflection would result in the vehicle leaving the defined road surface (fused from the camera), an evasive maneuver will then be chosen from a menu of decreasingly desirable options, in the same way a human driver performs, but with significantly less delay. The fused model balances vehicle speed, radius of trajectory curvature, and expected stopping distance to determine – near instantaneously – if an emergency braking maneuver, swerve into unobstructed space, or combination of the two presents the option with the greatest margin for error. If a human driver were in control at the time of the obstacle presentation, an audible and tactile warning, similar to aircraft terrain avoidance systems, would provide the best option, without the usual cognitive delay.

After determining which course of action to execute, the intelligent vehicle must then use a reverse kinematic approach to control the vehicle's brakes, motors, and steering. A high-speed braking maneuver would demand input from all four wheel speed sensors to sense wheel slip, a yaw sensor to sense vehicle attitude disruption, and an accelerometer to compute absolute position along the trajectory. These feed directly into the virtual model, ensuring all vehicle control inputs are informed of the current vehicle attitude and acceleration (Jing et al. and Liu, 2014).

If operated by a human driver, such algorithms will provide a measure of stability control in case the vehicle loses traction while maneuvering.

Next Steps in Intelligent Vehicles

Many automakers are integrating automatic object avoidance into their entire product lines. Such a system will use sensors to indicate an impending collision, and apply the vehicle brakes, as necessary, to prevent impact. The greatest hurdle to still achieve is the development of an intelligent system capable of reading the surface of the road, enabling the vehicle to remain in its lane, and following traffic signals (Curley, 2008; Sauck, 2009). Rather than make the leap directly to autonomous vehicles, the adoption and acceptance of intelligent driver aids will continue to ease the task load of drivers. Just as cruise control eases highway travel, lane guidance and GPS linked traffic management will allow discrete stretches of autonomous highway. Human drivers will still navigate in urban and surface street environments until these systems demonstrate overwhelming success on simpler terrain.

The next challenges that engineers have to face include the transition from the current transportation system to an intelligent vehicle-based transportation system. Current infrastructure may require upgrades to enable full integration of intelligent vehicles, while remaining useful to conventional vehicles. Engineers will soon be confronted with the economic, environmental, and societal challenges that are inherent with intelligent vehicle design, as current driving paradigms will likely have to change with technology. These transitional challenges will present unique opportunities to increase both the safety and efficiency of road networks. This research delimits at these issues; however, this field presents an excellent opportunity for investigation from multiple angles.

Current Research

This research focuses on the application of intelligent control systems to improve automotive efficiency, performance, and safety. Such systems include:

> *Sensor fusion:* A computer model which combines the input from multiple discrete sensors to provide a virtual image of the surrounding environment.
>
> *Fully electric drive:* A drive system which eliminates the transmission, driveline, and axle shafts from the vehicle, enabling total control over individual wheel speed and

torque, using individual wheel motors.

Differential torque stability control: The ability to modulate torque at each drive wheel, to enhance vehicle stability, reduce wheel slippage, and aid traction on uneven or slippery surfaces.

Steering yaw rate control: In conjunction with the stability control, yaw rate control compares vehicle yaw rate with expected yaw rate, based on steering input and speed. This differential indicates the amount of over-steer or under-steer, and can adjust power and braking to prevent loss of vehicle control.

Sensor fusion provides two critical capabilities to an intelligent vehicle. Foremost, it reduces the computational overhead of each sensor answering a query for its specific purpose. The following is just one example: Utilizing sensor fusion, a rear obstacle avoidance sensor will provide situational awareness input used for forward obstacle avoidance. If the model identifies a forward obstacle requiring emergency braking, a close following vehicle would present an additional hazard. By maintaining full situational awareness in one virtual model, the optimum trajectory calculation is simplified.

The second advantage of sensor fusion is information redundancy. Each sensor has a primary purpose, but many can produce overlapping information. Rather than slow the computing cycle with burdensome error correction, the virtual model will plot the overlapping sensor data. The aggregate of this plot becomes the single model presented for trajectory calculations. If a sensor were to malfunction, it would present an anomalous series of data points, which can be immediately rejected, by comparison to the whole of the fused inputs and the operator warned of system impacts. This graceful degradation is critical to ensure safe operation.

A fully electric drive system enables all of these advanced control subsystems to function at a much higher level than current mechanically driven vehicles. Conventional vehicles can only modulate individual wheel torque through selective brake application, wasting energy, and acting indirectly to only approximate torque variations. A direct drive electric traction motor may be modulated much more rapidly than a conventional drivetrain, with absolute torque control.

A fully electrically driven vehicle may still utilize an engine/generator, battery pack, or any combination of the two systems to provide primary power, without concern to the intelligent control systems. The traction motors may be located within the wheel hubs, or mounted inboard to facilitate a more conventional suspension and brake arrangement. The use of a constant velocity axle shaft would maintain direct drive functionality, while reducing un-sprung weight and allowing for greater protection of the motor.

The differential torque stability control provides a synthetic differential capability, which will prevent wheel slippage during tight cornering. In cases of reduced or uneven traction, the wheel speed and steering angle sensors will provide data used to prevent wheel spin but maintain the commanded acceleration or deceleration rate. In conjunction with the steering yaw rate control, this system will provide unparalleled traction and stability control. Such a system will prevent the wheel slippage required to activate conventional stability controls (Jin and Li, 2015; Jing et al., 2014). In the event wheel slippage occurs, the system will modulate individual wheel torque and steering angle to maintain the commanded vehicle path, while regaining traction.

The most significant application of dynamic control lies in coupling steering output with yaw rate sensing and applied wheel torque. If the vehicle computer senses a yaw rate inconsistent with the steering angle and vehicle speed (over or under steer), it will modulate the steering along with wheel torque to maintain the intended road position (Liu, 2014). In practice, such a maneuver is similar to an experienced driver steering into over-steer and "drifting" around a corner. The initial loss of vehicle control is quickly regained as yaw rate again matches input expectations, and the vehicle settles into a safe driving attitude. Such a system is essential in any fully intelligent vehicle because the driver will not be prepared to recover from an unexpected loss of traction. The alternative would be for an intelligent vehicle to operate at vastly reduced speeds in order to maintain an acceptable margin of safety. This system is critical for an intelligent vehicle, which relies on adherence to a planned trajectory for safe avoidance of obstacles (Lundquist and Schön, 2009).

Conclusion

As intelligent vehicle subsystems increasingly enhance driver control and safety, vehicle operators become more indirectly in control of their vehicles. As a result, fused sensors and vehicle control responses must be a consideration for intelligent control. The sensor and stability control systems overviewed herein will provide a layer of safety and enhanced performance when operating a vehicle in real-world conditions on varying road surfaces.

When actively driving, a vehicle operator will have advanced warning and traction control systems which aid decision making and prevent loss of control through haptic and audible feedback and individually tailored wheel torques. If emergency conditions arise, the systems will provide quick recovery and prevent a loss of control.

Intelligent vehicles will someday be capable of functioning without direct driver input. As such, they will require these capabilities to ensure occupant safety and graceful recovery from unexpected situations.

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