Autonomous vehicle technology has been a major research and development topic in the automotive industry during the last decade. The technologies developed in the automotive industry also has direct applications in construction, mining, agricultural equipment, seaborne shipping vessels, and unmanned aerial vehicles (UAVs). Significant R&D activities in this area date back three decades. Despite the heavy intensity of investment in technology development, it will still take a few decades before an entirely autonomous self-driving vehicle navigates itself through national highways and congested urban cities [1]. People have been trying to make self-driving cars, since the invention of the car. The past, present and potential future of driver assistance systems are reviewed by Benglar et al [8] and summarized in Figure 1. Early driver assistance systems were based on sensors that measure the internal status of the vehicles. These sensors enable the control of vehicle dynamics so that the trajectory requested by the driver is followed in the best way possible. In 1995, an additional dynamic driving control system such as electronic stability control (ESC) was introduced. The Second generation of driver assistance systems was introduced around the 1990s based on sensors that measure the external state of the vehicle with the focus of providing information and warnings to the driver.Figure 1: Evolution of Advanced Driver Assist Systems The following sensors that measure conditions outside the vehicle, and vehicle position relative to its environment are essential in driving assist systems and autonomous vehicle technologies: Vision, LIDAR, RADAR, ultrasonic range, GPS, and inter-vehicle communication. The latest generation of Driver Assist Systems (DAS), also called Advanced Driver Assist Systems (ADAS), defines and controls trajectories beyond the current request of the driver, i.e. overriding driver commands to avoid a collision. All these sensors have overlapping and complementary capabilities. Data fusion strategies that combine real-time information from these multiple sensors is an important part of the embedded control software. Actuation technologies, i.e. computer control steering, throttle, transmission, and braking, are mature and do not present any R&D challenges. The embedded control software development (that includes data fusion from sensors, inter-vehicular communication, real-time cloud computing support) is the key technical challenge. The on-road vehicle automation requires a standard set of regulations and terminology with a taxonomy and definitions. Some regulation and standard have been released [9]. The new standard J3016 from SAE International simplifies communication and facilitates collaboration within technical and policy domains. According to the standard as shown in Figure 2, the levels of driving automation can be divided into Conditional, High, and Full Automation. The standard does not provide complete definitions applicable to lower levels of automation (No Automation, Assisted, or Partial Automation). Active safety and driver assistance system that intervene to avoid and/or mitigate an emergency situation and then immediately disengage are also not included for the various levels of automation.The short-term goal is to automate driving in select well-defined situations as implemented by some of the technology companies, for example testing of self-driving taxi cabs in well-defined suburbs. The long-term goal is to achieve door-to-door automated driving in any situation. Some current ADAS examples include traffic jam assist, collision avoidance assist, pedestrian and oncoming traffic detection systems. 2. Sensors: Principles & Limitations Different sensors and systems are used for navigation and control of the autonomous vehicle as shown in Figure 3. Prominent sensors such as LIDAR, GPS, radar, vision, ultrasonic and inertial measurement unit, their working principle and usage are discussed in the following sections.LIDAR transmits a beam of light pulse from a rotating mirror, part of that light will reflect back to the sensor to detect any non-absorbing object or surface (Figure 4). The target distance is calculated as speed of light times the measured time period at multiple angles. It scans the field of view in 3D with a finite spatial resolution and frequency. Using the calculated distance, the sensor constructs a 3D map of the world including the objects around it. LIDAR uses infrared (IR), visible or ultraviolet (UV) waves of the electromagnetic spectrum for different applications and comes in various 1D, 2D and 3D configurations. They are the second most valued sensors, after vision for object detection like a vehicle, pedestrian and obstacles, as shown in a typical application of self-driving cars (Figure 4). Their performance is poor in rain, snow, dust and foggy environments. A high-end LIDAR sensor can measure multiple distances per laser pulse which is helpful to see through dust, rain and mostly transparent surfaces such as glass windows and porous object like wire fences. To reduce the signal to noise ratio, a higher power laser generation is desired but in order to prevent damage to the human eye, a laser power of 905nm is used to achieve desired range with low duty cycle [10]. Current cost of LIDAR sensor is relatively high [11, 12] and there are some issues with the long-term reliability of their mechanical scanning mechanisms. They have been used heavily in research applications, but not widely used in automotive OEM safety systems until recently2.2. RADAR Radar transmits electromagnetic pulses and senses the echoes to detect and track objects. Echoes sensed vary in frequency depending on the speed of the object. Radar can measure the relative distance, velocity, and orientation of the object [13, 14]. In case of monostatic radars in which the transmitter and receiver are located at the same location, range of the target is measured by using the round trip travel time of a pulse, times the speed of light divided by two. They are typically available for short (≈ 30), medium (≈ 60) and long-range (≈ 200 m) distances and range from 3 MHz (Very long range) to 100+ GHz (Short range) frequencies (Fig.4). Radar requires less computing resources compared to vision or LIDAR. Typical application include lane keeping, advance cruise control, object detection, etc [15]. 2.3. GPS GPS is used to locate the position of a GPS receiver (x,y,z coordinates) using four or more geostationary satellites. These satellites maintain their position relative to earth and broadcast reference signals. A GPS receiver on earth deciphers the actual location within meters accuracy. However, the so called ”differential GPS” can pinpoint a location within centimeter accuracy which is necessary for navigation of autonomous vehicle. GPS consists of three segments: space, control, and user segments. The space segment includes the satellites, control segment manages and controls them and user segment is related to development of user equipment for both military and civil purposes [16]. GPS based navigation application are greatly used to accurately predict the vehicle location with respect to map which is known as localization. However GPS based navigation are inaccurate and can lead to ghosting phenomena. 2.4. Vision Vision system is composed of a camera and image processing unit (Figure 5). A typical camera is a combination of focusing lens and array of photo-detectors for each pixel in the field of view (FOV). The array of photo-detectors send pixel information to image processing unit. This unit processes the information based on certain algorithms to detect desired objects. Vision sensors capture more visual information, hence tracking the surrounding environment more effectively than other sensors. They are categorized into mono and stereo types.

Mono camera systems are often used for lane marking, lane edge detection, basic object detection, road sign detection and localization. Multiple or Stereo camera systems provide depth for objects detection. Their primary advantage is their low-cost, off-the-shelf components and their software implementation. Their primary disadvantage is handling a full range of ambient and uncontrolled conditions such as lighting, shadowing, reflection, weather, dust, smoke. Also processing data from these sensors in real-time require a large amount of computational resources. Even with these limitations they are extensively used in autonomous vehicles.2.5. IMU A moving vehicle can experience linear and rotational motions along x, y, and z axes: lateral, longitudinal, and vertical which can be measured by inertial measurement unit including linear and angular accelerations. This information is used to improve GPS measurements. IMU includes accelerometers and gyroscopes 2.6. Ultrasonic Range Ultrasonic sensors are short range sensors (typical ≈ 2 m) which send an ultrasonic pulse wave and detect echoes returned from the obstacles using transmitter receiver pair. These are mainly used in relatively low speed ADAS modules like parking space detection and assistance [17] and obstacle detection during congested traffic conditions [18]. They are reliably detected under any weather conditions like rain, snow and winds. However they have range limitation which restricts them to be used as OEM vehicle sensors. 3. SENSOR FUSION In sensor fusion techniques, raw sensor data is received. After receiving the data, feature extraction, clustering and object detection hypotheses are conducted. These hypotheses are then associated with tracks showing state estimates of objects detected. The associated information is used by state estimators like Bayesian filters, to predict the current states [19]. The order of sensor measurements availability can be different from the order of raw data acquisition by the sensors. Buffering of information until all the data is available results in an unneeded dead-time which can degrade the performance of control system. To avoid performance degradation pseudo measurements that are aligned in time or asynchronous tracking systems that employ every measurement upon availability can be used