

Active Safety System Sensors

RATIONALE

This SAE Surface Vehicle Information Report is intended to provide comprehensive reference and background information pertaining to sensors used by automotive active safety systems.

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1. SCOPE

The current document is a part of an effort of the Active Safety Systems Committee, Active Safety Systems Sensors Task Force whose objectives are to:

- a. Identify the functionality and performance you could expect from active safety sensors
- b. Establish a basic understanding of how sensors work
- c. Establish a basic understanding of how sensors can be tested
- d. Describe an exemplar set of acceptable requirements and tests associated with each technology
- e. Describe the key requirements/functionality for the test targets
- f. Describe the unique characteristics of the targets or tests

This document will cover items (a) and (b).

2. REFERENCES

Lytrivis, P. T. (2009). Sensor Data Fusion in Automotive Applications. Dans N. Milisavljević (Éd.), *I-Tech* (pp. 123-140). Vienna, Austria: Sensor and Data Fusion, Ed. Milisavljević, N.

Richards, M. A. (2005). *Fundamentals of Radar Signal Processing*. NY: McGraw Hill.

Steinberg, A. N. (March 1999). Revisions to the JDL Data Fusion Model. *Proc. SPIE 3719, Sensor Fusion: Architectures, Algorithms, and Applications III*, (p. 430).

3. ACTIVE SAFETY SYSTEM SENSORS BASIC DEFINITIONS

Many Active Safety System sensors have some processing capability that goes beyond just the acquisition of a physical phenomenon. What we refer to generally as Active Safety System *sensors* are, in fact, sensing subsystems of variable complexity, designed to be integrated in an Active Safety *System* that manages one or more Active Safety System *applications*.

Active Safety System architectures must have an understanding of the processing architecture at the sensor level in order to fully understand how the data provided by sensors should be interpreted.

4. ACTIVE SAFETY SYSTEM PERCEPTION LAYERS

In discussions comparing “sensors” or sensor “technologies”, one must be able to describe the identified perceived features of the technologies:

- Nature of the information provided
- Limitations
- Strengths
- Applicability

A better understanding will come from being able to identify how the information is provided by a specific sensor.

The processing architecture can be described as processing “layers” of information starting with the initial acquisition of the surrounding physical environment up to the control or actuator layer.

The division of tasks between each of the processing layers varies greatly with sensor system architectures. It is not, as the following proposed model implies, a clear-cut separation between layers, nor is that separation necessarily implemented in different physical devices. The following discussion aims only at orienting the upcoming discussion on features of Active Safety System sensors.

4.1 JDL Data Fusion Model for Automotive

The functional model maintained by the Data Fusion Group of the Joint Directors of Laboratories (JDL) has been revised several times and eventually also for automotive purposes (Lytrivis, 2009) (Steinberg, March 1999). The standard model at different levels of revision generally has five levels in the data fusion domain that connects the data source to the human-computer interface.

- Level 0: source preprocessing – sensor measurement (pixel/signal) preprocessing
- Level 1: object refinement – estimation/prediction of entity states based on inferences from observations
- Level 2: situation refinement – estimation/prediction of entity states based on inferred relations
- Level 3: threat refinement – estimation/prediction of effects on situations or estimated/predicted actions by participants
- Level 4: process refinement – adaptive data acquisition and processing to support process refinement

In applying the JDL model to automotive, the Level 4 is not considered to belong to the fusion domain and hence it is left out, while a Level 5 which is the HMI layer is brought in. The revised JDL model for automotive has three layers in it:

- Perception Layer – includes Level 0 (Pre-processing) and Level 1 (Object Refinement)
- Decision Application Layer – includes Level 2 (Situation Refinement) and Level 3 (Threat Refinement)
- Action/HMI Layer – Level 5 (Human Refinement)

In support of this discussion, a special emphasis will be made on the “physical interface” to the exterior world, within the Perception Layer.

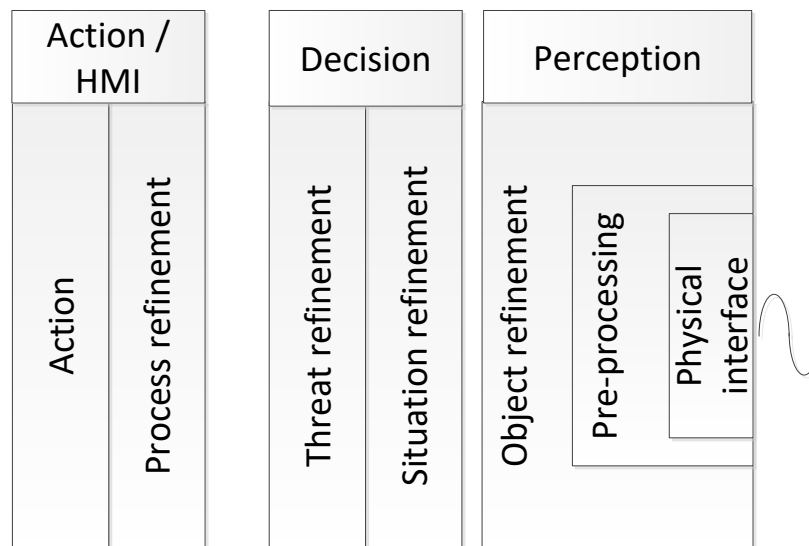


Figure 1 - Active safety system perception layers¹

¹Source: Phantom Intelligence Inc.

5. COMMON RANGE SENSOR EVALUATION PARAMETERS AND CONSIDERATIONS

This section covers some of the sensor evaluation parameters that are common to most technologies and highlights some of the aspects that should be taken into consideration when evaluating technologies.

5.1 Angular Resolution

In general², sensors measure the exterior environment from a single vantage point with a limited field of view (see Figure 2) from that vantage point.

Polar coordinate systems are often used to represent detection information from sensors, since the polar information (distance, vertical angle, and horizontal angle), relative to the sensor, is an adequate representation of the physical perception of devices.

As a consequence of this “polar” nature of sensors, the “transversal” resolution of sensors decreases with distance.

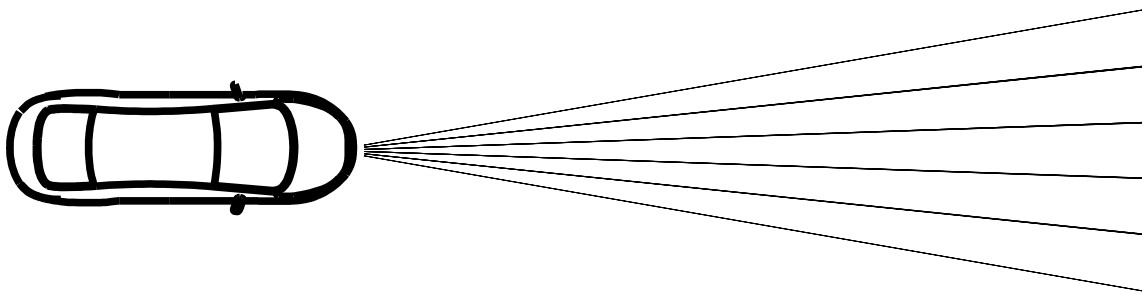


Figure 2 - Angular resolution³

This is the reason why, when specifying performances of a sensor, the “dimension” of a detectable object cannot be dissociated from the distance. One cannot say “the sensor must detect a 10 cm object”, but “the sensor must detect a 10 cm object at X meters”. This is also why the “resolution” of detectors cannot be dissociated from the “field of view” of a sensor. The “resolution” of a sensor is then best qualified using the “angular resolution” of the sensor.

Angular resolution is the ability of the measuring device to discriminate small details of an image, or to tell one object from another. A typical definition is given by: $\Delta\theta = a \frac{\lambda}{D}$ where a is a constant which depends on the aperture shape, λ is the wavelength, and D is the aperture size. $\Delta\theta$ has the units of radians. This equation is applicable to optical sensors as well as radars.

5.2 Distance Precision

For the reason stated above, the precision of a distance sensor is best qualified as a precision of the distance, calculated “radially” from the sensor.

It is worth noting, that, for a large number of the sensors, the precision of the measurement varies with distance (reasons for these variations vary with the physics of the sensor).

When a precision is stated without a distance, it should be assumed that it is the precision of the sensor at the maximum range stated.

²Some exception can be made with ultrasonic sensors, or fused sensors.

³Source: Phantom Intelligence Inc.

5.3 Range

The detection range of sensors may vary depending on a number of factors. For this reason, any range specification should be accompanied by a description of the measurement conditions.

Here is a sample list (non-exhaustive) of the common factors affecting sensor performance:

- Lighting conditions
 - For obvious reasons, lighting conditions can affect the range of optical sensors;
- Weather Conditions
 - The presence of rain, fog or other obscurants can have an effect on the range of numerous sensors;
 - Cloud coverage can significantly affect the performance of optical sensors for some applications.
- Humidity and temperature
 - Humidity and temperature have a notable effect on the transmission of sound waves. Humidity affects the transmission of light waves at certain wavelengths;
- Materials used for the reflection target and target size
 - Optical sensor measurement range specifications should specify the “reflectivity” of the object used as a reference, at the sensor wavelengths;
 - For radar, applications, radar cross-section of the target.
- Materials used to “enclose” the sensor
 - Some enclosure materials have varying effect on as they may affect the transmissivity of the signals used take range measurements. Although visually “transparent”, plastics or glass used to enclose optical sensors have varying “transmissivity” through the visible and invisible spectra. In a similar fashion, the materials enclosing a radio-wave based sensors can affect the sensor performance (the presence of metallic paint has been invoked as a range affecting issue with some radar-based sensors).
- For radars, the range performance is affected by radiated power levels, antenna gain (size), frequency of operation, and target characteristics (point, area, or volume targets).

5.4 Angle of View

A number of sensors do not have a uniform detection distance, depending on the angular position of the obstacle relative to the sensor. One should not assume a constant range over the entire field of view of the sensor. Figure 3 illustrates a potential variation of effective range within the field of view of sensors.

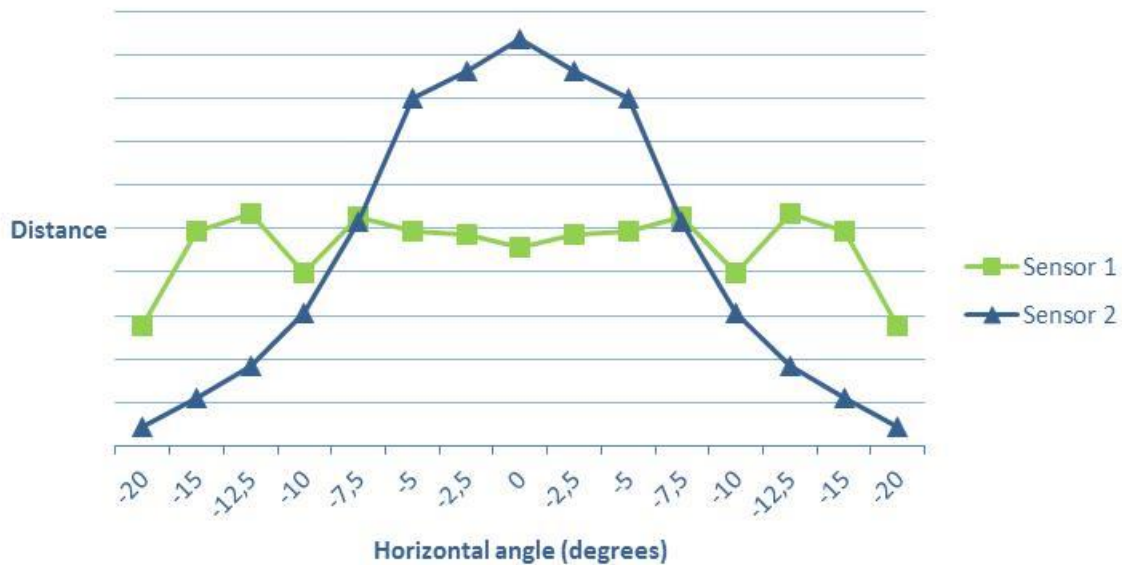


Figure 3 - Range vs Angle of view measurement (sample)⁴

5.5 Object Material

Different sensor technologies react differently as a function of the target material.

For example, given the wavelengths used, radar sensors typically are more sensitive to metallic objects than to “soft” material such as human clothing.

Optical technologies (cameras, LiDAR) rely on the material reflectance of the object, at the wavelengths for which the spectrum of the technology is designed to assess. In technologies designed to detect and/or emit non-visible wavelengths, the material reflectance can often be counter-intuitive. For example, a “black” material to the human eye can be highly reflective at the sensor’s wavelength.

5.6 Weather and Exterior Testing Conditions

The performance of sensors can be affected by a number of outside parameters.

Exterior illumination can affect camera systems, for example.

Other factors that can affect sensor measurement and qualification are fog, rain and snow. The presence of water on the ground can affect some sensors. Additionally, the sensor field of view should remain unobstructed during testing.

Comparisons between sensors must take into account those parameters, and, ideally, descriptions of sensor performance must outline the testing conditions.

6. RADAR

RADAR (**RA**dio **D**etection **A**nd **R**anging) is an « active » object detection system which uses radio waves to determine the range, direction, and speed of objects. The RADAR transmits pulses of radio waves or microwaves which bounce off any object in their path. The object returns part of the wave’s energy to a dish or antenna where it is sensed.

⁴Source: Phantom Intelligence Inc.

There are two general methods of measuring distance using radar, described in 6.1. The first is known as the direct propagation method and measures the delay associated with reception of the reflected signal which can be correlated to the distance of the reflecting object as a function of the speed of light and the period, or rather, the time delay in the transmission and receiving of the reflected waves. The second group of methods, known as indirect propagation, are methods where a modulated frequency is sent and received. The difference in the frequency can be used to directly determine the distance as well as the relative speed of the object.

Radar signals are very good at detecting objects that strongly reflect electromagnetic radiation (e.g., metal objects). Because they operate at wavelengths on the order of a few millimeters, automotive radar systems are pretty good at detecting objects that are several centimeters or larger. They are also good at looking through objects that are small relative to the sensor wavelength (e.g., the water droplets in fog)⁵.

Radars determine the angular position of an object using multiple overlapped antenna beams (or similar technology), digital beam forming, or mechanical steering of the beam to scan the space.

6.1 Types of Automotive Radar Systems⁶

6.1.1 Pulsed Radar

In pulsed radar architectures, a number of pulses are transmitted and from the time delay and change of pulse width that the transmitted pulses will experience in the round trip, the distance and the relative speed of the target object can be estimated.

Pulsed radars typically suffer from blind speed and ambiguous range issues. In addition, transmitting a narrow pulse in the time domain means that a large amount of power must be transmitted in a short period of time. In order to avoid this issue, spread spectrum techniques may be used.

6.1.2 Continuous-Wave Radar

In continuous-wave (CW) radars, a high-frequency signal is transmitted and by measuring the frequency difference between the transmitted and the received signal (Doppler frequency), the speed of the reflector object can be estimated. These systems are incapable of detecting the target range and they cannot distinguish between objects moving toward or away from the transmitter. The direction ambiguity can be eliminated by extracting the sign of the Doppler frequency using quadrature architecture.

6.1.3 Frequency-Modulated Continuous-Wave (FMCW) Radar

In FMCW radars, a ramp waveform or a saw-tooth waveform is used to generate a signal with linearly varying frequency in time domain. The variation of the instantaneous frequency is proportional to the ramp waveform. The generated signal is then transmitted. The down converted received signal is a frequency which is proportional to both the range and velocity of the object. The detector can estimate the velocity and the distance of the moving object using standard techniques.

6.1.4 Radar Sensor Architectures

Every radar system can be divided into two categories:

- Small-Angle Bi-static Radars⁷: In these systems, two separate antennas are used for transmitter and receiver. Transmitter-to-receiver leakage can be mitigated by physical separation of the antennas.
- Mono-static Radars: In these types of radars, a single antenna is used for transmitter and receiver. The main advantage of these radars is their compactness.

⁵<http://www.cvel.clemson.edu/auto/sensors/distance-radar.html>

⁶<http://www.sabertek.com/automotive-radar.html>

⁷ In automotive applications, bi-static radars are qualified as “small-angle” because of their relatively small antenna separation compared to their detection range.

6.2 Radar Frequency

The wavelength used by the radar directly influences two aspects of the design and performance of radar systems:

- Higher frequencies theoretically allow for better spatial resolution of the sensor
 - The horizontal beam width of the sensor has a much stronger influence on the spatial resolution
- Shorter wavelengths (higher frequencies) give the possibility of more compact design (they require smaller antennas)
- With shorter wavelengths (at the higher frequencies used by recent radar systems), systems are less susceptible to interference⁸

At higher frequencies, the atmospheric attenuation increases and for a given detection range, higher output power is required.

It is worth noting that two different frequency bands are currently being used in the industry:

- 24 GHz:
 - The low frequencies used by 24 GHz radar initially had the advantage of using components available from the telecom industry.
 - 24 GHz radars are used for some short to medium range applications.

Short-range radars typically have a range of up to 40 meters and a field of view $>\pm 60^\circ$. Short range radars are used in applications that require a highly accurate detection of the object in the range of 0 to 30 meters, such as blind spot monitoring, park assist, rear crash (cross traffic) collision warning, and adaptive cruise control. 24 GHz radars are also used for Lane Change Assist applications with detection ranges >70 meters.

- 76 to 81 GHz
 - With the advance of new and more tightly integrated microelectronics, short wavelength radars are increasingly more commonplace. The wavelengths in this bank have been divided in two separate usages:
 - 76 to 77 GHz is used for long-range applications.
 - 77 to 81 GHz is reserved for short/mid-range applications.

Long range radars have a range of up to 200 meters and a field of view of approximately $\pm 10^\circ$. Long range radars are used in applications that require detection of the object in the range of 100 to 175 meters, such as adaptive cruise control and automatic emergency braking.

6.3 Regulation

Since radars are based on the use of radio frequencies, the design of radar solutions is heavily regulated by national organizations, such as the FCC in the U.S.

These regulations define the frequencies that can be used and limit the output power of the devices.

For example, at the date of publication, the 77 to 81 GHz band is not yet authorized by the FCC. This band has been approved by the EU and Japan. It is expected that the FCC will approve this band in the future.

⁸ (in the W-Band – 75 to 90GHz) “*The high attenuation (here the influence of the oxygen molecules O₂) enhances the immunity to interference of these radar sets.*”

<http://www.radartutorial.eu/07.waves/Waves%20and%20Frequency%20Ranges.en.html>

6.4 Radar Limitations/Characteristics

6.4.1 Angular Resolution

Angular resolution of a radar sensor is limited by the radio frequencies of operation and the antenna aperture. It is not limited by the modulation bandwidth. The equation for angular resolution is given in 5.1.

6.4.2 Distance Resolution

The radio frequencies, modulation frequencies and radar type have a definite influence on the range and distance resolution of radars.

Given the high frequencies of radio waves, the distance resolution is also influenced by the acquisition speed of the electronics.

The distance resolution of a radar sensor is limited by the occupied bandwidth of the radar sensor transmission. This is limited by either the pulse bandwidth for a pulsed radar, or the modulation bandwidth of an FMCW or a phase modulated radar. The minimum range resolution of a modulated radar is given by:⁹

$$\Delta R = \frac{c}{2 \times OBW}$$

Where c is the speed of light, and OBW is the occupied bandwidth of the radar transmission in Hz.

6.4.3 Doppler Resolution

The Doppler resolution of a radar is limited by the observation time. If the total observation time (time duration of radiated power) of the radar sensor is T , then the minimum velocity resolution of the radar sensor is given by:¹⁰

$$\Delta v_{[\text{meters/sec}]} = \frac{\lambda_{[\text{meters}]}}{2T_{[\text{sec}]}}$$

6.4.4 Obscuration

While most radar sensors react well to adverse weather, there are reported cases where radar functions can be disabled by the accumulation of ice in front of the sensor. Some deployed radar sensors have built in heaters to melt ice, to reduce the effects of ice impairment.

6.5 Classification/Feature Extraction

Modern radar sensor return range, velocity (including sign) and angle (typically azimuth, but sometimes elevation as well) and signal to noise ratio. They may update this information at rates significantly faster than camera systems. Given that radar systems can provide distance, speed, azimuth angle and signal to noise ratio information, a reliable feature extraction and classification process has to be implemented either at the sensor level or the ECU level. To classify objects such as pedestrians and vehicles, the velocity profile and range profile signal features are used, along with other available parameters (size of the object, variations of the Doppler shift, etc.).

⁹ Mark A. Richards, "Fundamentals of Radar Signal Processing" p 9, McGraw-Hill NY, 2005

¹⁰ Mark A. Richards, "Fundamentals of Radar Signal Processing", pp168-169, McGraw-Hill NY, 2005

6.6 Radar Applications

Because of the limited spatial resolution of radar, radar sensors are often used in complementarity with vision sensors in applications that require precise shape recognition or object classification.

For lane change assistance applications, radar can identify approaching vehicles, and can localize to which lane the vehicle is in. This is true as long as either the target vehicle's range or velocity are different than the surrounding vehicles. If the condition above is not true, i.e., the ranges and velocities of the target vehicles are identical, vision systems can be used to augment the lane information.

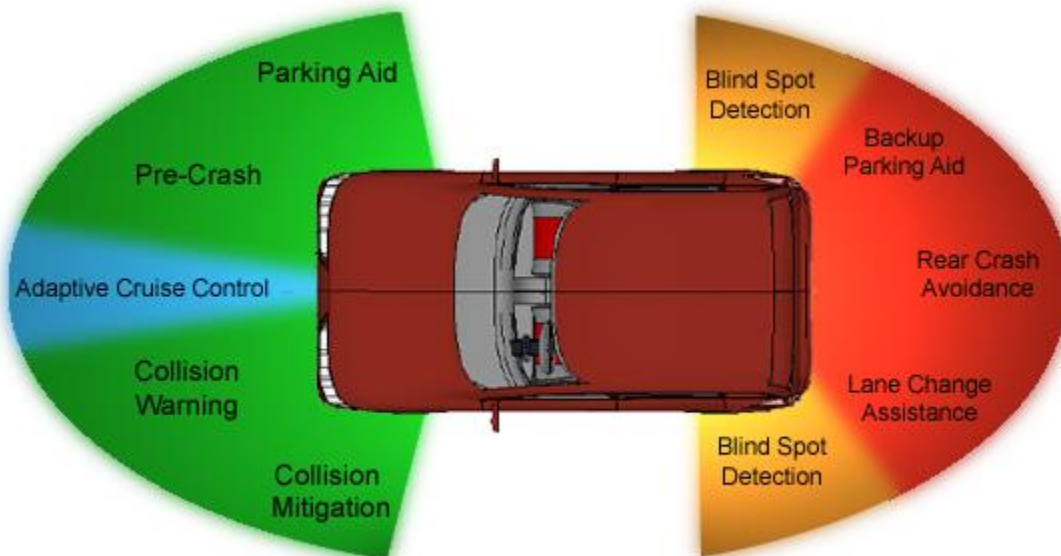


Figure 4 - Possible applications of a radar sensor¹¹

7. VISION SENSORS

Vision sensors capture the surrounding environments light intensity and color (for color cameras) in arrays of varying resolution and density.

Vision sensors are “passive”, in the sense that they do not require any special “emitter” and can rely on ambient lighting as a light source.

Since vision sensors closely mimic the human sense of vision, information obtained from the vision sensors can be directly displayed to be comprehensible to humans without further (or minimal) processing, or be used to overlay complementary information.

However, object information obtained from vision sensors typically relies on some supplementary form of processing of the acquired image.

Vision sensors are used in a very wide range of applications.

7.1 Types of Vision Sensors

Vision sensors used in active safety applications use two different technologies for acquiring the image, charge-coupled device sensors and active pixel sensors.

¹¹Source: <http://www.cvel.clemson.edu/auto/sensors/distance-radar.html>

7.1.1 Charge Coupled Devices

In a CCD imaging sensor, there is a photoactive region consisting of a capacitor array, and a transmission region or shift register. An image is projected through a lens onto an array, causing each capacitor to accumulate an electric charge proportional to the light intensity at that location. After the array has been exposed to the image, a control circuit causes each capacitor to transfer its contents to its neighbor (operating as a shift register). The last capacitor in the array transfers its charge into a charge amplifier, which converts the charge into a voltage. By repeating this process, the controlling circuit converts the entire contents of the array in the semiconductor to a sequence of voltages. In a digital device, these voltages are then sampled, digitized, and usually stored in memory; in an analog device (such as an analog video camera), they are processed into a continuous analog signal (e.g., by feeding the output of the charge amplifier into a low-pass filter) which is then processed and fed out to other circuits for transmission, recording, or other processing.

7.1.2 CMOS Devices

An active-pixel sensor is an image sensor consisting of an integrated circuit containing an array of pixel sensors, each pixel containing a photo detector and an active amplifier. There are many types of active pixel sensors including the CMOS APS used most commonly in cell phone cameras, web cameras, and in some DSLRs. Such an image sensor is produced by the CMOS process, and has emerged as an alternative to CCD image sensors.

The biggest advantage of a CMOS sensor is that it is typically less expensive than a CCD sensor. A CMOS camera is immune to the blooming effect where a light source has overloaded the sensitivity of the sensor, causing the sensor to bleed the light source onto other pixels.

The biggest disadvantage to a CMOS video sensor is that the image is captured a row at a time, within approximately 1/60th or 1/50th of a second (depending on refresh rate). This may result in a "rolling shutter" effect, where the image is skewed (tilted to the left or right, depending on the direction of camera or subject movement). For example, when tracking a car moving at high speed, the car will not be distorted, but the background will appear to be tilted.

7.2 Configurations

The sensor is usually incorporated into some form of camera that includes the lens, or lenses, power supply, and housing.

Some vision sensors include high-end image processing functions specific to the applications supported (e.g., sign recognition, lane recognition, distance estimation).

7.2.1 Mono versus Stereo Cameras

Monocular cameras have a single image sensor and lens. A stereo camera has two lenses with a separate image sensor for each lens. This allows the camera to simulate human binocular vision, and gives it the ability to capture three-dimensional images. The distance between the lenses in a typical stereo camera used for automotive applications is about 200 mm. The longer the base line (inter-camera distance) the more extreme the 3-dimensionality. Stereo cameras are typically used where the distance to an object needs to be determined. A depth estimation algorithm uses triangulation between the left and right images to determine the depth of objects in the field of view.

Some monocular camera use the displacement of the camera in a moving vehicle between two frames to simulate the binocular vision and supply the 3 dimensionality (a technology known as "structure from motion").

7.3 Vision Limitations/Characteristics¹²

Algorithms performing feature extraction from images rely heavily on the presence of “contrast” (either color-wise or intensity-wise) between objects and their background. For this reason, the following are the primary technical features of cameras for automotive applications:

- Dynamic range
 - Performance under extreme variations of illumination. Ability to accurately capture visual information under conditions such as approaching headlights, glare from other vehicles, tunnel entrances and exits, and rising or setting sun. Ability to reduce exposure response time.
- Imaging sensitivity
 - Efficiency in converting light to signal without producing excess noise. Higher sensitivity means less light is needed to produce a good signal-to-noise ratio (SNR) and thus useable images. A camera with high sensitivity can capture good pictures in low light.
- Spectral range sensitivity
 - Sensitivity to near-infrared (NIR) wavelengths enables a camera to capture wavelengths that are present in the night sky. Near-infrared can also be projected by special headlights as additional lighting because it is invisible to the human eye.
 - Far-infrared is emitted by an object. Night-vision devices using far-infrared do not require a light source.

Other features that must be considered, depending on the applications:

- Resolution
 - The sensors resolution has a direct impact on the capacity of the processing subsystems to perform feature recognition. On the other hand, it has an important impact on the transmission and processing bandwidth of the systems. For vision sensors used in distance estimation, the spatial resolution of the sensors has a direct relationship to the distance resolution of the sensor. A compromise must often be made based on the complexity of the scenes observed.
- Frame rate
 - The frame rate of sensors must be considered. The frame rate may be limited by the physical sensor or, for sensors providing some level of image processing, by the processing capability of the sensor and the complexity of the processing being performed.
- LED Flicker
 - LEDs are increasingly used in vehicle lights and street signs. Maximum brightness is achieved by pulsing the LED at high current. The pulse frequency is rapid enough to appear as a constant light to the human eye, but can appear to flicker to a vision sensor. If the pulse frequency of each of the LEDs in the scene is not synchronized to the camera shutter, the intensity of the LEDs can appear to vary temporally. In applications that potentially deal with such LED-based objects, both frame rate and integration time of sensors supporting applications that deal with such objects must be taken in consideration to compensate for that effect.

¹²http://www.sensata.com/download/whitepaper_automotive-camera-safety-apps.pdf