# A Survey of Sensors for Localization of Unmanned Ground Vehicles (UGVs)

Dr. Georgios A. Demetriou
Frederick Institute of Technology
3080, Lemesos
Cyprus
Tel. +357 25730975

## Abstract

*Acquiring knowledge about the environment is a fundamental task for Unmanned Ground Vehicles (UGVs). To accomplish this, UGVs must extract information from measurements that are gathered from various sensors. In search for a solution, scientists have developed a variety of sensors and techniques for extracting the information needed from the data gathered by sensors. This paper starts by giving a brief review of localizations techniques. It then reviews some of the most common sensors that are used by the localization techniques.*

**Keywords**: Unmanned Ground Vehicles, Mobile Robots, Sensors, Localization.

## 1. Introduction

Navigation is the process used by a mobile robot to move from an initial position to a final position with respect to an initial frame. In order for a robot to navigate, it must first localize itself. In general, the term localization means the determination of the locality (position) of an object. In robotics, localization refers to methods through which a robot can calculate or update its position through information gathered from sensors. A robot must achieve localization in its operational environment in order for path planning and navigation algorithms to work effectively.

Mobile robots work with and for people and thus operate in our everyday environments. To do that, they need to be able to acquire knowledge through perception. In other words they need to collect sensor measurements from which they extract meaningful information that is used for localization. A block diagram of the navigation control loop of Unmanned Ground Vehicles (UGVs) is shown in Figure 1.

Perception is achieved through sensors. A sensor is a device that measures or detects internal robot conditions or external environmental conditions, such as motion, heat or light and converts the condition into an analog or digital representation. There are a wide variety of sensors used in mobile robots. Most of these sensors are used for localization and in turn path palling and path execution (control) [2].

This paper surveys the sensors, and associated technologies that are used by UGVs for localization and navigation. In surveying the literature, one thing became apparent; there in not a single approach in which robotic systems utilize sensors. There is not even a single approach on the type of sensors that are used by UGVs. Borenstein [1] states that due to the fact that there is no truly elegant solution to the positioning problem, developers of mobile robots usually combine two methods for position measurements. For example, a vision system is rarely used alone for navigation; it is usually used in combination with laser rangefinders and/or ultrasonic sensors for distance measurements. UGV sensor selection depends heavily on the application and the

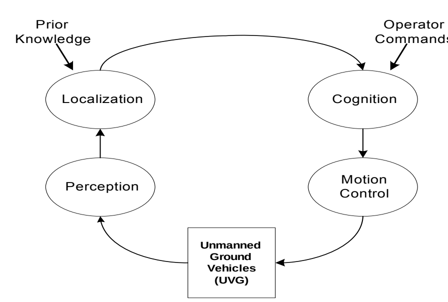


**Figure 1 Navigation Control Loop**

working environment of the robot.

We have not tested most of the systems and techniques, so the results and conclusions presented in this paper are derived from the literature. This survey is focused only on literature relating directly to UGVs. The field of mobile robot navigation is active and vibrant. The technology changes constantly and new ideas and solutions are developed continuously. Not all technologies and solutions are addressed in this paper, and many more approaches and examples can be found in the literature. This paper does not attempt to make any comparisons or judgments regarding the performance and functionality of the technologies and solutions that are presented.

The following section reviews some of the classic localization techniques used by UGVs. The next section classifies sensor technologies into categories. Finally, the last section describes and classifies sensors based on their functionality.

# 2. Review of Localization Techniques

Localization can be classified into two major categories: relative localization, and absolute localization. Each category uses different techniques and sensors to achieve localization.

## 2.1. Relative Localization (Local Localization)

Relative (local) localization works by evaluating the position and orientation using information provided by various onboard sensors. Examples of relative localization sensors are: encoders, gyroscopes, accelerometers, etc. Relative localization can be accomplished by two methods: odometry and inertial navigation.

### 2.1.1. Odometry

Odometry is the study of position estimation during wheeled vehicle navigation. Odometry is used to estimate (not determine) their position relative to a starting location. Odometry uses encoders to measure the distance traveled by each wheel. It uses the robot kinematics to evaluate the translation and rotation of the robot frame relative to the world frame. To estimate an absolute position, it integrates the relative translation and orientation between two encoder readings. Odometry performance is a function of the vehicle's kinematics.

Odometry is the use of data from the rotation of wheels or tracks to estimate change in position over time. Odometry is the most widely used navigation method for mobile robot positioning; it provides good short-term accuracy, is inexpensive, and allows very high sampling rates [1]. Its draw back is that it accumulates errors over time due to the fact that the fundamental idea behind odometry is the integration of incremental motion information over time. More specifically, large lateral position errors are caused by orientation errors as the robot travels. Despite these limitations, most researchers agree that odometry is an important part of a robot navigation system and that navigation tasks will be simplified if accuracy in odometry can be improved. Several methods have been proposed for fusing odometry data with absolute position measurements to obtain better positioning. Specific information on these methods can be found in [4], [5], and [6]. Rapid and accurate data collection, equipment calibration, and processing are required in most cases for odometry to be used effectively.

The equations of odometry are very simple and they can be found in [7]. These equations only hold true when wheel revolutions can be translated accurately into linear displacement relative to the floor. Problems can occur when wheel rotations do not translate proportionally into linear motion because of wheel slippage and/or some other more subtle causes. An important procedure in odometry is the measurement of odometry errors. A method that does this is the *University of Michigan Benchmark* (UMBmark) [8].

Errors in odometry can be classified into two categories: systematic errors and nonsystematic errors. Systematic errors are important because they lead to additive errors. On regular terrain, they are more important than non-systematic errors because they depend on the robot and/or sensors characteristics. Systematic errors occur when the robot has different wheel diameters, the mean wheel diameter is different from the nominal, the wheels are not aligned, and/or due to the fact that the encoder has a finite resolution and sampling time. Non-systematic errors are more important on irregular terrains. These errors take place if the motion is on irregular surfaces, is over unexpected obstacles, and/or if there is wheel slippage.

### 2.1.2. Inertial Navigation

Inertial navigation is when localization is done through the robot's motion state evaluation (velocities and accelerations). Inertial navigation uses gyroscopes and accelerometers to measure the rate of rotation and acceleration, respectively. Measurements are integrated to yield position. Inertial navigation systems have the advantage that they are self-contained, that is, they don't need external references. However, inertial sensor data drift with time because of the need to integrate rate data to yield position. Inertial sensors are thus mostly unsuitable for accurate positioning over an extended period of time.

## 2.2. Absolute Localization

Obtaining the absolute position is done using beacons, landmarks or satellite-based signals (e.g. GPS). Absolute localization can be achieved by any of the following techniques: active beacons navigation, landmark navigation, or model matching.

### 2.2.1. Active and Passive Beacons

Active and passive beacon navigation systems are the most common navigation techniques used by mobile robot systems. This method computes absolute location by measuring the direction of incidence or the distance to three or more beacons. Beacon localization can be accomplished reliably and provide accurate positioning information with minimal processing. Advantages of this approach are that it allows high sampling rates, and that it yields high reliability. A major disadvantage is that it has a high initial installation cost and maintenance. Two popular methods of beacon systems are trilateration and triangulation. Beacon localization has faced many difficulties when indoors and it is usually avoided.

Trilateration is the determination of a vehicle's position based on distance measurements to known beacon sources [1]. Using time-of-flight information, the system computes the distance between the stationary transmitters and the onboard receiver. An example of trilateration is the global positioning system (GPS). Trilateration can be configured by placing three or more transmitters mounted at known locations in the environment and one receiver onboard the robot. Or it can be configured by placing one transmitter onboard and receivers mounted in the environment.

In triangulation there are three or more beacons mounted at known locations. A rotating sensor on board the robot registers the three angles at which it “sees” the transmitter beacons relative to the vehicle's longitudinal axis [1]. From these three measurements the unknown x- and y- coordinates and the unknown vehicle orientation can be computed. One problem with this configuration is that in order to be seen at distances of greater than 20 meters or more, for instance, the beacons must be focused within a cone-shaped propagation pattern. As a result, beacons are not visible in many areas. This is a big problem because at least three beacons must be visible for triangulation.

### 2.2.2. Landmark Navigation

Landmarks are specific environment features that a robot can recognize with its sensors. Landmarks have a fixed shape and size (e.g. rectangles, circles, letters, bar codes, etc), as well as a fixed and known position, relative to which a robot can localize itself. Landmarks are carefully chosen to be easy to identify; for example, they must be easily distinguished from the background. The main task of the robot is to recognize the landmarks and then calculate its position relative to the landmarks. Landmarks can be classified as artificial or natural. Detection of artificial landmarks is much easier than natural landmarks [10]. The sensor of choice for this task is computer vision.

### 2.2.3. Map Matching Positioning

Before the process starts, a global map of the environment is stored in the robot’s memory. The pre-stored map can be a CAD model of the environment, or it can be constructed from prior sensor data [1]. Then, as the robot moves around the environment, it generates local maps using its sensors. These maps are compared with the global map, stored in memory, and if a match is found, then the robot can compute its actual position. Map-based positioning is normally used in indoor mobile robots in cases when the environment is static. This method is advantageous because it uses the naturally occurring structure of typical indoor environments to derive position information without modifying the environment.

### 2.2.4. Time of Flight (TOF) Active Ranging

Active ranging sensors continue to be the most popular sensors in mobile robotics [2]. They are primarily used for object detection and collision avoidance, but they are also used for localization. Many of today's range sensors use the *time-of-flight* (TOF) method. The measured pulses typically come from an ultrasonic, RF, or optical energy source. Therefore, the relevant parameters involved in range calculation are the speed of sound in air, and the speed of light. Using elementary physics and geometry, distance can be determined easily. The measured time is representative of traveling twice the separation distance (i.e., out and back) and must be reduced by half to result in actual range to the target [11].

The advantages of TOF systems arise from the direct nature of their straight-line active sensing. The returned signal follows essentially the same path back to a receiver located coaxially with or in close proximity to the transmitter. In fact, it is possible in some cases for the transmitting and receiving transducers to be the same device. The absolute range to an observed point is directly available as output with no complicated analysis required, and the technique is not based on any assumptions concerning the planar properties or orientation of the target surface. Furthermore, TOF sensors maintain range accuracy in a linear fashion as long as reliable echo detection is sustained, while triangulation schemes suffer diminishing accuracy as distance to the target increases [11].

In summary, this method measures the distance from the observer to a target. Some devices use active methods to measure (such as sonar, laser, or radar), while others measure distance using trigonometry.

Potential errors for TOF systems include the following: variations in the speed of propagation, particularly in the case of acoustical systems; uncertainties in determining the exact time of arrival of the reflected pulse; inaccuracies in the timing circuitry used to measure the round-trip time of flight; and interaction of the incident wave with the target surface [11].

### 2.2.5. Vision Based Sensors

Computer vision is the study and application of methods which allow computers to extract meaningful information from images. When an image is recorded through a camera, a 3 dimensional scene is projected onto a 2 dimensional plane (the film or a light sensitive photo sensitive array). Using stereo imaging or triangulation methods, vision can become a powerful tool for robot localization. Techniques used for visual range sensors are depth from focus and stereo vision (triangulation).

# 3. Classification of Sensors

Sensor systems for UGVs are usually relatively small, lightweight, and inexpensive. Automated Guided Vehicles (AGVs) are not considered in this paper. AGVs use magnetic tape, buried guide wires, or painted stripes on the ground for guidance. These vehicles are thus not freely programmable and they cannot alter their path in response to external sensory input [1].

As mentioned is the introduction (Section 1), a combination of sensor readings are typically used by UGVs for localization. Some major advantages of multiple sensor synthesis are:

- Redundancy: Redundant information is provided from a group of sensors or by a single sensor over time when each sensor observes (possibly with different reliability) the same features of interest
- Complementarity: Complementary information from multiple sensors allows for the perception of features that are impossible to be observed using just the information from individual sensors operating separately. An example of this is using a camera to detect obstacles and a laser range finder to detect their distance.
- Timeliness: More timely information may be provided by multiple sensors due to the actual speed of operation of each sensor, or to the processing parallelism that is possible to be achieved as part of the integration process.
- Cost: Integrating many sensors into one system can often use many inexpensive devices to provide data that is of the same or even superior quality to data from a much more expensive and less robust device.

A UGV has to perceive, analyze and interpret the state of its surroundings. Measurements in a real world environment are dynamically changing and error prone. Sensor reading errors can be caused by changing illuminations, specular reflections, light or sound absorbing surfaces, and/or the cross-sensitivity of the robot sensor to robot position and robot-environment dynamics.

Sensors can be classified into two categories according to their purpose: *proprioceptive* and *exteroceptive*. Proprioceptive sensors measure the internal values of the robot (e.g. motor speed, wheel load, heading of the robot, battery status, etc). Exteroceptive sensors gather information from the environment surrounding the robot. Examples include distance measurements and light intensity. Exteroceptive sensor measurements are used by robots to extract meaningful environmental features [2].There are two types of sensors that are used by robots: *active* and *passive* sensors. Passive sensors measure ambient environment energy entering the sensor. Examples include CCD and CMOS cameras. Active sensors emit energy and then measure the energy reflected back from the environment. One of the major problems of active sensors is the interference between its signal and the environment. For example, signals emitted by other nearby robots, or similar sensors on the same robot, may influence the resulting measurements. Examples include laser rangefinders and ultrasonic sensors [2]. A good sensor must be sensitive to what it measures, at the same time, it should be insensitive of the environment surrounding it and it should never influence the environment [9].

# 4. Review of Sensors

In this section we will review some of the sensors and application techniques used in UGV localization and navigation.

## 4.1. Wheel / Motor Sensors

An encoder is a rotary device that outputs digital pulses in response to incremental angular motion. Encoders have many uses in positioning applications. Wheel encoders, for example, measure the position or speed of the wheels. Wheel movements can be integrated to get an estimate of the robot's position. They are very inexpensive and thus they are used on most wheeled robots. There are many types of encoders including optical, magnetic, inductive, and capacitive encoders. The most commonly used and most reliable is the optical encoder. Encoders are proprioceptive heading sensors. They can be either active or passive. Their draw back is that they require significant corrections from other sensors, such as heading sensors (described in Section 4.2), in order to be used for localization.

## 4.2. Heading Sensors

### 4.2.1. Compasses

A compass is a valuable sensor for UGVs because it provides a measure of absolute heading. Heading is the most significant of the navigation parameters (x, y, and θ) in terms of its influence on accumulated dead-reckoning errors.

Using these sensors for indoor mobile applications is sometimes impossible because the earth's magnetic field is often distorted near power lines and steel structures. There are many different types of compasses: mechanical magnetic, fluxgate, hall-effect, magnetoresistive, and magnetoelastic compasses. The compass most commonly used in mobile robotics applications is the fluxgate compass. Compasses are passive exteroceptive heading sensors.

### 4.2.2. Gyroscopes

A gyroscope is a device for measuring or maintaining orientation, based on the principle of conservation of angular momentum. The essence of the device is a spinning wheel on an axle. The device, once spinning, tends to resist changes to its orientation due to the angular momentum of the wheel [9]. This is the definition of the classical gyroscope, also known as spinning mass gyroscope. The most popular gyroscopes used in mobile robots are the optical gyroscopes and the mechanical gyroscopes.

Gyroscopes are of particular importance to positioning of mobile robots because they can help compensate for the foremost weakness of odometry. They can be used to correct the orientation errors before they accumulate. The accuracy and the low prices of laser gyroscopes have made them a very good solution for UGVs. Gyroscopes are passive proprioceptive heading sensors.

### 4.2.3. Inclinometers

An inclinometer is an instrument for measuring angles of elevation or inclination. An inclinometer is an instrument used for measuring angles of slope (or tilt), elevation or inclination of an object with respect to gravity. Inclinometers are exteroceptive heading sensors that can be either active or passive sensors.

## 4.3. Global Positioning System (GPS)

GPS is a beacon-based localization system based on satellites. A constellation of twenty four (plus three spare ones) GPS satellites transmit encoded RF signals to GPS receivers. Using advanced trilateration methods, GPS receivers can compute their position by measuring the travel time of the satellites' RF signals, which include information about the satellites' momentary location. Knowing the exact distance from the ground receiver to three satellites allows for calculation of the receiver's latitude, longitude, and altitude anywhere on Earth. GPS sensors are not used for indoor applications because the receiver reception is limited inside buildings. Recent commercial GPS receivers allow position calculations down to a couple of meters or less. GPS has become one of the most important localization sensors for outdoor mobile robots. GPS is an active exteroceptive sensor.

## 4.4. Active Ranging Sensors

### 4.4.1. Ultrasonic sensor

Ultrasonic sensors work by sending packets of (ultrasonic) pressure waves toward the object and measuring how long it takes for the pulse to bounce off the target and return to the sender. The distance of the echoing object can be calculated based on the propagation speed of sound and the time of flight (as explained in Section 2.2.4). The generation of sound wave is done by piezo or electrostatic transducers. The sound beam propagates in a cone like manner with opening angles around 20 to 40 degrees. Ultrasonic sensors do not work efficiently when there are soft surfaces in the environment that absorb most of the sound energy or when the surfaces are not perpendicular to the direction of the sound (specular reflection) [2]. Ultrasonic sensors are active exteroceptive time of flight sensors.

### 4.4.2. Laser Range Sensors

A laser range-finder is a device that uses a laser beam in order to determine the distance to an opaque object. It works by sending a laser pulse in a narrow beam toward the object and measuring how long it takes for the pulse to bounce off the target and return to the sender. The distance of the reflecting object can be calculated based on the propagation speed of light and the time of flight (as explained in Section 2.2.4). The accuracy of a laser range-finder is determined by the shortness of the laser pulse and the speed of the receiver. A laser range-finder that uses very short (sharp) laser pulses and has a very fast detector can range an object to within a few centimeters [9].

Despite the beam being narrow, it eventually spreads over long distances due to the divergence of the laser beam. Some of the laser light might reflect off other objects which are closer than the object being detected, giving an early return and a reading which is not correct. Laser range sensors are active exteroceptive time of flight sensors.

### 4.4.3. Triangulation

Triangulation is the process of finding a distance to a point by calculating the length of one side of a triangle, given measurements of angles and sides of the triangle formed by that point and two other reference points. Optical triangulation-systems are widely used mobile robotics applications. These systems involve some type of scanning mechanism operating in conjunction with fixed-location references strategically placed at predefined locations within the operating environment. Given a point on a visible surface in the world, two optical systems determine the angles $\alpha_1$ and $\alpha_2$ formed by the projection rays that connect the surface point with the centers of projection of the two optical systems. Together with the baseline, these two angles determine the shape of the triangle completely, and simple trigonometry yields the distance to the surface point.

There are two main classes of triangulation systems: passive and active. In passive systems, two cameras are used (stereo vision) [12]. These systems require solving the so-called correspondence problem, which amounts to determining which pairs of points in two images are projections of the same point in the world. This is a very computationally expensive problem. In addition, due to the geometry of triangulation systems, the resolution drops drastically as objects move away from the camera.

Active systems employ one camera and one structured light emitter [13]. The structured light system may be any form of light with a known pattern. In order to apply triangulation, the projected light pattern needs to be well differentiated from the other objects and ambient light falling on the scene. This requires that the projected light be high powered and well focused. In many cases, it also requires scanning the light through the scene, which makes it difficult to obtain high frame rates.

There are two methods of triangulation-based active ranging: optical triangulation (1D sensor) and structured light (2D sensor). In optical triangulation (1D sensor) the receiver measures the position of the reflection along a single axis. A beam (e.g. LED) is transmitted towards the target. The reflected light is collected by a lens and projected onto a position-sensitive device (PSD) or linear camera. Using basic trigonometry, the distance to the object is calculated. These type of sensors are used for distances up to maybe 2 meters. They are thus used in combination with other sensors to calculate the absolute position of a mobile robot within an already defined world.

In structured light (2D sensor) the receiver measures the position of the reflection along two orthogonal axes. A 2D receiver, such as a CCD or CMOS camera, is used to capture and calculate the the distance to a large set of points.

## 5. Conclusion

This paper presented an overview of existing sensors and techniques for mobile robot positioning. For outdoor navigation, GPS is becoming the localization standard for almost all automated vehicle systems.

Unfortunately, an indoor equivalent to GPS is difficult to realize because none of the currently existing RF-based trilateration systems work reliably indoors. For indoor applications, no standard solution appears to exist when it comes to robot localization. Solutions for indoor application tend to be application dependent.

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