Localization of Autonomous Mobile Ground Vehicles in a Sterile Environment: A Survey

Aidan F. Browne, David Vutetakis
The University of North Carolina at Charlotte

Abstract

A capstone design project required students to implement a localization system for a rover to operate in a sterile planetary environment. Localization is the methodology of determining a vehicle's position and orientation within its environment, which is necessary for navigation and obstacle avoidance. A sterile environment has no pre-existing useful technology to aid in localization. Thus, effective methodologies would be limited to on-board sensors or beacon based systems. Such environments may include factory logistics, construction sites, planetary exploration, search and rescue, and human or equipment transportation. In order to communicate the angles or distances for calculating position, many systems employ the use of lasers due to their ability to transmit at high speeds and frequencies coherently over long ranges, allowing resolution of position and orientation. This survey reviews current localization techniques that were explored in the process of design selection.

Keywords

Localization, triangulation, trilateration, robot, laser

Introduction

Undergraduate university students, as part of their capstone design project, were tasked with development of an autonomous planetary rover. The rover's intended operational environment was to be sterile in nature, meaning there were no pre-existing stimuli from which the vehicle could determine its location. This created the need for an effective localization system.

Localization is the methodology of determining a vehicle's relative or absolute position and orientation within its environment[1]. With this perception, path planning and map building can be achieved for the purpose of navigation and obstacle avoidance[1]. The accuracy of a navigation system is limited initially by the accuracy of the localization system design.

Localization technology is a rapidly increasing field as its applications are realized and expanded[2-5]. GPS systems have made this technology commonplace in todays developed societies, being portable enough to fit in a cell phone[6]. However, GPS has a variety of technological limitations, primarily regarding its operational effectiveness in remote or shielded locations [7]. Without proper reception, GPS is rendered ineffective.

A sterile environment can be described as any location where there is no pre-existing useful technology such as GPS or Wi-Fi that could be utilized to aid in localization or navigation. In these types of environments, effective methodologies would be limited to on board sensors or beacon based systems placed in or around the area of navigation to provide reference points or to convey to the vehicle any information necessary to resolve location and orientation.

Example localization applications that may take place in a sterile environment include factory automation, planetary exploration[8], search and rescue, and human or equipment transportation. For these roles, it is imperative that localization be reliable, robust and accurate when errors could result in human injury or high monetary loss.

In order to communicate the angles or distances vital to calculating position, many systems employ the use of various laser based technologies due to their ability to transmit at high speeds and frequencies coherently over long ranges[4, 7, 9-18]. Subsequently, triangulation, trilateration or a combination of both can then be applied to resolve both position and orientation.

This survey encompasses relevant localization techniques for sterile environments as well as current research towards future technologies. Its key focus regarding the evaluation of current techniques covers their concept of operation, any history of use, effectiveness and limitations. With this information, the design team could them make an informed decision regarding the ideal localization technique to pursue.

Localization Fundamentals

Localization relies on gaining information regarding vehicular heading and location in multiple coordinate planes with respect to some origin[1]. Two categories can be derived from this process; angulation and lateration[2]. Angulation involves measuring the angles from known reference points to an unknown point and using those angles to resolve the distance to the unknown point using trigonometric relationships, called angle of arrival (AOA)[2]. Instead of angles, lateration measures the distances from multiple reference points for positioning[2]. This typically involves time of flight (ToF) or time of arrival (TOA) measurements, but may also be accomplished by measuring the time difference of arrival (TDOA) of multiple signals to resolve location, or received signal strength (RSS)[2].

Many variations of localization systems presently exist using a variety of differing methodologies[1, 2, 19]. The fundamental categories include the use of varying forms either electromagnetic or ultrasonic energy[1]. However, sound waves require a transmission medium, which may or may not exist in certain sterile environments such as planets with no atmosphere, therefore ultrasonic based techniques were dismissed up front.

The electromagnetic spectrum consists of many useful methods of angle or distance communication such as visible light or lasers[1], which will be the main focus of this survey. One of the obvious advantages obtained through harnessing this type of energy is in its speed of transmission.

Each methodology has certain advantages that may make them more suitable for one application over another. For example, vision systems possess versatility through the ability to perceive shapes, colors, or patterns, but are sensitive to luminance and may have difficulty acquiring geometric information without specific controlled conditions[20].

Laser

Lasers have the advantage of being able to transmit a focused coherent beam on a single point or coordinate plane close to instantaneously. Vital information needed to resolve position can either be transmitted to the robot from an external source, or the robot can gather information about its surroundings by emitting light beams and analyzing information reflected back from its surroundings, or by communicating with external beacons. A variety of different techniques make use of lasers, which are explored in this section.

A popular technique that is utilized by many authors is laser scanning[1, 4, 7, 12-14, 16, 17, 20-22]. In this technique, a laser emits rapid pulses that are usually reflected off a rotating mirror[1]. The time of flight is measured and used to calculate distances[1]. This is performed at high rates, obtaining dense point by point distance measurements of the environment for the purpose of map building[1, 13]. This can either be compared to a priori knowledge, if available, or to acquire new perception[19].

Laser scanners are often combined with other technologies to reduce errors. Laser scanners combined with inertial navigation systems are currently explored for GPS denied locations by researchers[7]. Lines can be used as reference features in man-made environments for the purpose of navigation[12]. However, not all environments have such easily distinguishable features, increasing difficulty.

Laser scanner trilateration is often used in industrial settings in combination with landmarks[23]. This becomes problematic if a landmark becomes obstructed in a dense environment. An alternative is to use native landmark recognition, which are facilitated more efficiently with camera systems[23].

A solution for environments lacking landmarks combines laser scanners with other sensing devices like magnetic sensors for determining direction [4]. Significant errors can occur if the field is disrupted though. Odometry of the wheels can be used, but is ineffective if wheel slippage occurs[4]. Gyroscopes or accelerometers can be used to improve accuracy[24, 25].

Corbellini, et al. developed a novel approach which uses four laser receivers on the vehicle and a reference laser receiver fixed to the ground in the localization area[15]. A rotating laser beam then communicates the necessary angular information by measuring the time intervals between these receivers. Experimental results yielded an effective range of up to 0.5 kilometers with 1 meter accuracy.

Some authors make use of novel approaches to localization involving beacon systems. Capitaine, et al. use a single rotating beacon system that communicates the necessary angles for localization to the robot through laser modulation[26]. This provides a low complexity and low cost solution, but some limitations include the speed of rotation and limited operating distance. Other authors also developed beacon based systems[27-29].

Camera

Camera based localization technology has recently become more practical with developments in processing speed and capability[19]. These technologies use the Angle of Arrival (AoA) principle in order to accomplish triangulation, but may also be supported by supplementary sensors, such as range finders or odometry[19]. Camera receivers can either utilize active or passive illumination of the landscape for reference[19]. Sometimes coded targets are placed in static locations in the environment to simplify reference points[19]. Sometimes these reference points are projected rather than placed in the environment[19]. This is a limitation for dense or otherwise restricted locations.

Optical positioning systems use a variety of techniques to obtain relative pose, but all require a reference for successful localization in the global environment. Mautz, et al. efficiently categorize vision based localization into distinct genres that are useful for this survey, including a priori image comparison, acquired image comparison, coded target reference, projected target reference, and external sensor reference[19].

Monocular vision systems use a single camera for sequential image comparison of the scene under movement to obtain depth information[19, 30, 31]. This is sometimes referred to as synthetic stereo vision, but the baseline distance between two images can only be obtained through external measurement and introduced a source of error[19]. Images are analyzed taken by a single camera at different locations[31]. One way to do this is to use edge detection in the scene, which is effective, but causes errors when complex textures or illumination are not controlled[30]. One way around this is to use color detection, but complex textures still pose a problem[30]. This method is therefore not ideal for complex or dynamic environments.

Monocular vision may use feature tracking[32]. In a simplistic environment, this method can be quite effective. However, the more complicated the environment becomes, the processing quantity and time requirements increase[32]. This can be remedied by adding unique features to an environment that may be projected by the robot, or physically located within the area of interest[19]. Using one camera requires the vehicle to be in motion to be able to generate new location data, and also require supplementary sensors to track movement distance. Sometimes IMU devices are used to track changes, but accurate units can be very costly[33]. Real time performance can also become an issue[34]. Vision also doesn't provide and direct distance information, it must be inferred or calculated[31].

Because of the problems with monocular vision, two cameras are usually employed; a technique called stereo vision. The predetermined baseline distance between two cameras remains constant, providing a more robust system[19, 23, 31]. Depth can be perceived in this method by comparing points between two stereoscopic images, or by using the structured light method to create points for comparison [19]. One of the more notable applications of the stereo camera technique is NASA's Mars Exploration Rovers (MER)[9]. This system was combined with an inertial measurement unit (IMU) and wheel odometry to compute the rovers pose with 6-DOF and errors often less than 2.5%[9]. The necessity for distance between the two cameras can sometimes be problematic if space or placement is restricted[31] and image data is also very processing intensive[11].

Time-of-flight (ToF) cameras differ from monocular or stereo cameras as they rely on distance measurements instead of angular measurements[35]. These cameras combine either pulsed or continuous wave modulated lasers, measuring the time taken for the light to return to the receiver to calculate distance[35]. ToF cameras are similar to laser scanners, only they operate at a much faster rate. Instead of analyzing distances point by point, all of the distances in a scene can be captured in a single frame[31]. Although laser scanners can provide detailed range measurements, they lack any further information of the environment such as texture, color or intensity. ToF cameras are advantageous because they combine the aspects of range scanners as well as 3D information obtained through cameras at the same time[31]. Each pixel registers all of this information about the current scene simultaneously[31]. Because of this, Hussmann, et al. suggest that ToF camera systems are advantageous over laser range finder based systems[31]

Odometry

Odometry is the measurement of only relative positional changes[1]. When focusing on ground-based vehicles, this is often accomplished through measurement of wheel rotation using optical encoders on the wheel shafts[25]. This technique is fairly effective on flat man-made surfaces, but on unstructured surfaces wheel slippage can cause large errors[4]. Error compounding is the main problem with odometry, making it suitable for complementary measurements, but not as a stand-alone system[24]. Other internal sensors such as accelerometers or gyroscopes can be added to assist in tracking positional changes and reduce error[25].

Conclusions

Localization systems are continually being researched and developed to produce more accurate results in real time. Every system has certain advantages and disadvantages, therefore choosing a technique to research or employ depends on the nature of the application. In order for a researcher to make this assessment, it requires a working understanding of current techniques regarding their advantages and disadvantages. This survey has outlined that knowledge as needed by a capstone design team to design a rover for autonomous operation in a sterile environment.

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Aidan F. Browne

Dr. Browne is an Assistant Professor at The University of North Carolina at Charlotte. His current research areas are mechatronics, mission critical operations, instrumentation and controls. His core courses are an undergraduate three-semester embedded controller practicum and a graduate mechatronics course. He mentors a Senior Design team that competes in the NASA Robotic Mining Competition. He received his B.S. from Vanderbilt University and his M.S. and Ph.D. in Biomedical Engineering from the University of Connecticut. Dr. Browne serves as the Chair of the Engineering Technology Division of the Southeastern Section of ASEE; he also does extensive volunteer work for the FIRST Foundation.

David Vutetakis

Mr. Vutetakis is a graduate student at The University of North Carolina at Charlotte. He is currently pursuing a Master of Science degree in the Applied Energy and Electromechanical Systems program. He received his B.S. in Electrical Engineering Technology from UNC Charlotte. His areas of interest are robotics and electromechanical systems. He is also a graduate research assistant at The University of North Carolina at Charlotte in areas such as mission critical operations and mechatronics.