Obstacle Avoidance using Range Data in Autonomous Navigation of Mobile Robot

Ming Yang    Hong Wang    Kezhong He    Bo Zhang
The State Key Laboratory of Intelligent Technology and Systems
Tsinghua University, 100084, Beijing, China
Phone (010) 6278 3191    E-mail: ym@s1000e.cs.tsinghua.edu.cn

Abstract - This paper describes the use of laser radars in autonomous navigation of a mobile robot. Merits and demerits of several kinds of laser radars are discussed first along with the principle of each laser radar’s operation. Then the Laser Measurement System (LMS) made by SICK is introduced, and its technical data is provided. The time-varying potential field algorithm is presented which is used to avoid obstacles. This algorithm is applied to data collected from the LMS. Example data will be shown. Some problems that are specific to this class of sensors are then described. These problems can significantly impact the quality of the range data and limit the use of the LMS. The LMS has been successfully tested on an outdoor mobile robot – the Tsinghua Mobile Robot V (THMR-V).

I. INTRODUCTION

Sensing capabilities are a key technology for the success of a mobile robot. Data about the robot’s surroundings is used to navigate, avoid obstacles, and perform task specific functions. Sensors acquiring such data need large fields of view (FOV) to encompass the entire workspace, high scan rates to provide fresh, timely data, and the ability to function while mounted on mobile robots.

The classical computer vision approach to range sensing is to use passive techniques such as stereovision. However, those techniques are not yet sufficiently fast or reliable to be used in many applications, most notably real-time mobile robots. Active sensors, which generate the illumination instead of using only the ambient illumination, have received increasing attention as a viable alternative to passive sensors.

Unlike passive visual-based techniques, active sensors are not usually impaired by shadows, surface markings, or ambient light (or sound) sources. Furthermore, the transmitter and receiver in active systems are essentially coaxial which eliminates the “missing pieces” problem that structured light and stereo methods suffer from.

In recent years there has been a growing number of applications of laser radars in navigation systems of mobile robots. The tendency stems from useful characteristics of the laser-based distance measurement technology, particularly from its relatively high accuracy and high resolution. By way of scanning a laser beam or a laser plane in two or three dimensions, state-of-the-art radars are able to deliver huge amounts of fairly accurate data at relatively high frequencies. The laser radars have been proposed as a better compromise among accuracy resolution and speed requirements than any other range sensors, especially in the context of mobile robotics.

II. COMPARISONS OF LASER RADARS

A. Principle of Laser Radar Operation

The basic principle of laser radar is to measure the time between transmitting a laser beam and receiving its reflection from a target surface. Three different techniques can be employed to measure the time of flight, which is proportional to the range.

- TOF, which measures the time of flight (TOF) of a discrete pulse;
- AMCW, which measures the time of flight indirectly by measuring the shift in phase between an amplitude-modulated continuous-wave (AMCW) emitted beam and its reflection;
FMCW, which measures the time of flight indirectly by measuring the beat frequency of a frequency-modulated continuous-wave (FMCW) emitted beam and its reflection.

Among the three methods described above, FMCW is seldom used in laser radars because of its high requirement to the laser diode. Therefore, we will discuss in detail only the more widely used TOF and AMCW laser radars.

**B. TOF vs. AMCW**

Compared with TOF laser radars, AMCW laser radars have better accuracy because they apply beat frequency to measure the shift in phase. This technology is very useful in measuring exceedingly small time of flight, while TOF has difficulty in this situation. However, there are two main problems due to fundamental limitations of AMCW laser radars.

The first problem is “ambiguity interval”. For AMCW laser radars, the range to target is proportional to the shift in phase as following,

\[ r \ \frac{?}{4?} \]

where \( ? \) is the wavelength of the modulation. Since the phase is defined modulo \( 2? \), the range is defined modulo \( \frac{?}{2} \), which is called the ambiguity interval. Therefore, an inherent limitation of this principle of operation is that it cannot measure range uniquely, i.e., it measures range only within an ambiguity interval. In practice, it is not possible to distinguish between range \( r \) and \( r \ \frac{?}{2} \) without employing external constraints, or two beams with different modulation frequencies. Therefore, the maximal range of AMCW laser radars is limited by the wavelength of the modulation.

The second problem is caused by “mixed pixel”. Mixed pixels are those that receive reflected beams from two surfaces separated by a large distance. Mixed pixels can result in reported ranges that are on neither surface, but somewhere between the two ranges, or even worse, either behind or in front of both surfaces. This is an inherent problem with AMCW laser radars and cannot be completely eliminated.

Besides these problems, AMCW laser radars are also slower than TOF in time measurement due to the phase measurement by beam frequency. They are also more sensitive to the temperature of the surroundings and the reflectivity of target surfaces.

In most autonomous navigation, the interest region is between 20m and 150m in front of the mobile robot. Therefore compared with the interesting range, the accuracy of range data is not very important, a range resolution of 10cm is enough. On the other hand, the maximal range of laser radars is important. TOF are more suitable than AMCW in this aspect.

**C. 2D Laser radar vs. 3D Laser Radar**

Unlike 2D laser radars, data returned from 3D laser radars is fully three-dimensional, so structural, CAD, or solid models can be built from the raw data with post processing. However, 3D laser radars have some problems in practice.

Typically, 3D data is gathered by two mechanically controlled mirrors, which raster-scan the beam across a scene, measuring the range at regularly sampled points. This brings up mechanical problems. For example, elevation angles for the same point in space can vary even more if downswing elevation angles are compared to upswing elevation angles because of backlash, or slop, on the vertical pivot gear for the mirror.

Another problem is the data acquisition time. Because more data are collected from 3D laser radars than 2D ones, more acquisition time is needed for 3D laser radars. Typically, the acquisition time of 3D laser radars is more than 200 ms while 2D laser radars can acquire the range data in less than 20 ms. In autonomous navigation, data acquisition time is limited by real-time requirements. Thus, 2D laser radars are more suitable here than 3D laser radars.

Furthermore, in most navigation applications, a system needs only to know the location of the target. The shapes of targets don’t contribute much to navigation. Therefore, 2D laser radars are enough for navigation.

**D. Conclusion**

Through the comparisons above, we can draw the conclusion that 2D TOF laser radars are more appreciated than other laser radars in autonomous navigation. In general, 3D AMCW laser radars are suitable for static modeling while 2D TOF lasers are suitable for real-time autonomous navigation. The laser radar described in this paper is the LMS 220-30103 made by SICK Optical Electronics Company of Germany. Details about this radar are provided in the next section.
III. THE LMS LASER RADAR

In this section we address the LMS laser radar, covering both its principles and practical characteristics.

The LMS 220 is a pulsed time-of-flight radar system with a maximal range of 50m, a range resolution of 50mm, an angular resolution of 0.5 degree, respondent time of 40ms, and a maximum pixel rate of 13.9 kHz. The scanner mechanism provides a 180° horizontal field of view. Active fog correction is built into the sensor. Rain and snowfall interference is cut out using pixel-oriented evaluation. The LMS 220’s enclosure rating is IP65 and IP67, which make the LMS capable of operating outdoors. The LMS is safe enough, having laser protection class I.

The LMS 220 operates by measuring the time of flight of laser light pulses. The time between emission and reception of a light pulse, after it has been reflected from a surface, is directly proportional to the distance between the light source and the object. The pulsed laser beam is deflected by a rotating internal mirror to provide a scan of a wide area.

As a result of the low beam divergence and the diameter of the individual spots, the spots overlap on the object to be measured. As distance from the scanner increases, the spacing between the spots expands. As the individual spot diameters also increase with increasing distance from the scanner, a gap between the individual spots is avoided.

IV. THE OBSTACLE AVOIDANCE ALGORITHM

A. the Obstacle Avoidance Problem

What is an obstacle? In its most general meaning, an obstacle is a region that a vehicle can not or should not traverse. Objects typically found in a target environment could include humans and similarly sized obstacles, vehicles of varying sizes, and a wide assortment of natural materials including rocks and dirt.

One of the essential problems in autonomous navigation of mobile robots is obstacle avoidance using range data obtained from laser radars. There is a need for fast and practical processing techniques, capable of handling massive data streams generated by laser radars in real time and in a memory-efficient manner. In this section we apply a novel approach to obstacle avoidance for a mobile robot equipped with laser radar and designed to work in partially structured environments.

B. Time-Varying Potential Field

Usually in real environments, obstacles around a mobile robot may be moving while the mobile robot is moving. Thus the environment should be regarded as time varying rather than static, and the environmental potential field is not only a function of position \((x, y, z)\), but also of time \(t\).

We use the algorithm described in [3] to calculate the dynamic potential \(U(x, y, t)\) representing the environment around the mobile robot as follows:

\[
U(x, y, t) = \sum_{i=1}^{n} \left( k_1 \frac{V_m}{d_i^2} \right) \left( k_2 \frac{V_i}{d_i^2} \right)
\]

where:
- \(V_m\) is the velocity of the mobile robot,
- \(V_i\) is the velocity of obstacle \(i\),
- \(d_i\) is the distance from mobile robot to obstacle \(i\),
- \(n\) is the number of obstacles,
- \(k_1\) and \(k_2\) are assumed to be constant coefficients.

The time-varying potential field method described above is different from the known potential field method in,

1) The velocity control of mobile robot is adapted by the environment around it. While free space becomes larger, the speed of mobile robot increases, and otherwise decreases. The moving direction of mobile robot is directly controlled by the dynamic potential, not the sum of the force.

2) The point information from the laser radar is regarded as a point obstacle or a point free space in this method. The shapes of obstacles and free space are not concerned in this method.

C. the Control Scheme

We can define the left-side and right-side dynamic potentials of a mobile robot using (2) as follows:

\[
\begin{align*}
U_L(x, y, t) &= \sum_{i=1}^{n} \frac{n^p k_1}{d_i^2} \frac{k_2 V_m}{d_i^2} \frac{\nabla U(x, y, t)}{d_i^2} \\
U_R(x, y, t) &= \sum_{i=1}^{n} \frac{n^p k_1}{d_i^2} \frac{k_2 V_m}{d_i^2} \frac{\nabla U(x, y, t)}{d_i^2}
\end{align*}
\]
Then we can compute the velocity of the mobile robot, which is adaptively controlled by calculating the dynamic potential using (3).

\[ V^2 = U_{\text{max}}^2 + U_{\text{min}}^2 + \frac{U_{\text{max}}^2}{d_{\text{min}}} \]

\[ \theta^2 = \frac{U_{\text{max}}^2}{d_{\text{min}}} + \frac{U_{\text{max}}^2}{d_{\text{max}}} \]

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Where:

- \( Q^2 \) is the steer angle of the mobile robot at \( t \),
- \( V^2 \) is the speed of the mobile robot at \( t \),
- \( Q_{\text{max}} \) is the maximum steer angle of the mobile robot,
- \( V_{\text{max}} \) is the maximum speed of the mobile robot,
- \( d_{\text{max}} \) is the maximum range of the laser radar,
- \( d_{\text{min}} \) is the minimum distance for collision avoidance,
- \( k_3 \) and \( k_4 \) are assumed to be constant coefficients.

D. Experiments

While the algorithm described above is applicable to many obstacle avoidance systems, the implementation details are oriented toward the Tsinghua Mobile Robot V (THMR-V) project. In this project, the LMS is controlled by a MMX-200 computer. Through our experiments, we found that this algorithm is fast enough for the real-time navigation requirements.

Within 40 ms, the computer can complete the data acquisition and calculation of speed and steer angle.

In Fig. 2 and Fig. 3, the regions in black are obstacles detected by the LMS. The target marked with a circle is a moving obstacle. Using (3) and (4), we can calculate the steer angle and speed of the mobile robot at \( t \). The result of calculation is represented as an arrow in the Fig. 2 and Fig. 3.

Fig. 2 shows that the moving obstacle is on the left. From the calculation using (3), we found that the potential on the left is greater than that on the right. Therefore, the result is that the mobile robot turns to the right along the arrow shown in Fig. 2. Similarly, Fig. 3 shows that the moving obstacle is on the right, and it makes the mobile robot turn left according to (3) and (4).

V. PROBLEMS

In this section, we will focus on some problems that are specific to this class of sensors including calibration, bumping of the mobile robot, optical properties of the target’s surface and stray light.

A. Calibration

Because the LMS is two-dimensional laser radar, the result of scanning is a plane. The calibration problem of LMS is how to make this plane horizontal. This problem can be serious if calibration is ignored. For example, if there is an error in elevation, the horizontal error at 50m will be 0.87m, which results in failure to detect distant objects.
As the laser beam is near infrared, it is invisible to human eyes. Special devices are needed to calibrate the LMS. SICK provide a device called the TOPCON Level Sensor LS-70B to detect the laser beam location.

A simple way to calibrate the LMS without any special device can also be used as follows. Put two targets at different orientations to the LMS. These two targets should have the same height from the ground as the laser beam plane and the same horizontal range to the LMS. Adjust the elevation angle of the LMS until the two targets appear in the data from the LMS at the same time.

B. Bumping of the Mobile Robot

Bumping is unavoidable for a mobile robot, which significantly impacts the quality of the range data if the road is irregular. The influence is similar to the calibration problem.

One of the best solutions for this problem is to design a laser beam with a special spot shape. For example, a laser beam whose spots are long in the vertical and short in the horizontal can solve this problem. Unfortunately, it is difficult to design such a special laser beam because the laser beam is spinning during the scanning. The spot shape of the LMS is circular. Thus, this problem can only be solved through software compensation.

C. Optical Properties of Target Surfaces

Generally, the higher the reflectivity of a target surface, the longer the laser radar can measure. But for the objects like a mirror with very high reflectivity, the surface’s finish is very high, and nearly specular reflection occurs rather than diffuse reflection. In this case, these objects are hard to detect because the laser beam can seldom be reflected exactly to the small receiver.

On the other hand, some objects such as clean classes, have a reflectivity so low that the laser beam can seldom be reflected back to the receiver. But this class of objects may have a high transmissivity, so the objects behind the classes will be “seen” in the range data.

D. Stray Light

The signal received by LMS is a pulsed optical signal. For steady background light, little noise is introduced into the result if the photoelectric detector is not saturated. However, most light sources are broad band sources with unsteady intensity, which will significantly impact the quality of the range data. For example, it is obvious that the maximal range of LMS in the sun is shorter than that in the shadow. Therefore, the LMS should be covered from sunlight.

VI. CONCLUSION

In this paper, we discuss the merits and demerits of several kinds of laser radars in the autonomous navigation of a mobile robot. A time of flight laser radar – the LMS220, which is used in the THMR -V, is described in detail, and technical specifications are given. Experiments show that 2D-laser radar is sufficient for navigation of a mobile robot. An effective algorithm is present in this paper, which is simple and fast for obstacle avoidance. Some experiments are given to support this method. Some special problems – Calibration, bumping of the mobile robot, optical properties of target surfaces and stray light are also discussed in this paper. Some solutions to these problems are given.

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REFERENCES