International Journal of Natural and Engineering Sciences 10 (3): 23-27, 2016
ISSN: 1307-1149, E-ISSN: 2146-0086, www.nobel.gen.tr

Detection of Obstacle-Free Gaps for Mobile Robot Applications Using 2-D LIDAR Data

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Received: September 25, 2016
Accepted: December 20, 2016

Abstract

Mobile robotics is one of the most studied scientific and technological fields, which is still in progress. Several research interests such as path planning, point stabilization, localization, obstacle avoidance and passable gap detection are commonly studied fields. Gap detection task affects the path planning characteristics of a mobile robot. Especially under presence of limited information about robot's environment, passable gap detection is necessary for steering the mobile robot towards a goal autonomously. This paper concentrates on passable gap detection for unconstructed environments, which contain only positive obstacles. The method considers specific obstacle configurations such as presence of wall-type obstacle, maze type environments and random placed small sized obstacles. The method proposed in this study is based on reading distance of the obstacles in a certain range and detecting the borders of passable gaps. The detected gaps are re-organized depending on the priority assigned by the robot's passage order of the gaps. The proposed method not only utilizes simple derivation of the measurement data but also extracts hidden gaps in the environment. The proposed scheme assumes the mobile robot is equipped with laser range sensor (LIDAR). A real LIDAR is utilized and adapted to the developed algorithm. The algorithm is developed in Matlab.

Keywords: Gap detection, Mobile robot, 2D Range finder

INTRODUCTION

Mobile robotics is one of the most popular research areas. Mobile robots can perform various tasks by utilizing sensor fusion. The main function of sensors in mobile robotics is sensing environmental effects. Environment of a mobile robot can contain both static and dynamic obstacles in real time. In most cases, obstacle motion characteristics cannot be predicted. Sudden changes may occur around a mobile robot while navigating through a target. Therefore, a robust and safe path planning method is a crucial task. Path planning types can be divided into two main topics: local and global path planning. Immediate obstacle profile of a mobile robot is main source of local path planners. Collected information can be evaluated for monitoring, obstacle avoidance and other navigation tasks such as point stabilization, localization and velocity control. Acquiring the environmental data is the basis to enable a wheeled autonomous mobile robot to detect obstacles and avoid collision. Various schemes have been proposed for environment modelling and gap detection. Kesper et. al. used laser range finder (LIDAR) to enable a hexapod to traverse difficult terrains [1].

LIDAR sensors do not be affected by light, air conditions, heat therefore; it has a wide field of area [2]-[8]. Although laser range finder sensors supply high accuracy and reliability, they have high prices, thus, it can be unaffordable for so many applications. To tackle this problem, several methods are given in [9], [10]. Reducing the cost makes physical implementation of laser range finders easier. Acquiring data from LIDAR is possible by day, by night or in shadowed areas [11]. Thus, these sensors are commonly used in mobile robotics. LIDAR is used to detect static, dynamic and even negative obstacles [12]. In the study in [13] traversability scores are assigned to a grid-based map using 3-D LIDAR. They have focused on modelling the terrain and detection of negative obstacles. In the study in [14] an optimal gap detection algorithm has been proposed. They have focused on manipulating the robot with minimum steering angle by defining a high punishment in the cost function. Complex indoor environments can also be modelled by using laser sensors. The study in [15] proposes a technique based on digitalizing the large indoor environments.

One must consider the proposed method is feasible to the mobile vehicles located in a flat surface. Unexpected collisions may occur if the method is desired to apply on a mobile robot moving on rough terrain or a ground with holes and ditches. One of the main assumptions is only the gaps bordered with the obstacles directly seen by LIDAR, can be detected efficiently. Laser measurement plane is parallel with the surface on which the mobile robot is located. Therefore, obstacles under or over this measurement plane will not be detected by LIDAR.

The method is proposed as a basis for path planning and obstacle avoidance algorithms. Sensor data is acquired from on a real LIDAR sensor. The acquired data was processed in two steps: pre-processing and post-processing. The processed measurement data is a one-dimensional array, which keeps distance measurements of the mobile robot's current environment. Larger changes than a certain threshold in LIDAR data are assumed as the initial gaps. The initial gaps are obtained by derivation. The pre-processed gaps are then filtered by two reverse searches and the final gaps are obtained. Final gaps can be eliminated depending on physical size of the mobile robot or any custom criterion. The following sections of this paper are organized as follows: First of all, we present the proposed methodology and data processing steps. Then we present the results of the method under different scenarios. In the last section, we discuss and conclude on performance of the developed algorithm.

METHODOLOGY

This section underlines detection of passable gaps through obstacles. The obstacle detection and gap extraction procedures are based on laser range finder (LIDAR) measurements. Difference between two consecutive measurement data bigger than a certain threshold is assumed to be a gap. Several gap elimination criterions are considered to obtain the final passage. These criterions are physical size of the mobile robot, passage order and corner type of the gaps.

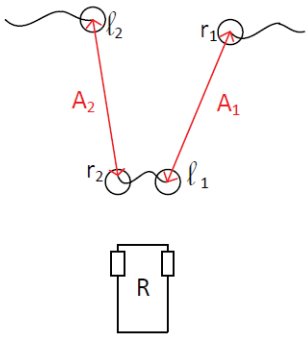

Figure 1. Illustration of the detected gaps

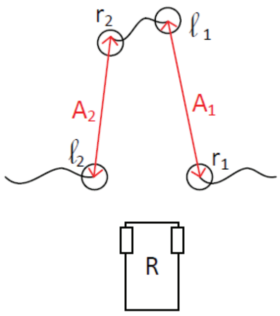

Figure 2. Sample gap configuration before re-organization

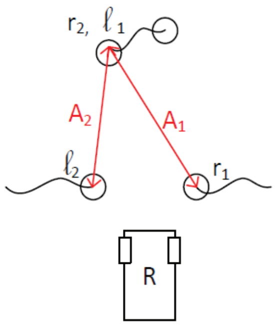

Figure 3. Updating the left corner of a gap

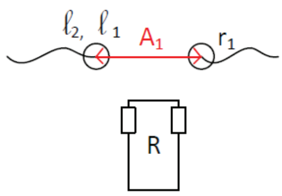

Figure 4. Final gap organization after re-organization

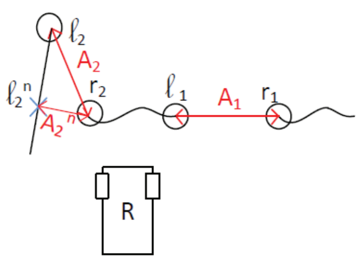

Figure 5. Wall-end gap elimination

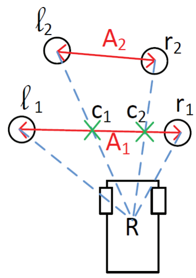

Figure 6. Aliasing gaps

Gap Detection Procedure

Gap detection procedure is the first step of the proposed algorithm. LIDAR measurement data is processed to achieve the initial gaps. These gaps are post-processed by a series of sub-procedures. In this topic, gap detection procedure is explained on a real LIDAR measurement data.

L={d0, d1, d2, d3, ... d90, ... d178, d179, d180} (1)

LIDAR measurement model (L) is an array of distances from the center point of LIDAR to the points on an obstacle lying on the corresponding angle. The symbolic demonstration in Eq 1 denotes a measurement data of a LIDAR, which has 180^o scanning angle and 1^o angular resolution. Therefore, length of the measurement array is assigned to 181. Taking the 1st derivative of the 1D distance array, marginal differences between two consecutive measurements are detected. The sudden changes, which are bigger than a pre-defined minimum allowed gap length, are the assumed to be the current gaps. In Fig 1, R denotes the mobile robot, the continuous curve illustrates the obstacle surface; r_1, r_2, l_1 and l_2 are sudden change points on the obstacle surface. As seen in Fig 1, $|r_1l_1|$ and $|r_2l_2|$ are sudden transitions in the 1st derivative of the LIDAR measurement data. These points are called as gap pairs. The order of the gaps is restorated by a series of re-organization processes operated on the gap pairs. In some situations, reorganization operations are not necessary as given in the sample scenario given in Fig 1. On the other hand, the gaps detected by derivation are not feasible in real time.

Gap Re-organization

The corner points identify the gaps detected by derivation. Effectiveness of the gap detection process is increased by updating the corners of the detected gaps. This leads to filter out undesired gaps, which can cause collision. After the filtering operation, the resulting passages are eliminated. The re-ordering operation of the gap corners is performed in two main steps. The corners are searched in clock-wise (CW) and counter-clock-wise (CCW) manner. The right corner of each gap is checked if any corner point on the left side of the current left corner, which is closer than the pair of the right corner is available. The left corner of the corresponding gap is updated with the closest left-side point. This search resumes from the updated left corner and the gap corners between the updated gap pair are skipped. This search is reversed and the same procedure is performed by updating the right corners of the gaps. These loops provide a way to force the mobile robot to steer through the gaps, which are primarily seen by the mobile robot. Another updating criterion is the distance of the gap corner to center of the mobile robot. Even though a corner point is closer to the current corner, if the further pair is closer to the mobile robot, this corner is not updated. An example scenario for this criterion can be seen in Fig 1 where the condition $|r_1, l_2|<|r_1, l_1|$ is satisfied but l_1 is not updated with l_2 as the second criterion $|l_2, R|>|l_1, R|$ conflicts with the first condition.

Gap re-ornanization steps of a sample gap configuration constructed by derivation, corner-updating operation and final gap configuration after over-all process are given in Fig 2, Fig 3 and Fig 4 respectively. The gaps A_1 and A_2 are identified by r_1, l_1, r_2 and l_2 respectively. The final gap configuration given in Fig 4 encompasses the initial gap replacement by reducing the steering effort of the mobile robot through the global target. The gap A_1 in Fig 4 represents the gaps A_1 and A_2 given in Fig 2. However, the final A_1 must be passed through before passing both A_1 and A_2. Thus, such a re-organization process is performed to force the mobile robot steering the gap through which it has to pass primarily. Right and left corners of the gaps are updated with the new corners which minimize the distance between the current gap corners and the distance between the candidate new corner and the mobile robot. The gap re-organization procedure is executed on the basis of these two main criterions.

First step of the gap corner updating scheme is given in Eq 2-3. Following Eq 3, a pseudo code is given to explain the gap re-organization scheme in CCW manner.

$$j^* = \min(|r_i\, r_j|) \wedge |R\, r_j| < |R\, l_i| \Leftrightarrow j > i \tag{2}$$

$$k^* = \min(|r_i\, l_k|) \wedge |R\, l_k| < |R\ i| \Leftrightarrow k > i \tag{3}$$

Pseudo code 1:

If j≠NULL ʌ k*≠NULL*
  If $|r_i\, r_j^*|<|r_i\, l_k^*|$
    $l_{i\_updated} = r_j^*$
  Else
    $l_{i\_updated} = l_k^*$
  Endif
Endif

The second step of the gap re-organization scheme is given in Eq 4-5. Following Eq 5, a pseudo code is given to explain the gap re-organization scheme in CW manner.

$$j^* = \min(|l_i\, r_j|) \wedge |R\, r_j| < |R\, r_i| \Leftrightarrow j < i \tag{4}$$

$$k^* = \min(|l_i\, l_k|) \wedge |R\, l_k| < |R\ i| \Leftrightarrow k < i \tag{5}$$

Pseudo code 2:

If j≠NULL ʌ k*≠NULL*
  If $|l_i\, r_j^*|<|l_i\, l_k^*|$
    $r_{i\_updated} = r_j^*$
  Else
    $r_{i\_updated} = l_k^*$
  Endif
Endif

,where *l,r,R* denote the left corner of the gap, right corner of the gap and position of the mobile robot respectively. The gap re-organization scheme includes gap corner updating with two pass in CCW and CW manner. Updated left and right corner of the gaps are denoted with $l_{i\_updated}$ and $r_{i\_updated}$ respectively. The updated gaps are filtered depending on the phsyical size of the mobile robot and the gaps smaller than the robot's diagonal are discarded.

Special Condition: Wall-End Gaps

Wall-type obstacles are the objects, which have flat and long surfaces. An extra filtering process must be executed in presence of wall-end gaps which has at least one corner point lying on a wall-type obstacle. The procedure is executed on each gap corner.

First, a corner is selected to check if it has a pair lying on a Wall-type obstacle. The closest LIDAR measurement point to the selected gap corner is scanned in the point cloud starting from the pair of the selected corner to the end of the LIDAR measurement array. If the eliminated point is closer than the pair of the selected corner, then the pair is updated with the corresponding LIDAR measurement point. If the selected gap corner is a right corner, then the point cloud starts from the left pair of the selected one to the last indexed element of LIDAR measurement array. Conversely, if the selected corner point is a left corner, the point space to search the closest point to the gap corner starts from the right-side pair of the selected corner to the first element of the LIDAR measurement array.

Assuming r_i, l_i, A_i, A_{in}, l_{in} are right corner of the i^th^ gap, left corner of the i^th^ gap, the i^th^ gap, the updated i^th^ gap, the updated left corner of the i^th^ gap; an illustrative demonstration is given in Fig 5. Assuming the gap A_2 is eliminated by the gap detection and gap re-organisation schemes, even though it is a valid passage in terms of the main principles, this gap may cause collisions as the narrow semi-continuous wall-type end. Therefore, l_{in} point is calculated as the closest measurement point to the corner point r_2.

The wall-end gap elimination procedure provides two critical benefits to the current gap detection and gap re-organization schemes: The mobile robot can vision the primarily passed gaps rather than the secondary passages. In addition, in some cases, a secondary gap could be physically large enough for a mobile robot to pass, but the primary passage could have a critical size. The collisions caused by this conflict can highly be avoided by eliminating the primary gaps between any corner point and semi-continuous wall-type obstacles.

Aliasing Gap Avoidance

After the gap detection, corner updates and several eliminations, aliasing gaps may occur. This may cause unnecessary gaps in robot's vision. In other words, the secondary gap should be deleted to reduce the computational cost in real-time applications. For this purpose, starting from each corner of the gaps, line segments are defined through center point of the mobile robot. If these lines interrupt any gap in two different points, the gap from which these lines start is assumed to be the secondary gap, therefore it is deleted. A sample scenario for aliasing gap avoidance scheme is given in Fig 6. The line segmets $|l_2R|$ and $|r_2R|$ interrupt the gap A_1 at two separate points: c_1 and c_2. On the contrary, the line segments $|l_1R|$ and $|r_1R|$ do not interrupt any other gap. Thus, the gap A_2 is assumed to be the secondary gap and it is disregarded by the mobile robot.

RESULTS and DISCUSSIONS

In this section, experimental result of the developed scheme is presented. Gap detection, re-organization and elimination performances in presence of various obstacle configurations are discussed. During performance test Sick LMS100 series LIDAR is used as range sensor. A certain number of real objects are placed on the environment.

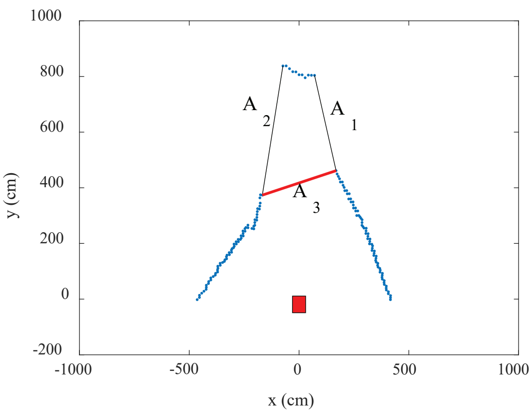

Figure 7. Experimental result-1

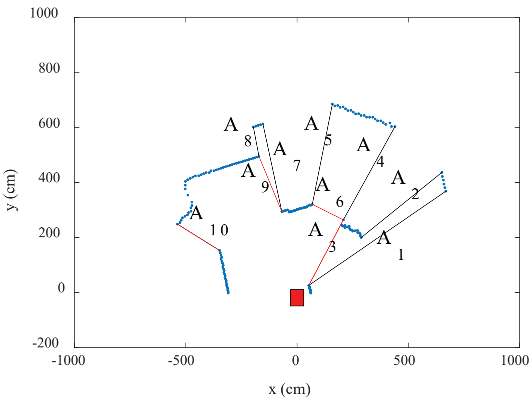

Figure 8. Experimental result-2

This placement is configured in such a way underlining the major principles of the proposed scheme. The scanning frequency of LIDAR is 60 Hz, scanning angle is 270º and the average computation time is 10 milliseconds. The connection of the sensor is supplied via TCP/IP protocol. Sensor reading interface is developed in Matlab 2016. The final passable gap configurations are demonstrated on this interface.

In Fig 7-10 it is demonstrated the experimental results. It is assumed that the red-colored rectangle depicts the mobile robot equipped with LIDAR, blue-colored dots depict the sensor measurement points, the line segments between certain measurement points depict the gaps.

In Fig 7, as expected from the measurement model and gap getection procedure, the gaps A1 and A_2 are eliminated by first derivation. A_1 and A_2 are reduced to the final gap A_3 by applying Eq 2-5 on the detected gaps. The mobile robot is forced to steer through the primary gap A_3 instead of heading to A_1 or A_2. Similarly, Fig 8 demonstrates the gap detection and re-organization procedure in a relatively more complex environment. The gaps A_1, A_2, A_4, A_5, A_7, A_8 and A_{10} are eliminated by the first derivation process. These gaps are re-organised by the scheme explained in Eq 2-5 and the pseudo code 1-2. The gaps A_1 and A_2 are reduced to A_3; A_4 and A_5 are re-ordered to A_6; where A_7 and A_8 are converted to A_9. The final gap configuration consists of the gaps A_3, A_6, A_9 and A_{10}. As seen in Fig 7 and Fig 8, the gap detection and gap corner updating procedures succed to reduce the initial gaps detected by simple first derivation.

The wall-end gap elimination procedure test is figured in Fig 9 and Fig 10 respectively. As seen in Fig 9, the gap A is eliminated by the first derivation. However, even though the length of gap A is enough to be passed by the mobile robot, the robot may be stucked between the corners r and l_n while trying to pass through A. The proposed sub-procedure eliminates the hidden gap, which the robot has to pass primarily. The hidden gap A_n is eliminated by the operating steps as given under the related topic and Fig 5.

Fig 10 depicts an experimental result containing both gap re-organization and wall-end gap detection procedures. The initial gaps are A_1, A_3 and A_4; where the updated final gaps are A_2 and A_5. A_1 is converted to A_2 by the wall-end gap detection scheme where A_3 and A_4 are reduced to A_5 by gap re-organization procedure.

The path planning algorithm executed on the mobile robot has to take into account the final gaps instead of the initial passages. This is necessary for avoiding sudden maneuverings, unexpected collisions caused by the sudden heading angle changes and the smoothing the robot's motion. In addition, the computational cost of many type of path planning algorithms reduce with reducing number of passages have to be processed. Thus, the proposed method also provides a way to reduce the computational cost of path planning.

The results of real-time tests show that, the proposed gap detection procedure outperforms the gap configurations eliminated by simple first derivation. This leads the mobile robot to visualize its environment in a simplier format by reducing the number of passable gaps.

Safety of navigation is increased by detecting hidden gaps and avoiding wall-end passages which are not wide enough for passing.

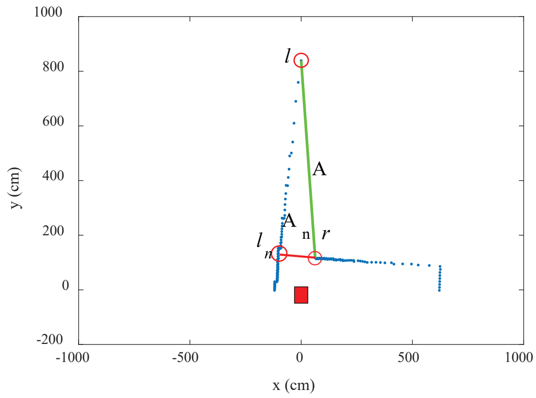

Figure 9. Experimental result-3

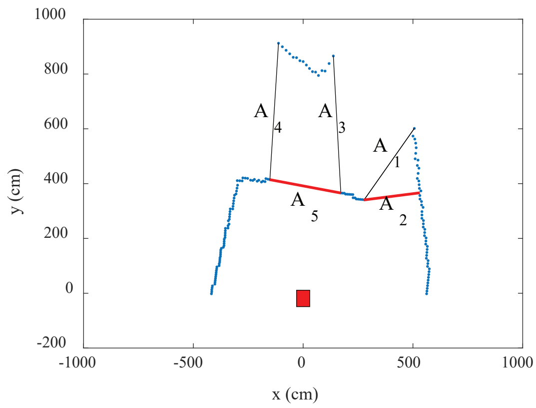

Figure 10. Experimental result-4

CONCLUSIONS

The method proposed in this paper provides an effective way to calculate passable gaps for mobile robot applications. The gaps detected by using this technique are not only verified in theory but also it is executed in real time. Main assumption of this scheme is the sensor used for the gap detection procedure is a 2-D range finder. Accuracy of the algorithm increases with increasing scanning frequency and angular scanning resolution of the LIDAR sensor. Another assumption is the obstacles around the mobile robot must be positive obstacles to achieve the gap detection benefits. The negative obstacles which are placed under the surface on which the mobile robot is steerd are not considered in the scope of proposed technique. The certain metarials such as glass, shining metals, water etc. can not be sensed by laser range finders; therefore the gap detection procedure will not be executed in presence of such obstacles made from such metarials.

This study can be a road map for mobile robot researchers, manufacturers and students. The real time tests proof that all the sub-procedures (derivative based gap detection, gap re-organization, and corner updating, aliasing gap avoidance) give satisfactory results for many ground mobile robot applications.

ACKNOWLEDGEMENT

This study is a part of the project supported by the Scientific and Technical Research Council of Turkey (TUBITAK) under the grant TUBITAK-113E777 and BIDEB-2211.

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