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Dynamic Object Identification by a Moving Robot Using Laser Data

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Abstract: Detection of moving objects around a mobile robot is important for safe navigation. This paper presents a robust technique for detecting moving objects using a laser ranger mounted on a mobile robot. After the initial alignment of the two consecutive laser scans, each laser reading is segmented and classified according to object type, stationary, non-stationary or indeterminate. Laser reading segments are then analyzed using an algorithm to maximally recover the moving objects. The proposed algorithm has the ability to recover all possible laser readings that belong to moving objects. The developed algorithm is verified using experimental results in which, a walking human is detected by a moving robot.

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1. INTRODUCTION

Laser range sensor has been used in moving object detection in mostly trivial scenarios where simple free space consistency is used to detect the motion in objects. However, in many other situations moving object detection is found non-trivial. When the object relative velocities are low, the laser data separation between two successive scans will be low. In addition the reflection of the object in the laser scan changes with the time for complex objects. As the robot moves, the ares that were previously occluded but stationary and will become visible to the laser and thus the detection algorithm should be able identify these occluded areas to prevent them been classified as moving objects.

1.1 Previous Work

Moving object tracking is a popular and widely researched topic in computer vision. The computer vision based methods use color and features of objects for the detection and employ numerous estimation techniques for tracking. Computer vision based tracking of moving objects by moving robots (or moving platform, in general) still remain a significant research challenge. In comparison to laser range based methods, computer vision based methods exhibit some drawbacks. Among others they include, the low precision in position estimation, susceptibility to lighting conditions, and reduced field of view when regular lenses are used. In contrast laser range finders provide accurate range data of the environment in a wider field of view.

A rule based method of classifying laser scan segments for moving robots in shown in Wang (2004). Human tracking systems using moving robots are demonstrated by Kleinehagenbrock et al. (2002), Fod et al. (2002), and Lindstrom et al. (2001). An interesting occupancy grid based moving object detection method is presented by Schulz et al. (2003). Montemerlo et al. (2002) provides a multi robot localization and people tracking method based on particle filtering. In all the reported cases the limitations include: failure in detecting object when they move at either low relative velocity, failure to detect when objects move side ways, and also in some cases those methods fails to identify all the corresponding laser data of the objects of interest. In this paper a systematic algorithm is proposed to maximally recover the moving objects from laser range scans. The proposed method can recover multiple moving objects regardless of their direction of movement with respect to the robot. The algorithm has two distinct steps, laser scan segmentation which is presented in section 2 and detection of the moving objects in the laser scan segments and the calculation of their position which, is presented in section 3.

2. LASER SCAN SEGMENTATION

The objective of a laser scan segmentation algorithm is to identify the laser scans corresponding to the moving objects. At any given time lets denote the two subsequent laser range readings as L_P and L_C, where subscripts C and P stand for the current and previous laser scans, respectively. L_C represents a set of range readings returned by the scanner in a single scan. Each reading is represented by the superscripts i or j, which is a 2D position vector. Two sample laser scans are shown in Fig. 1.

In this algorithm we assume that initially two laser scans are perfectly aligned with all their stationary objects. This implies that in each laser scan there should be a significant amount of scan points that belong to stationary objects. This method will not suffice for environments that are highly cluttered with moving objects, because there will not be adequate data to properly align any two subsequent scans.

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2.1 Definitions

The two sets of laser readings can be divided into different mutually exclusive sets, depending on their physical representation, as shown below.

$$L_P = A_P \cup O_P \cup M_P \cup N_P \tag{1}$$

$$L_C = A_C \cup O_C \cup M_C \cup N_C \tag{2}$$

where A_C and A_P are the laser readings that represent the same stationary objects in the two scans. O_P are the readings in L_P that will be occluded by the readings of L_C, when the robot moves to the current position. O_C are the readings that have been occluded by the readings of L_P, when the robot is in the previous position. M_C and M_P are the readings belonging to the moving object in the respective laser scan, but not occluded by the other. N_C and N_P are the readings that are out of the field of view of each scan when the robot is at the other position. Fig. 1 shows the regions in the scans that belong to the corresponding sets.

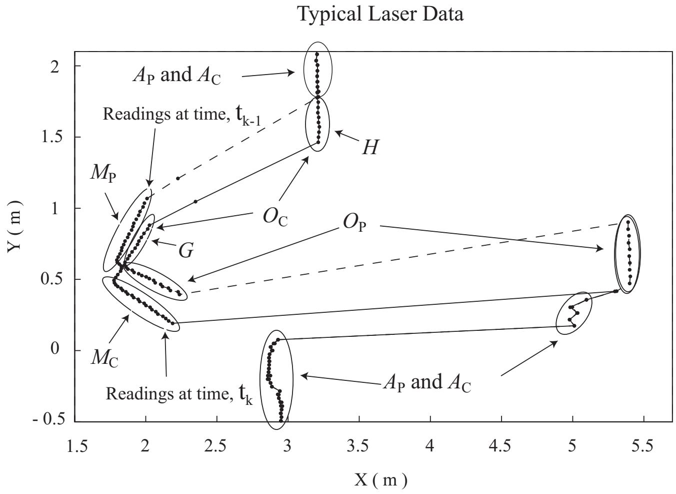


Fig. 1. Typical laser scans from a stationary robot. The object on the left hand side moves downward in negative y-direction.

The following observations can be made regarding the range reading sets presented above.

1. The laser scans that are spatially close to each other (after proper alignment) belong to A_C and A_P. Therefore A_C and A_P can be identified by searching for the spatially closest points in two laser scans, L_C and L_P.
2. M_P^i is on or close to the scan line, which emanates from the laser when the robot is at the current position resulting in O_C^j. Similarly, O_P^i is on or close to the scan line, which emanates from the laser when the robot is at the previous position resulting in M_C^j. Apart from yielding different sets, this relationship would also yield a point to point correspondence between the pairs (M_P^i, O_C^j) and (M_C^i, O_P^j).
3. In the point to point correspondences identified according to observation 2, the following is always true for the range values of the corresponding pairs of laser readings.

$$r(O_C^j) > r(M_P^i)$$
$$r(O_P^i) < r(M_C^j)$$

where $r(\cdot)$ is the range value of the corresponding laser reading.

2.2 Segmentation Algorithm

The main objective of the segmentation algorithm is to classify the laser readings into sets, A_C, M_C and O_C. The algorithm has three main stages. These are: (1) identification of A_C and A_P, (2) separation of M_C and O_C, and (3) segmentation of identified sets. These three stages are discussed below.

1. Through an element by element comparison the closest points of the two laser scans can be identified and removed. The set A_C will be retained for further processing in the moving object identification step described in section 3. This operation can be described as a set operation as described in (3), assuming that the closest elements are common elements in the sets L_C and L_P.

$$(L_C \cup L_P) - (L_C \cap L_P) = \underbrace{O_C \cup M_C \cup N_C}_{B_C} \cup \underbrace{O_P \cup M_P \cup N_P}_{B_P} \tag{3}$$

2. Algorithm 1 can be used to further identify the sets M_C and O_C from B_C.

Algorithm 1 Algorithm to identify M_C in B_C

```
Require: $B_C \neq \emptyset$ and $B_P \neq \emptyset$
Initialize $M_C$, $M_P$, $N_C$, $N_P$, $O_C$ and $O_P = \emptyset$
for Each element $B_C^i$, in $B_C$ do
    if $\exists$ a $B_P^j$ in $B_P$ that is close to scan line of $B_C^i$ then
        if $B_C^i < B_P^j$ then
            $O_P \leftarrow O_P + B_P^j$ and $M_C \leftarrow M_C + B_C^i$
        end if
        if $B_C^i > B_P^j$ then
            $M_P \leftarrow M_P + B_P^j$ and $O_C \leftarrow O_C + B_C^i$
        end if
    else
        $N_C \leftarrow N_C + B_C^i$
    end if
end for
$N_P \leftarrow B_P - O_P - M_P$
```

3. The identified sets M_C, O_C and A_C may have zero (empty set) or more continuous segments of readings. A continuous segment is a string of consecutive readings. Usually in a laser scan, a continuous segment represents a single object. During this step continuous segments within each set are identified. For example, in Fig. 1, G and H are continuous segments of the reading set O_P. The segmented sets will be represented by the superscript s and it can have zero or more continuous segments. For example, $O_P^s = \{G,\ H\}$.

2.3 Parameter selection

The following parameters have to be carefully chosen for proper operation of the moving object detection algorithm.

Time interval between laser data, Δt: The data acquisition time from the laser range finder is denoted as δt, which is a constant for a given sensor and the computer. The Δt can be chosen to be $n\delta t$ (n is any positive integer), where n has to be chosen according to the minimum relative velocity that has to be detected, as defined in (5).

Closest point detection threshold, Δd_c: In order to identify the stationary objects, the laser data points that are closer to each other have to be detected. The closest points can be easily defined as follows: if a point in the current scan is closer to a data point in the previous scan by a threshold Δd_c, then the points are identified as representing stationary points in their respective laser scans. However, due to the projective nature of the laser beam, the distance between two consecutive laser points in the same scan that are equi–range changes linearly with the range. Therefore a fixed threshold would not suffice for the detection of the closest points, as the points that are further away have greater separation than the points that are closer to the scanner. Thus a variable value for the Δd_c is chosen based on:

$$\Delta d_c = k \tan(\pi/360) r \qquad (4)$$

where $\pi/360$ is the resolution of the laser, r is the range to the first laser point and k is a suitably chosen tuning parameter to counter the noise levels in the scanner readings. Once the stationary scan points have been identified, the laser readings have to be grouped in segments. A series of consecutive laser readings that is spaced by less than a threshold with each of it neighbors is identified as a segment. Since the same spacing properties as above applied in selecting a threshold, a similar variable threshold is chosen for segmentation with a different tuning parameter k.

The minimum size of the moving object The objects that are further away from the scanner are represented as smaller objects (in the number of laser data points) than the objects closer to the laser. Also the noise levels increase with range (property of the laser range finder). Therefore a fixed threshold is selected for the minimum number of laser points that is needed in a segment to label it as a valid segment (not noisy).

The separation of a moving object in the world frame between two laser scans is directly related to the magnitude of the relative velocity between the object and the robot. Based on the above parameters, the minimum detectable relative velocity of an object will be:

$$V_{\min} = \frac{\Delta d_c}{\Delta t}. \qquad (5)$$

2.4 Moving Object Detection

After achieving the final segmentation, the next objective is to accurately and completely identify the moving object. Generally, the segments in M_C^s represent moving objects. However, there are instances where M_C^s either represents only a part of the moving object or does not represent any moving objects ($M_C^s = \phi$), when actually there are moving objects present in the laser scans. To facilitate a development of a systematic algorithm to completely recover the moving object, the following possible case scenarios are enumerated along with their properties.

(1) Case 1: (Object is perfectly separate in two scans)
Fig. 2 provides an example of this case. The complete object is represented by M_C^s, and as such no further processing is required.

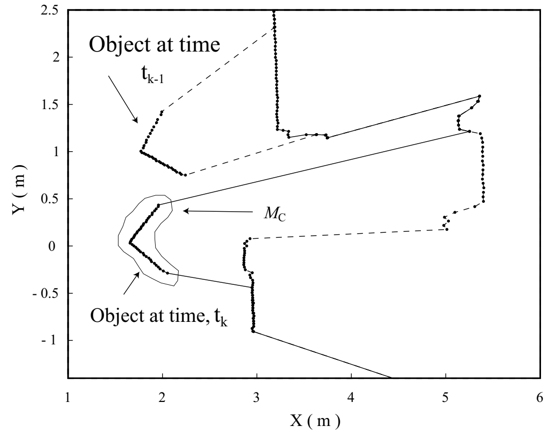


Fig. 2. Perfectly separated object positions.

(2) Case 2: (Object is only partially separated in two scans)
Fig. 3 provides an example of this case. Only part of the object is represented by M_C^s. Also in this particular case it is observed that one continuous segment in O_C^s belongs to the moving object. This is a common observation when scans are taken with a higher sampling time or when the object itself is moving slowly.

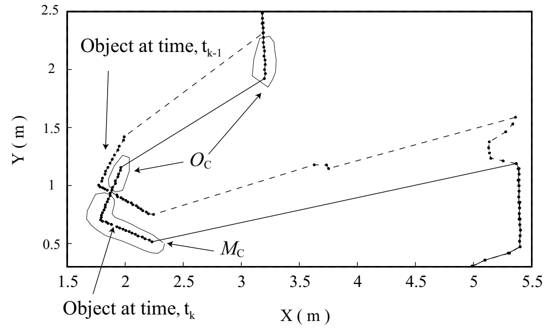


Fig. 3. Partially separated object positions.

(3) Case 3: (Object moving away from scanner)
An example of an object moving away from the scanner is provided in Fig. 4. As can be seen in the figure, the moving object will be completely missing in the M_C^s. Further, the moving object will be represented by a segment in O_C^s. It can be concluded that, if the set $M_C^s = \phi$, with $O_C^s \neq \phi$, then a segment in the O_C^s will correspond to the actual moving object. However, when $M_C^s \neq \phi$, we cannot conclude that a moving object is completely missing from M_C^s; for example, when there is more than one moving object and only one of them moves away from the scanner.

In such a case $M_C^s \neq \phi$, but there will be one missing moving object in M_C^s.

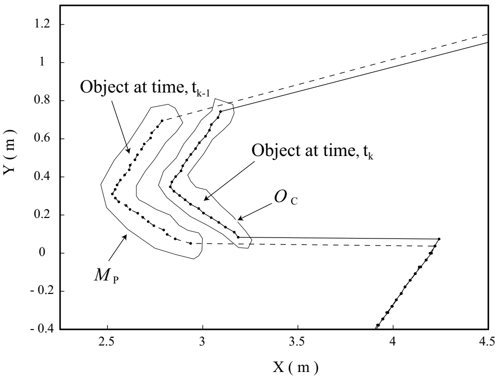


Fig. 4. Object moving away from the scanner.

(4) Case 4: (Object moving towards the scanner) This is the opposite of case 3 and M_C^s will represent the complete moving object. Thus, this is similar to case 1 and no further processing is required.

(5) Case 5: (Lateral movement with minimum or no radial movement) In this case, M_C^s only has a partial representation of the moving object. The missing part of the moving object will belong to the continuous segment set, A_C^s.

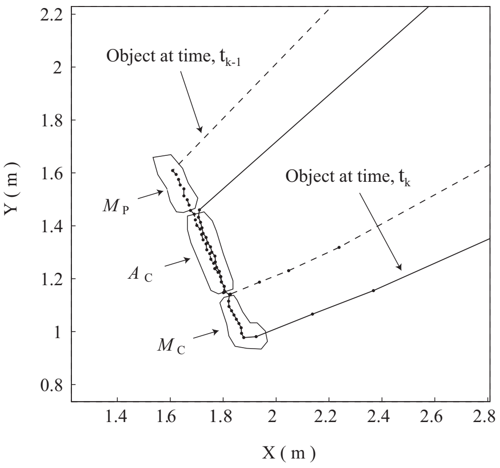


Fig. 5. Partial laterally separated object positions.

From the above five cases it is clear that in some cases straightforward segmentation would not yield the complete moving object. In cases 2, 3 and 5 further processing is necessary to recover the complete object. It should be noted that the issues relating to false positives are relevant to all five cases.

Of all the cases, the 3rd case is the most difficult to resolve, especially in the presence of false positives and/or multiple moving objects. In order to resolve the 2nd and 5th cases a set join operation is defined.

Definition: (Join of two continuous segment sets, Join(A,B)) When either end of a continuous segment of set A is adequately close to a either end of a continuous segment of set B, they are joined and placed in the set A, replacing the contributing element of set A. The joined segment is deleted from the second set to avoid repeated join of the same segment in set B with multiple segments in set A.

The above operation can be iteratively applied until there is no reduction in the number of segments in set B. Generally, one pass could properly reconnect most of the disconnected segments. Algorithm 2 is applied to recover the complete moving objects that belong to cases 2 and 5.

Algorithm 2 Recover the complete M_C^s

```
if $M_C^s \neq \phi$ then
    $M_C^s \leftarrow$ Join($M_C^s, A_C^s$)
    $M_C^s \leftarrow$ Join($M_C^s, O_C^s$)
end if
```

The first statement connects the segments in M_C^s with the segments in A_C^s and the second connects from O_C^s. A_C^s is joined first, since in the 2nd case there could be segments in A_C^s that represent the moving objects in crossing points between the scans of the moving objects.

Algorithm 3 can be used to recover the moving object when M_C^s is empty (in some instances of case 3). It should be noted that this method is susceptible to introducing false positives from the segments in O_C^s that correspond to stationary objects. As a rule for implementation, this algorithm should be used when only one moving object is present in the environment. This single moving object condition can be detected from the number of segments in O_C^s.

Algorithm 3 Replace M_C^s

```
if $M_C^s = \emptyset$ and $O_C^s \neq \emptyset$ then
    $M_C^s \leftarrow O_C^s$
end if
```

2.5 Experimental Results

This section provides the results of the object detection algorithm described in the previous section. In each of these experiments 50 scans are acquired in approximately 10 seconds. Each laser scan is taken with a field of view of 180 degrees at a resolution of 0.5 degrees. The laser remained stationary during all the experiments. When laser readings are closer than 10cm to each other, they are assumed to correspond to the same object. Fig. 6 and 7 show the final results of the segmentation algorithm. As can be seen, the algorithm shows acceptable results in recovering the complete object scenarios relevant to cases 2 and 5.

3. MOVING OBJECT DETECTION AND POSITION CALCULATION

Once the laser segments are identified they have to be labeled according to the object that they represent, either moving or stationary. When the moving objects are isolated from the laser segments, the object position (centroid of the foot print of the object) has to be calculated for the purposes such as velocity estimation.

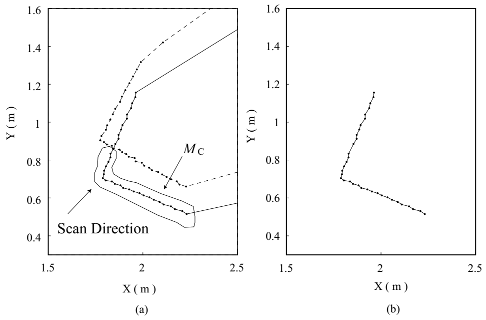


Fig. 6. The detection of a moving object similar to case 2 in section 3. (a) Two laser scans. (b) Detected moving object.

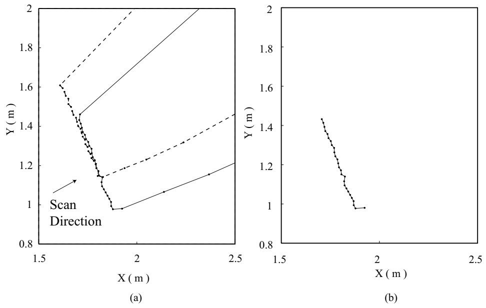


Fig. 7. The detection of a moving object similar to case 5 in section 3. (a) Two laser scans. (b) Detected moving object.

3.1 Moving Object Position Calculation

The position of moving objects is estimated from all the recovered information that is available in the form of scan segments. In order to support any higher level functions related to moving objects their position has to be accurately calculated. The most common method for object position calculation is to estimate the centroid of the footprint of the object based on the laser data, where the object position can be calculated directly using the current data corresponding to the object. As the laser range finder always observes only one side of the object at any given time, this method will only yield an approximate position estimate. If the object is observed over a long period of time or the object is actively observed, the complete object can be reconstructed using the data from scanning multiple directions.

In this work the object position is recovered by constructing the simple convex hull of the laser readings in each segment in M_C^s. Also, M_C^s might contain false positives that may appear as very short segments compared to the actual objects. Thus, the segments that are below a predefined size threshold are ignored. Threshold value must be selected with careful consideration to the nature of the moving objects in terms of their size and their distance to the scanner. Once the convex hulls of the selected scans segments are constructed, the actual object position can be considered to be at the centroid of the convex hull. Accuracy of the object position will depend on the shape and size of the moving object. Therefore it is very difficult to quantify the absolute uncertainty of the object position from the observed data. Fig. 8 shows an example of a segmented object, its convex hull, and the estimated position, along with a view of the real object from the scanner.

Alternatively, the object position can be calculated using the bounding rectangle of the laser segment data. This method usually allows for greater accuracy (through overestimation of the object area) than the convex hull. Therefore in the results shown in the next section bounding rectangles are used to display the position of the object.

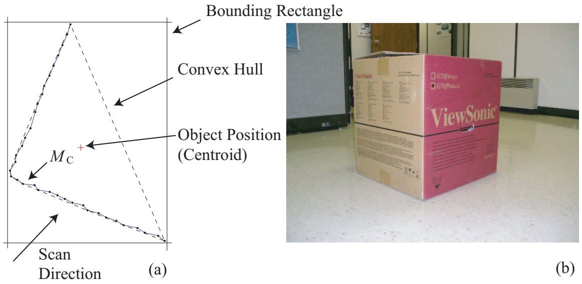


Fig. 8. (a) The final moving object segment, its centroid of the convex hull (calculated object position) and the bounding rectangle. (b) The actual view of the object.

3.2 Experimental Results : Detection of a person moving across the field of view

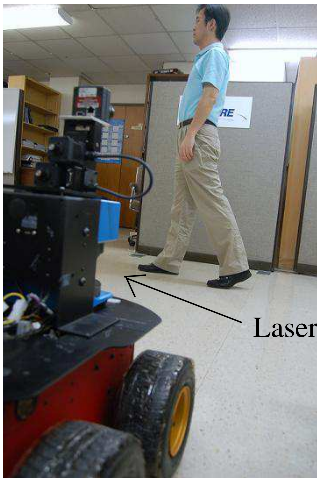
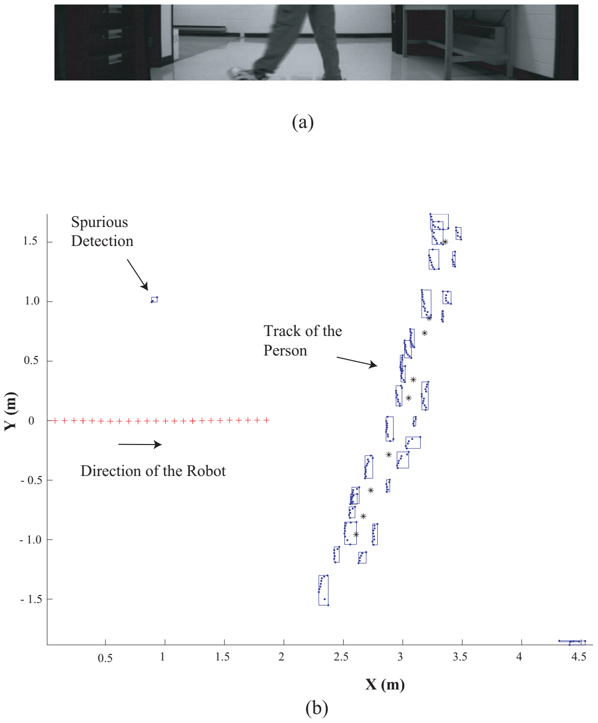


Fig. 9. A typical application scenario where a person is walking in the field of view of the laser scanner mounted on a moving robot.

This section shows some examples of the tracking results obtained with people moving in the field-of-view of the moving robot. The laser scanning plane is located about 35cm above the ground level. Thus when a person walks across the field of view only the legs are visible as two different moving objects. Fig. 9 shows a typical application scenario where a person is moving in the field of the view of the laser scanner. In the first result in Fig. 10 the person is moving close to the robot and as it can be seen from the figure the two legs are visible from time to time as each leg becomes occluded by the other in the walking gait. The data is acquired at 5Hz ($\Delta t = 200$ms) and for closest point detection a threshold of 5cm is used. The black stars in the Fig. 10 represent the possible torso position of the person when the scan segments from the two legs are available. In the second result shown in Fig. 11 which, is similar to the first result but the person is walking a distance away from the robot. From both results it is clear that the two legs of the person is not always detected. Apart from the obvious reason of occlusion, other main reason is that the two legs of a person moves at varying velocities during the gait. Therefore when the velocity is below the minimum detectable, the leg will be undetectable. Another possible cause for missing detection is that the object is represented by less than the minimum number of laser data points.



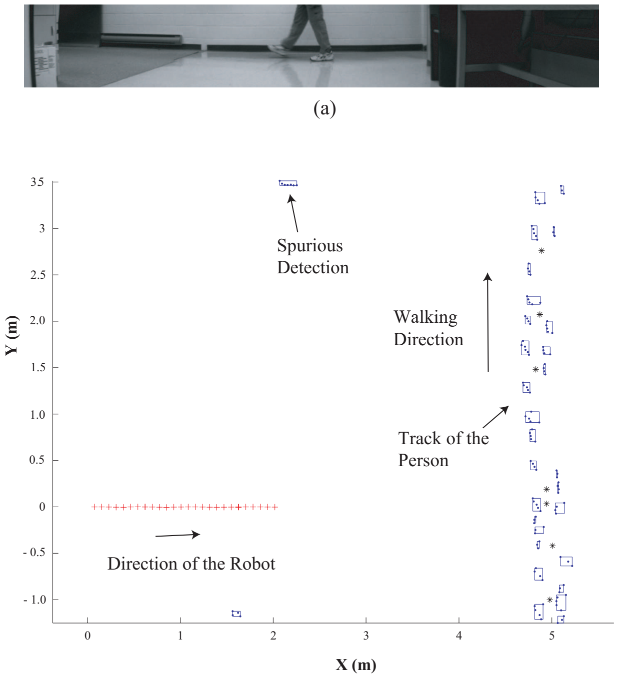
(a)

(b)

Fig. 10. Track of the walking person. The blue bounding boxes represents the detected moving objects while the black stars represent the possible torso position of the person when the scan segments from the two legs are available.

4. CONCLUSION

In this paper a general moving object detection algorithm was presented. The algorithm uses some specific properties of the laser scan data corresponding to the moving objects to successfully detect them. Proposed algorithm can be easily used to detect multiple moving objects from a moving platform in a dynamic environment. Additionally, in comparison to other methods, the proposed algorithm has the ability recover the complete moving object when the object is moving at a low relative velocity and when the object is moving sideways with respect to the scan direction. Through the tuning of the parameters, the detectable minimum relative velocity can be adjusted to suit the application. The results demonstrate that the proposed algorithm can be used to successfully track many different types of moving objects. In regular SLAM implementations the environment (or the landmarks) are assumed to be stationary. Therefore, apart from the direct use of moving object detection and tracking, the proposed method can be used as a data preprocessing step in regular SLAM applications to remove the data related to the moving objects from the sensor data. This will type of preprocessing will aid in improving the stability of the SLAM filters by preventing any moving landmarks from corrupting the data structures.



(a)

(b)

Fig. 11. The track of a person walking about 5m from the robot. The blue bounding boxes represents the detected moving objects while the black stars represent the possible torso position of the person when the scan segments from the two legs are available.

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