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Hierarchical Object Recognition Algorithm Based on Kalman Filter for Adaptive Cruise Control System Using Scanning Laser

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Abstract Not merely running at the designated constant speed as the classical cruise control, the adaptive cruise control (ACC) maintains safe headway distance when the front is blocked by other vehicles. One of the most essential part of ACC System is the range sensor which can measure the position and speed of all objects in front continuously, ignore all irrelevant objects, distinguish vehicles in different lanes and lock on to the closest vehicle in the same lane. In this paper, the hierarchical object recognition algorithm (HORA) is proposed to process raw scanning laser data and acquire valid distance to target vehicle. HORA contains two principal concepts. First, the concept of life quantifies the reliability of range data to filter off the spurious detection and preserve the missing target position. Second, the concept of conformation checks the mobility of each obstacle and tracks the position shift. To estimate and predict the vehicle position Kalman filter is used. Repeatedly updated covariance matrix determines the bound of valid data. The algorithm is emulated on computer and tested on-line with our ACC vehicle.

1. Introduction

ACC system is the improved version of conventional cruise control. Beside maintaining the constant vehicle speed set by driver, the headway is detected by range sensor and adjusted by automatically controlled throttle and brake system. With the range sensor it should be possible to

- continuously measure the position and speed of all objects in front
- ignore all irrelevant objects (e. g. crash barriers, approaching traffic)
- distinguish vehicles in different lanes
- lock on to the closest vehicle in the same lane.

As the prime candidate for the range sensor, worldwide automotive manufacturers are considering scanning laser and multibeam millimeter-wave(MMW) radar. Cause scanning laser uses near infrared beam of which the wavelength is close to visible ray area, it does not perform reliable operation similarly in the situation where the human suffers invisibility. MMW radar works well in bad weather condition and even at night that it is strongly recommend as the range sensor for the first generation ACC system. The diminishing cost due to the continual improvement of monolithic microwave integrated circuit (MMIC) technology also eases implementation.

In ACC system, the steering is not automatically controled, so the thorough road curvature information is not needed. However, to distinguish the objects in different lanes and outside the road, self motion detection sensors such as wheel angle sensor and yaw sensor are combined with the main range sensor. Under the assumption that all the cars are running on the road of same curvature, motion trajectory of itself is enough to estimate the road curvature and distinguish the target vehicle in the same lane. Other exceptional cases which do not coincide with the assumption(e. g the ACC vehicle is just about to enter the winding road) are regarded as transient so that no serious functional degradation occurs if throttle and brake are controlled in the limited operation range. Although the vision sensor is the unique solution to acquire the overall road information, the signal processing hardware, which usually consists of digital signal processing (DSP) chips, becomes very expensive to fulfill the required resolution. It may be feasible for the second generation ACC system in the future.

We implemented our own ACC vehicle with throttle and brake automatically controlled, which is equipped with scanning laser. In this paper, HORA is proposed to process raw scanning data and acquire valid distance to target vehicle. Two concepts are devised to play that role. First, the concept of life quantifies the reliability of range data to filter off the spurious detection and preserve the missing target position. Second, the concept of conformation checks the mobility of each obstacle and tracks the position shift.

In section 2, the architecture of our ACC system is briefly introduced. Section 3 explains the histogram algorithm which can process a lot of scanning data and calculate the valid headway real time. To overcome the defects of the histogram algorithm, the grouping algorithm is suggested in Section 4. Section 5 is the key to our data processing algorithm and HORA is explained in detail. Section 6 describes newly developed Kalman filter estimator for conformation process. In Section 7, the experimental result is shown using sensor data collected while cruising real road. Finally, section 8 is the conclusion.

2. ACC System Implementation

Our ACC System consists of scanning laser, range signal processing note PC and electronically controlled brake/throttle which controls vehicle speed.(Figure 1.) For details of our vehicle speed control refer to [1]. The scanning laser is the product of Riegl Co. named LSS390 the specification of which is listed on Table 1.

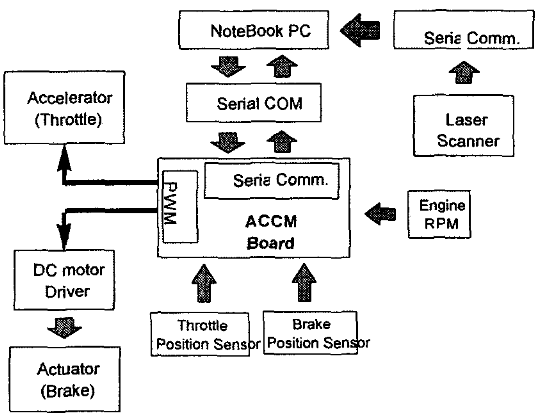

Figure 1. ACC System Implementation

Table 1. Scanning Laser Characteristics

LASER SCANNING SENSOR PARAMETER	
Scanning angle	$\pm 10^{\circ}$
Scanning rate	20Hz
Resolution	$\pm$10cm
Range	1~80m
Point per Scan	100 Point

3. Histogram Algorithm

Our scanning laser gathers one hundred distance measurements during one scan and send these through serial communication. Using 133 MHz Pentium PC the serial data is missing if the program size exceeds certain bound.

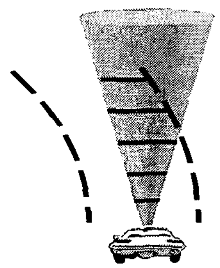

Figure 2. The Histogram Algorithm

The histogram algorithm is widely used to reduce the computational burden by sacrificing the measurement resolution.[2] In this application one point measurement is received and checked whether it belongs to the driving lane. It is possible to roughly estimate the road curvature by detecting the steering angle.(See Figure 2.) The conformed data is truncated to the resolution of meter and accumulated. Finally the histogram in Figure 3. is constructed. To filter off the noisy data the threshold is adjusted varying along the distance to compensate the detection probability which grows bigger while certain obstacle approaches.

The problems of histogram algorithm are as follows.

- Noisy ground detection due to pitch motion
- Distinction between the target and the other obstacles
- Velocity information corruption due to the decreased resolution

These defects can be overcome through the concept of life and the concept of conformation in HORA.

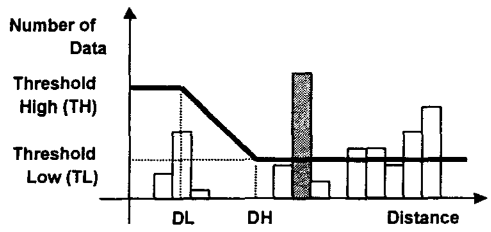

Figure 3. Histogram Method

4. Grouping Algorithm

Though the histogram algorithm accelerate processing, it loses the angular information. Therefore, multi-target tracking is infeasible essentially. If the road curvature ahead is available(e. g with vision system), the histogram algorithm is enough to find the target vehicle. Otherwise tracking is the only solution to determine the target. For this purpose grouping algorithm is devised to utilize angular information.

As the scanning laser sequentially collects the distance data in certain direction, the grouping algorithm groups samples in the neighborhood. To determine the group which a point belongs to, the various criteria can be used. In the experiment, if the distance difference of adjacent two points is bigger than the threshold, the new group is made and the previous group with small members is deleted.

The information extracted using the histogram algorithm and the grouping algorithm is confined to one scan. Both generate primitive information which is input to HORA. The difference is that the histogram algorithm generates only one primitive while the grouping algorithm generates lots of groups.

5. HORA

Once the primitive information is extracted from one scan, all the objects repeatedly appear in the similar position should be tracked. Even when the tracked object suddenly disappears, the previous location should be kept in memory for short span. All the objects on the road have their own physical constraints on the position shift. The amount of position shift between sampling times are limited. Thus each primitive can be linked to previous primitives which are estimate to be the previous position.

The concept of conformation means checking the satisfaction of the physical constraints. Cause the maximum speed of vehicles are limited, two continual measurements of one object can not be disperse over the certain bound. If this condition is met, the measurement is called "conformed".

The concept of life quantifies the reliability of the measurement. If a measurement occurs near the previous primitive, the measurement is judged more reliable that the life is increased If the life exceeds the prescribed critical value, the level of recognition is raised, i. e a group is promoted to vehicle in Figure 4. Once a vehicle is made, it is endowed with maximum vehicle life. Thus, though the vehicle is not detected for a few times due to noise and malfunction of scanning laser, it can survive until the life becomes zero. Grouping algorithm in Figure 4 can be either histogram algorithm or grouping algorithm in previous sections.. If primitives are generated by grouping algorithm, the initial life value is one. Through conformation process the primitives inherit the previous life value. If conformed by vehicle, the primitive becomes vehicle at once.

To decide the target vehicle among the vehicles, we estimate the road curvature by steering angle sensor. The closest vehicle to road center line is selected as the target. Using this algorithm the target vehicle is properly switched even when a vehicle is intercepting from side lanes.

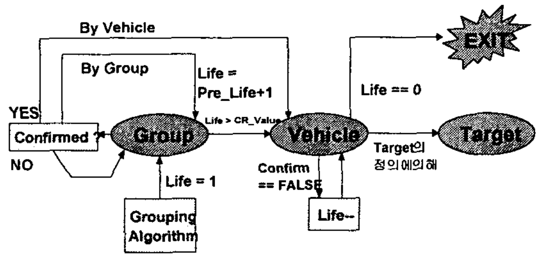

Figure 4. Object Recognition Level Transfer

6. Kalman Filter

In our previous research[1], simple maximum speed bound is used for the conformation process. To increase the accuracy of estimation and prediction we decided to add Kalman filter to HORA. If it is assumed that the targets are not maneuvering, i.e. have constant velocity, the dynamics may be described by the following linear state-space equation:

$$X_{k+1} = FX_k + Gw_k$$

where

$$w_k \sim N(0, Q_k), Q_k = E(w_k w_k^T) = \begin{bmatrix} q_x & 0 \\ 0 & q_y \end{bmatrix}.$$

The noisy measurements are modeled by the following matrix equation:

$$z_k = HX_k + n_k$$

where

$$n_k \sim N(0, R_k), R_k = E(n_k n_k^T) = \begin{bmatrix} r_x & 0 \\ 0 & r_y \end{bmatrix}.$$

In our application, X_k is 4 by 4 matrix which includes relative distances and velocities along the respective direction cause the control algorithm needs the velocity information. z_k is 2 by 1 matrix of each directional distance transformed from scanning laser measurement.

To initialize the Kalman filter for target tracking, the estimated state vector and estimated state error covariance matrix must be initialized. Assume unconditional unbiased state estimate and conditional unbiased state error covariance estimate, then

$$E(X_0) = \hat{X}_0$$
$$E[(X_0 - \hat{X}_0)(X_0 - \hat{X}_0)^T] = P_0$$

Once these two values are determined, the Kalman filter can begin tracking the target using a series of recursive equations. First, the state vector estimate and state error covariance matrix estimate for time k are made based upon the state and state error covariance estimates for time $k-1$:

$$\hat{X}_{k|k-1} = F \hat{X}_{k-1|k-1}$$
$$P_{k|k-1} = FP_{k-1|k-1}F^T + GQG^T$$

Next, the predicted measurement vector is extracted from the predicted state vector.

$$\hat{z}_{k|k-1} = H \hat{X}_{k|k-1}$$

Define estimation error $\tilde{z}_k = z_k - \hat{z}_k$, then

$$W_k = E(\tilde{z} \tilde{z}^T) = HP_{k|k-1}H^T + R.$$

From the innovation covariance matrix, a parameter known as the Kalman gain is determined:

$$K_k = P_{k|k-1}H^T W_k^{-1}$$

After determining the Kalman gain, the state update estimate equation is

$$\hat{X}_{k|k} = \hat{X}_{k|k-1} + K_k \tilde{z}_k.$$

Finally, the state error covariance matrix is updated:

$$P_{k|k} = P_{k|k-1} - K_k W_k W_k^T$$

Using the predicted measurement $\hat{z}_k$ and the innovation covariance matrix W_k, the spurious clutters and separated target segments can be eliminated by investigating whether the Mahalanobis distance of i-th group given by $r_k^{i2} = (\hat{z}_k - z_k^i)^T W_k^{-1} (\hat{z}_k - z_k^i)$ is greater than prescribed threshold η. In case that more than two groups are detected in the validation gate, minimum azimuth angle criterion chooses one target.[4]

7. Experiment

Equipped with scanning laser and HORA, ACC vehicle is tested on school road. These cases below were troublesome without HORA.

- Climbing bumps, the pitch motion causes the erroneous detection of ground or sky for about 500 msec.
- The roadside obstacles such as trees, blocks, etc. are recognized as the target.
- The distance data with centimeter accuracy is not sufficient for the velocity extraction.

The situation that the scanning laser looks up the sky due to the pitch motion can be easily treated by maintaining the previous vehicle position through the concept of life. When the ground is detected, the meandering line moves so fast that no conformation occurs. The concept of conformation works successfully.

Confining data processing within the running lane the roadside obstacles are filtered off. The residual noise can not compose a group by the lack of members and also hard to be confirmed.

In fact, calculating velocity from distance differentiation the resolution of distance rarely affects that of velocity. Referring to the result of Kalman filter[3] the steady state covariance of velocity estimation is proportional to 1/4 square of the distance resolution. However, in this application additional code is needed to calculate velocity with meter accuracy. Histogram algorithm can be modified to contain accurate data separately.

The estimation of road curvature from steering angle sensor is not reliable. Essentially human driver does not recognize small offset from the center line.

The cruising experiment reveals good performance and Figure 5 shows one shot range data obtained in the real road.

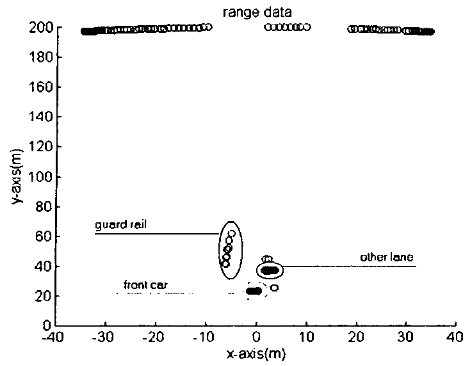

Figure 5. Road Information
Measured by Scanning Laser

8. Conclusions

Range sensor is the significant part for ACC system. With scanning laser, we developed the robust and reliable processing algorithm for scanning data. The concept of life and conformation enables us to track the target vehicle and filter out the noisy detection. HORA can be applicable to other scanning type range sensors and becomes more perfect with auxiliary vision system. To induce the beam numbers optimal for ACC application and ACC algorithm for various situations are remained as further study.

References

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