特集 Pedestrian Detection and Tracking using in-vehicle Lidar for Automotive Application*

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This paper presents an approach to pedestrian recognition using in-vehicle Lidar. In automobile applications for reducing pedestrian-involved accident, ADAS sensors are required to provide high detection performance with environmental robustness, applicable to variety of pedestrians under the variety of driving condition. DENSO has developed the high resolution in-vehicle Lidar installing inside the cabin for higher environmental robustness, and pedestrian recognition algorithm with high tracking ability, adaptable to traffic-congestion condition seen in urban environments. Several experiments show these developments have high potential for achieving effective pedestrian safety system.

1. INTRODUCTION

In recent years, reducing the traffic accidents is an important social responsibility and the various improvement of the vehicle safety capability has some effects on the reduction of the traffic accident. However, the amount of the accidents involving pedestrians is still high especially in urban areas, and it has become a next issue for the automotive industry.

Car-makers have worked on this issue with variety of approaches. One of the recent active approaches is developing the advanced driver assistance system (ADAS) that monitors the vehicle surroundings with in-vehicle sensors. The system works on the dangerous situation occurred by some factors, such as the driver's distraction, stimulating the driver to take actions or applying the automatically braking to reduce the vehicle speed and / or to avoid the collision. There are various methods to detect obstacles, including pedestrian, and dangerous situations, such as Radar or Lidar (used in this paper) that measures the distance to unspecified object by emitting electromagnetic radiation, or camera sensor which discriminates the specified object by analyzing captured image. Each sensors have advantages and disadvantages based on their physical characteristics, and therefore they are used in the suitable application or in combination as needed.

DENSO has launched the products in the market of ADAS field with Radar, Lidar, camera, and so on [1]. Among these sensors, Lidar has the distinct feature of scanning the vehicle surroundings at high resolution by emitting laser beam of high directivity, which allows highly precise measure of the road environment. It contributes especially to detecting the comparatively small object like a pedestrian with high geometrical accuracy relative to ego-vehicle. In addition, the ongoing technological advancement has been considerably improving the performance in the adverse environment, which had long been the issue for Lidar. Therefore, considering the above, Lidar seems to be thought as one of the effective measures for pedestrian detection.

In the following sections, the technology of in-vehicle Lidar and its performance are described. In section 2, the specifications of developed Lidar are outlined including the environmental robustness, and the algorithm for pedestrian recognition is described in section 3. In section 4, several experiments including application to the collision avoidance system are reported, and it shows the effectiveness of our Lidar to the application for the pedestrian safety.

2. LIDAR

2.1 Specifications

For the application that needs to detect pedestrian, Lidar is required to provide the following performance:

- Long range pedestrian detection with high accuracy and reliability
- Robust detection against the variety of pedestrian

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under the variety of environment.

In order to meet these requirements, we have developed the prototype in-vehicle Lidar. **Fig. 1** shows the appearance and **Table 1** shows the main specifications of the Lidar.

Table 1　SPECIFICATIONS

Term	Spec.
Detection range of vehicle (reflector)	200 m
Detection range of pedestrian (black clothes)	60 m
Horizontal field of view	40 deg
Vertical field of view	4 deg
Horizontal angular resolution	0.1 deg
Vertical angular resolution	1 deg
Detection frequency	10 Hz

Fig. 1　DENSO's Lidar

One of the main features of this Lidar is the coaxial synchronous scanning between transmitting and receiving that achieves high detection sensitivity with high resolution. This means the long- range detection of the relevant target like the vehicle and pedestrian. For example, the reflector equipped on the rear end of the vehicle could be detected over 200m away and the pedestrian in black clothes, with the reflection rate of approx. 10%, is detectable over 60m away in the sunny day, which are both quite hard condition for the Lidar. The field of view is 40 degree in horizontal direction and 4 degree in vertical direction, which is almost enough to cover the critical pedestrian-involved accidents, such as in case of pedestrian crossing the road. Moreover, the angle resolution is 0.1 degree in horizontal and 1 degree in vertical direction, which enables the high precise detection of the pedestrian and discriminable from other non-cubic objects like the road surface.

Another feature is the installation in the wiping area behind windshield inside the vehicle cabin, shown in **Fig. 1**. This improves the environmental robustness that had been one of the issues for the conventional Lidar, such as in cases when the splash or dirt attaches on the sensor surface.

Moreover, since the in-vehicle installation behind the windshield leads to attenuate the energy of the laser beam when it goes through the windshield, this Lidar corresponds to the laser class 1, as the safety criteria of laser regulated in the Japanese Industrial Standards.

2.2　Pedestrian Detection

This Lidar measures the distance to the object accurately by Time-Of-Flight method with high resolution 2-dimentional scanning. For the pedestrian detection, this allows highly precise position and movement estimation by applying the tracking process mentioned later in section 3. In addition, it is robust against the clothes, carrying bags, pushing stroller, pose and the partial occlusion, that is a very advantageous characteristic for the application that activates the vehicle using the position or movement of the pedestrian. **Fig. 2** shows the example of pedestrian detection on the community road. All the Lidar measurements, expressed as the dots, are plotted on the 2D-plane from the bird view. And the

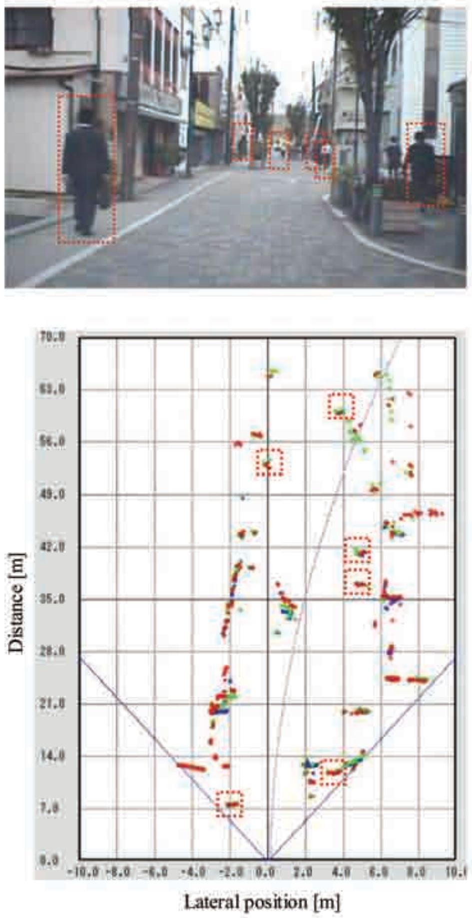

Fig. 2　Pedestrian detection

measurements in the dashed-rectangle correspond to the pedestrians existing in this scene. Several pedestrians walking near by the buildings or roadside trees could have been detected from approximately 60m away, showing an advantage of our Lidar, which enables the long-range and high resolution pedestrian detection.

2.3　Environmental Robustness

In general, the ADAS sensor requires the robustness under the environment of daily driving situation. For an optical sensor such as a Lidar, the performances in the rain, backlight and at nighttime are typically discussed.

1) *Rain*: Lidar's detection performance under the rainy condition has been discussed for a long time and technically two points should be considered. First, light diffusion and refraction caused by drops of water on the sensor surface, and second, the reduction of the light transmittance due to the raindrops in the air. Our Lidar is designed to minimize the effects of these factors. For example, the frequency of water drops attached is decreased by installing the sensor in the wiping area behind the windshield inside the cabin, and moreover the coaxial synchronous scanning between transmitting and receiving minimizes the effect of light diffusion and refraction. In addition, the sensor detection sensitivity has been improved to enable long-range object detection even under the environment with low light transmittance. **Fig. 3** shows the detectable distance of pedestrian against the change of light transmittance. The 'plus' marker represents the experimental results of the pedestrian detection, and the curved line means the theoretical detectable distance based on the maximum distance in the condition with no-degradation of the transmittance. The experimental results almost correspond to the theoretical estimation, meaning the validation of the experiment.

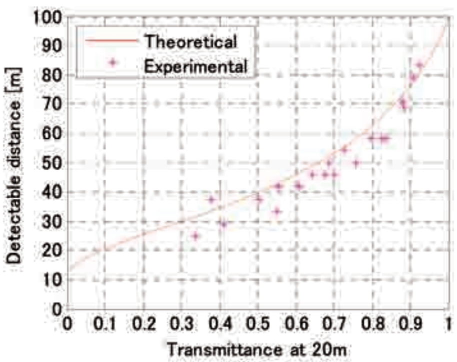

Fig. 3　Effect of light transmittance on pedestrian detection

The condition with the rainfall of 50mm/h, which is the guideline of the Japan Weather Association to issue a heavy rain warning, corresponds to the transmittance value of almost 0.6. Under such condition, the detection performance decreases to some extent, although as a worst-case scenario, a pedestrian can be detected from 45m away. Here we consider the action of the driver after noticing the pedestrian, such as pushing the brake pedal and decelerating the vehicle, the detection distance of 45m has the potential to be able to avoid the collision to pedestrian in the vehicle's speed range of almost 50km/h. So the decrease in performance under the rainy condition is limited as described and the magnitude of the negative effect has become much smaller than before.

2) *Backlight*: Generally, the detection performance of Lidar could be discussed by the way of signal to noise ratio (S/N) between the reflected signal from the object to be detected and the background noise signal caused by the disturbance. In this frame, the backlight leads to increase the amplitude of background noise and it could lead to decrease in the detection performance. However, as describe above, our Lidar narrows the light receiving view to the minimum by coaxial synchronous scanning between transmitting and

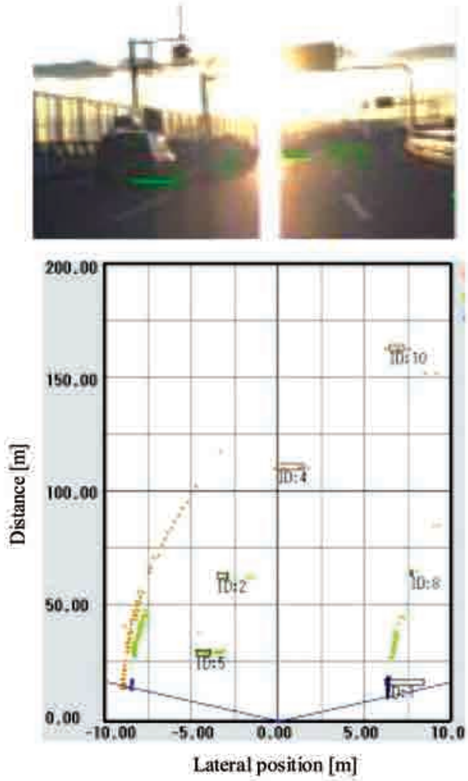

Fig. 4　Detection performance under backlight condition

receiving and limit the frequency of sunlight incident. It means only the few scanning direction from the sunlight are affected by the increasing of background noise. In other words, only the object detected at almost same direction as sunlight in both horizontal and vertical has the negative-affect by the sunlight. **Fig. 4** shows an example of driving toward the sunlight. Forward vehicles could be detected over 150m away in such the environment, where the vertical smear of CCD sensor appears in the captured image, and it seems to have practically little influence on the detection performance of Lidar. Concerning about pedestrians in this kind of situation, less encountered in urban area, our Lidar could keep enough performance as in the same manner.

3) *Nighttime*: As described above, the detection performance of Lidar could be estimated by S/N, and this way is also applicable to discuss the performance in the nighttime. Here, the amount of the reflected signal has no difference between at daytime and nighttime. However, the amplitude of the noise signal is decreased at nighttime, because the received energy from the sunlight as disturbance is significantly smaller compared with the daytime. Accordingly, the Lidar's S/N is higher at nighttime, which enables the better detection performance, not only the distance but also the accuracy. This characteristic is preferable to tackle the accidents at nighttime caused by the poor visibility of pedestrians.

As discussed in this section, regarding the environmental robustness, our Lidar has enough capability for the usage in the real world.

3. RECOGNITION ALGORITHM

This section explains an algorithm for pedestrian recognition. Algorithm consists roughly of two components, as shown in **Fig. 5**. One is the object tracking and classification, estimating mainly the position, movement and the size of the pedestrian. And another is the lane recognition function, which uses the additional measurements detected by lower scanning especially towards the road surface. This component is used to estimate the risk of the recognized pedestrian, outputted by the object tracking component, to collide with the ego-vehicle, considering whether the pedestrian is inside the driving lane at the moment or walking into the lane in the near future. The following section describes in detail.

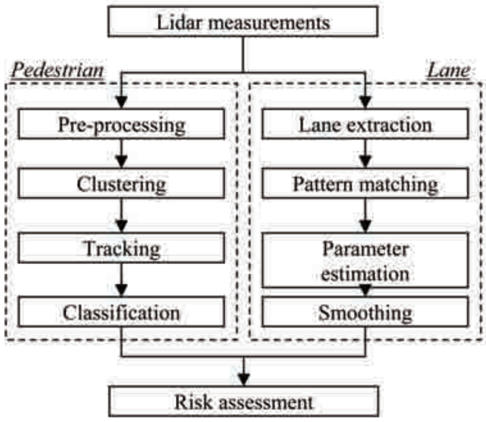

Fig. 5　Algorithm overview

3.1　Pedestrian Tracking and Classification

This component estimates the object state and attribute by processing the Lidar measurements, including the distance, intensity and width of the received pulse signal in each scanning direction. Since the measurements contain the several kinds of reflections from the surroundings of the ego-vehicle, it's important to eliminate the disturbance for the object tracking, such as the road surface, rain drops and so on. For this purpose, we have been approaching the classification and extraction of the relevant measurements using multiple criteria in the stage of pre-processing.

Here focusing on the classification of the measurement to the "cubic" object that might be pedestrian or "non-cubic" object that might be road surface, we apply the physical and geometrical analysis of the measurements. The former is derived from the feature of the reflected signal, such as the intensity and width of the received pulse. Since the shape of the pulse is comparatively different between the reflections from the 'cubic' and 'non-cubic' object because of the basis of time-of-flight measurement, we could discriminate e.g. the road surface by analyzing the above features. And the latter is derived by analyzing the spatial distribution of measurements in the vertical direction, based on the geometrical manner that the 'cubic' object could be detected by multiple layers. Moreover to enhance the effect of this approach, the ego-motion compensation between each scanning direction according to the corresponding time delay is conducted to all-directional measurements in order to cancel the movement of the ego-vehicle. Also this compensation has the advantageous effect to the following tracking stage.

Next, the clustering process is implemented using the extracted measurements, in which the measurements are grouped by criteria based on the position and the received signal intensity of each measurement. The cluster is expressed by the rectangle model with the orientation aligned to the measurements. After that, the cluster which is considered as undeserving to track is eliminated, e.g. referring to the application requirement.

Next, the generated cluster is tracked and the state of the object is estimated. The state vector is composed of

$$\mathbf{x} = \begin{pmatrix} x & v_x & a_x & y & v_y & a_y & \theta & \omega & w & d \end{pmatrix}^T \tag{1}$$

where x, y represent the position of center of gravity, v_x, v_y are the velocity and a_x, a_y are the acceleration of the rectangle model. θ, ω are the orientation angle and the angular speed, and w, d are the width and the depth of the model. The states are estimated by the IMM filter to handle the flexible motion and its transition of pedestrian by using multiple models [2) 3) 4)]. In addition, since the ego-vehicle movement between each measurement cycle could be known by the on-board sensor of the vehicle speed and the yaw rate sensor etc, the change of the sensor coordinate system itself is canceled from the state of the tracks before the correction step in the IMM. This means we might consider the uncertainty of the state transition of only the target (pedestrian) and enables more precise modeling of the target motion. Therefore this approach enhances the tracking performance especially under the condition with moving coordinates such as when the ego-vehicle considerably accelerates or turns. The formula (2) shows the IMM state transition model, where ΔT is sensor measurement cycle. A_1 represents the constant velocity in the translation movement and no-yaw rate in the rotational movement, and A_2 represents the constant acceleration and constant yaw rate, in both the shape of the rectangle model has the constancy with time. Moreover it's simply described without correlation of the components of translation, rotation and the size of the rectangle model, considering the processing speed for the implementation of the algorithm to on-board microcomputer.

$$\mathbf{A}_1 = \begin{pmatrix} 1 & \Delta T & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & \Delta T & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\mathbf{A}_2 = \begin{pmatrix} 1 & \Delta T & \Delta T^2/2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & \Delta T & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & \Delta T & \Delta T^2/2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & \Delta T & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & \Delta T & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \tag{2}$$

The state estimation, in particular the observation update process, needs the data association between the observed value and the predicted value. Concerning the application with the pedestrian recognition working in the congested environment such as urban area, it becomes especially more important. So the probabilistic association is used in our algorithm. First the gating is executed based on the mahalanobis distance between the track and observation and the less-probable combination is rejected [2) 5)]. After that, when multiple tracks and observations co-exist in the gate region, the solution of association that totally optimizes inside the gate region could be derived by the Auction algorithm [2) 6)] to maximize the following function.

$$c_{ij} = -d_{ij}^2 - \ln\left|\mathbf{S}_i\right| \tag{3}$$

where d_{ij} is mahalanobis distance and S_i is the residual covariance matrix between the track and observation [5)].

The process mentioned above enables to estimate the object state including pedestrian. In the application that requires the attribute of tracked object, the classification is subsequently executed. The idea is based on the Bayesian classification [2)] using the object characteristics such as mainly the size, motion and received signal intensity of the tracked object.

3.2　Lane recognition

Although the lane recognition is widely approached by the camera, the Lidar has also the capability [7], because the lane mark has comparatively high diffusion against the infrared light emitted by the Lidar. So we combine multiple criteria using the received signal intensity to extract the lane mark from all the measurements. The basic criteria are the contrast and gradient of the intensity value, which are similarly used in the image processing. The contrast is calculated using the difference of intensity between the lane mark and road surface mostly paved with the asphalt or concrete. And the gradient is calculated by the difference of intensity in the horizontal direction on each vertical layer. The measurements with higher contrast and gradient are extracted as the candidates of the lane mark, compared with the threshold adapting to the situation. After this, the line detection and parameter estimation are performed to achieve the robust recognition.

4.　EVALUATION

4.1　Pedestrian recognition

We tested the performance of our Lidar on the public road including the urban area. **Fig. 6** shows an example of pedestrian recognition, where the rectangle with arrow on the bird view represents the tracked pedestrian and its velocity vector. Several kinds of pedestrians could be well recognized with the valid position and movement.

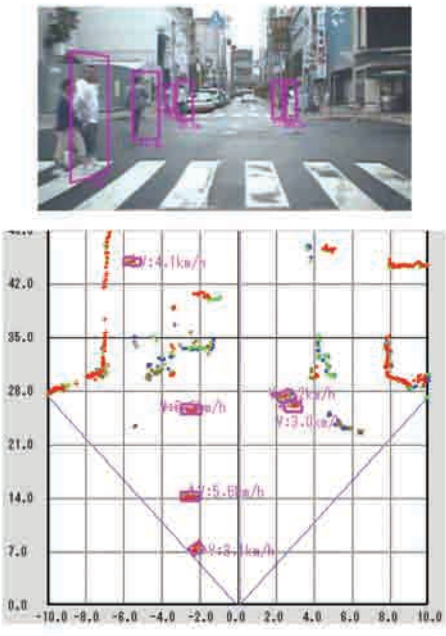

Fig. 6　Pedestrian recognition

The recognition rate without classification is approximately 97% to over 1000 pedestrians. Most recognition error has occurred to crowd of pedestrians repeatedly merging and separating. It requires further algorithm improvement mainly of the object clustering and tracking. And the performance including the classification is almost 80% in a typical scene of independent pedestrian walking. In order to obtain more precise classification, it requires not only the improvement of algorithm but also the improvement of the sensor hardware, especially about the resolution of vertical direction.

In addition, the accuracy of the recognized distance to the pedestrian was compared with the mono-camera, introduced into the market for the pedestrian safety system applying the pattern-based classification. The test was conducted under the situation of pedestrian crossing the road in front of the ego-vehicle, referring the true distance. **Fig. 7** shows the mean value and maximum error. The performance of the Lidar keeps within almost 50cm error through all the distance until 70m. Otherwise, the distance by the camera has a large error especially over 30m. This result indicates the advantage of Lidar in terms of long-range detection and high accuracy.

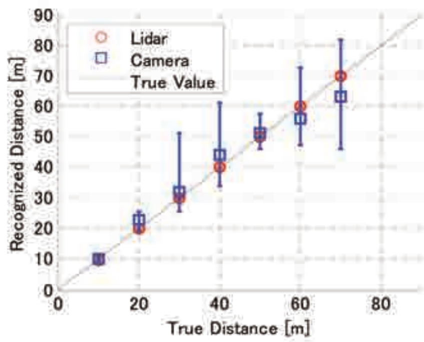

Fig. 7　Accuracy of recognized distance

4.2　recognition

Fig. 8 shows an example of the lane recognition. The solid line represents the recognized lane position and the dashed line means the predicted position of the lane over the detected distance. The crossing pedestrian almost 60m away, showed by a rectangle, could be estimated as positioned inside the lane. Combining the pedestrian and the lane recognition has the potential of the understanding the situation and contributes to the further advancement of the application.

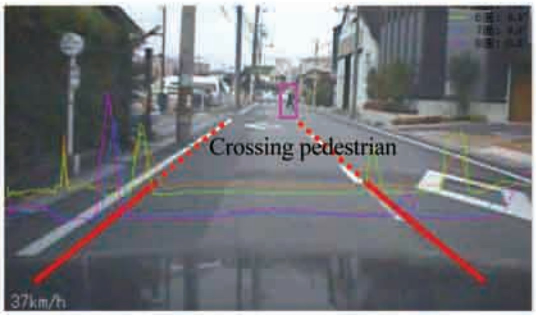

Fig. 8　Lane recognition

4.3　Application to the collision avoidance system

We also tested the performance of our Lidar by applying to the collision avoidance system [8], which requires the stable and accurate pedestrian detection. The test simulated the typical traffic accident of pedestrian crossing the road, shown in **Fig. 9**. Several scenarios, including the full lap and offset approaching with the speed of almost up to 40km/h, were implemented and the collision was successfully avoided at all the trials. The gap to the pedestrian when ego-vehicle was stopped with emergency brake was within +/- 0.5m against the target distance of 1m, which is caused by several uncertainties such as the time lag between the sensing and control, the brake response and sensor detection error. Generally considered, the Lidar seems to show the preferable potential for this kind of safety application.

Fig. 9　Application to collision avoidance system

5.　CONCLUSION

This paper has presented the approach to the pedestrian detection using the DENSO-developed in-vehicle Lidar. Discussing the feature of the Lidar, referring several experiments, has showed the improvement of environmental robustness and the advantage in the pedestrian detection to the application for pedestrian safety. Future work will cover the further algorithm development and hardware optimization for the usage in the real-world as well as the extension of the sensing function for the future advanced application.

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