Disturbance Rejection Filter for Depth Sensor

Masashi HAMAGUCHI*1, Dr. Takashi HIEKATA*2
*1 Applied Physics Research Laboratory, Technical Development Group
*2 General Administration Department, Technical Development Group

In recent years, data obtained from sensors attached to excavators are being widely used in assisting the operators. The processing unit logic of such a sensor system has been developed to ensure flexibility in the design of the sensor system. As a part of this development, an effort has been made to solve the problem of detecting disturbances, such as rain, snow, and insects, when the depth sensor is used for outdoor measurements. An object placed in front of a depth sensor in a raining environment was moved back and forth while continuously measuring the appearance of the object. In the measured data, points with possible disturbances were chosen. The speed, direction, and acceleration between frames were calculated as feature quantities, which led to the development of a disturbance rejection filter that eliminates the points above set thresholds. This filter has been confirmed to detect the position of objects while ignoring the influence of rain in real applications.

Introduction

Recently, data obtained from sensors are being widely used in assisting operators. For example, a system has been developed having a monitoring camera attached to the rear of an excavator to display the backside image, and thus to warn the operator when surrounding objects or people approach.[1) Also, a system has been developed that uses 3D point cloud data acquired with a camera sensor to perceive the current status of a construction site in a short time.[2)]

The sensor systems adopted to these applications are often made by specialized sensor manufacturers with their original know-how. Relying on another company for a sensor system may result in its detection unit and processing unit being integrated into a black box (**Fig. 1**), making it difficult to change the sensor, or to add functions to the processing section as needed. This leads to increased development period and development cost.

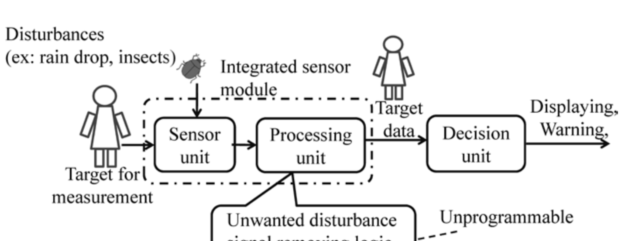

Fig. 1 Components of sensor system

In order to solve the above problems, a processor logic has been developed in-house while using general purpose products for the sensors. This paper relates to a distance sensor attached to an excavator to detect objects approaching the excavator in outdoors. This report describes a newly developed technique for eliminating disturbances caused by rain, snow, insects, etc.

1. Sensors used for excavators

Japan Construction Machinery and Construction Association Standard[3)] lists laser sensors, ultrasonic sensors, and ultrasonic transponders for danger detection, along with closed circuit televisions and the like for blind-spot assistance, and defines their test methods and standard performance requirements.

These sensors are attached to an excavator to make measurements in the area surrounding it, to perceive the status of work, assist operation, and detect/give a warning when approaching objects. An excavator must be capable of measuring the distance to each object; hence, distance sensors are used for this purpose.

Laser sensors and ultrasonic sensors are most commonly used for distance measurement. A laser sensor is superior in accuracy and responsivity thanks to the high speed of light waves; however, it has a risk of malfunctioning when refraction occurs due to water wetting or smearing on its emission port. An ultrasonic sensor is superior in environmental resistance thanks to the characteristics of sound waves, which are less prone to refraction even in the rain, or dust and the like; however, its resolution is poor due to the low propagation speed and low frequency of sound waves, causing errors of centimeter order in distance measurement. Assisting excavator operators in perceiving the surrounding area requires high measurement accuracy over a wide range of subjects. Therefore, the depth image sensor described in this paper employs a laser type that can two-dimensionally measure the distance to each object.

2. Influence of disturbance on sensors

When a depth image sensor is used outdoors, there is a risk that the distance to the measurement object cannot be measured correctly due to rain, snow, insects, or the like. Therefore, this study investigated the influence of rain on the measurement results of the depth image sensor. An object (approximately 75 cm square) was placed in front of a depth sensor in a raining environment as a detection target and was moved back and forth manually for two rounds (**Fig. 2**). The motion of the object was captured by a depth image sensor that can measure continuously at a rate of several tens of frames per second. The two-dimensional distance data obtained was used to detect the most proximal distance between the sensor and object.

Fig. 3 shows the detection results of object positions. The vertical axis shows the most proximal distance, and the horizontal axis shows the elapsed measurement time. This figure shows the most proximal distance measured and the median value of the most proximal distances measured in the last 3 frames.

The graph of the detection results is supposed to have a shape such as that shown in **Fig. 4** with two gentle peaks indicating the two rounds of back and forth movements. The detection results in Fig. 3, however, indicate that the sensor reacts to the laser reflection on raindrops, and the detected position changes greatly in a short time. In addition, even when the median value of the last 3 frames was adapted to the processing, the detected positions still changed greatly in a short time, indicating that the influence of rain could not be removed. Since it was envisaged that other flying objects such as snow and insects would cause similar effects, a study was conducted on a filter for removing these disturbances.

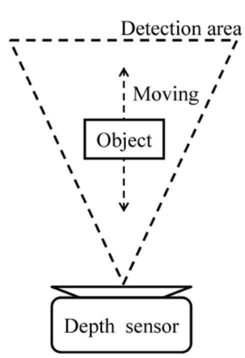

Fig. 2 Equipment layout for experiment

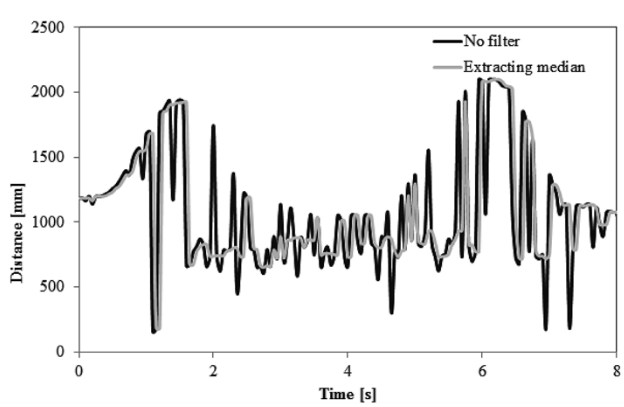

Fig. 3 Detection of object position

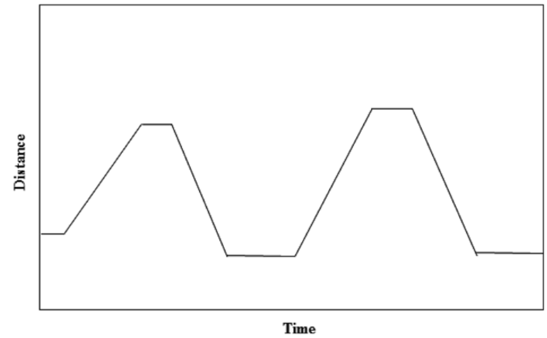

Fig. 4 Image of object position change

3. Development of disturbance rejection filter

To develop a filter that rejects disturbances caused by rain, snow, insects, etc., a study was conducted on a technique that comprises extracting multiple points including the detection target as disturbance candidates for each frame, calculating velocity, direction and acceleration as feature quantities on the basis of the distance traveled in the preceding frames, and determining the point exceeding the numerical value that can be taken by the detection target as disturbance.

The basic flow chart of this technique is shown in **Fig. 5**. First, a distance image is acquired from the depth image sensor, and an initial filter (such as a smoothing filter for noise rejection) is applied to the distance image obtained. After that, the point which is most proximal to the sensor is sought in the distance image and taken as one of the disturbance candidates. In order to extract a plurality of disturbance candidates, circular ranges, each with a predetermined radius r and centered at respective points found previously, are rejected from the search range in the distance image. After this, the most proximal points are sought again. These operations are repeated for a predetermined number of times to extract disturbance candidate points. They are also performed for all the measured frames.

Next, disturbance candidate points are associated time-wise. An example of the association of disturbance candidate points is shown in **Fig. 6**. For each disturbance candidate point $p1(n)$ at a

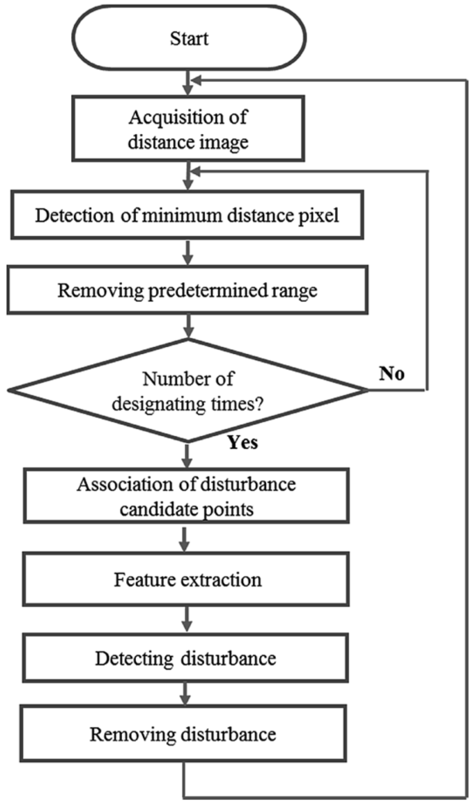

Fig. 5 Flowchart of disturbance rejection filter

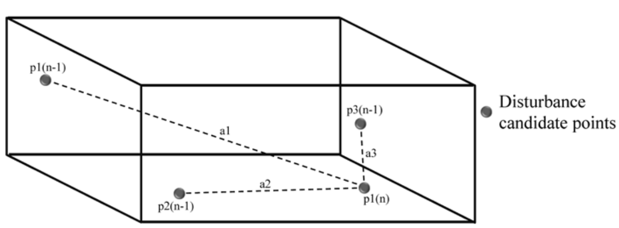

Fig. 6 Association of disturbance candidate points

certain time, n, the distance from the disturbance candidate point of the immediately preceding frame is calculated, and this is carried out for all the combinations. Here, the point that gives the shortest travel distance is regarded as the same point in the immediately preceding frame and is associated time-wise. In Fig. 6, there are three disturbance candidate points in the immediately preceding frame n-1; namely, $p1(n$-$1)$, $p2(n$-$1)$, and $p3(n$-$1)$, and the travel distances are expressed as $a1$, $a2$, and $a3$, respectively. Here, it is assumed that $a1>a2>a3$. At this time, the shortest travel distance is given by $a3$, and thus the same point in the immediately preceding frame of the disturbance candidate point $p1(n)$ is associated time-wise with $p3(n$-$1)$.

After the time-wise association of the disturbance candidate points is performed as described above, the speed, angle, and acceleration are calculated as feature quantities for determining the existence of a disturbance. When the disturbance candidate points

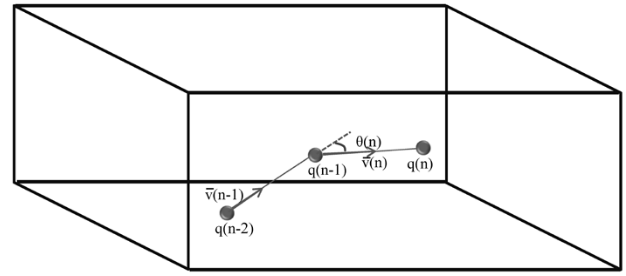

Fig. 7 Position of disturbance candidate points

are positioned as in **Fig. 7** and the candidate points of each frame are associated time-wise with $q(n)$, $q(n$-$1)$, and $q(n$-$2)$, the velocity vector, $\bar{v}$, is calculated by Equation (1) and Equation (2).

$$\bar{v}(\mathrm{n}) = (q(n)\text{-}q(n\text{-}1))/\Delta t \quad \cdots\cdots (1)$$

$$\bar{v}(\mathrm{n\text{-}1}) = (q(n\text{-}1)\text{-}q(n\text{-}2))/\Delta t \quad \cdots\cdots (2),$$

wherein Δt is the time length between the frames.

Subsequently, the angle θ of the velocity vector between the frames is calculated by Equation (3).

$$\theta(\mathrm{n}) = \angle(\bar{v}(\mathrm{n}), \bar{v}(\mathrm{n\text{-}1})) \quad \cdots\cdots (3)$$

Further, the acceleration vector, $\bar{a}$, is calculated by Equation (4).

$$\bar{a}(\mathrm{n}) = (\bar{v}(\mathrm{n})\text{-}\bar{v}(\mathrm{n\text{-}1}))/\Delta t \quad \cdots\cdots (4)$$

A disturbance is judged to exist when any one of the results of calculating Equations (1) to (4) exceeds the set threshold. It should be noted that the velocity vector and the acceleration vector are determined by absolute values.

The points judged to be disturbances by the disturbance rejection filter described above are excluded from the distance measurement on the distance image to prevent erroneous detection.

4. Verifying effects of disturbance rejection filter

The most proximal points were extracted from the results of the test performed in Section 2, in which the disturbance rejection filter described in Section 3 was applied, and the results are shown in **Fig. 8**. Here, the search range exclusion radius of each disturbance candidate was r=150 mm, the number of extraction times for each disturbance candidate was 10, and the thresholds for the judgement of a disturbance are set at 5 m/s for the speed, 3 m/s^2 for the acceleration, and 90 degrees for the angle. The time interval between the frames was set at 50 ms. For the setting of each threshold, reference was made to the falling velocity of 6.5 m/s for a raindrop with a standard size (diameter 2 mm)[4] and the acceleration of approximately 4.8 m/s^2, which is the minimum value of the acceleration measured for an insect (fly),[5] to set respective values lower than these. For the angle, there was no suitable data, and a numerical value was provisionally determined.

The results of the position detection of the object exhibit a graph clearly showing the back and forth motion of the object for two rounds, showing that the influence of disturbances is rejected to allow the position detection of the detection target.

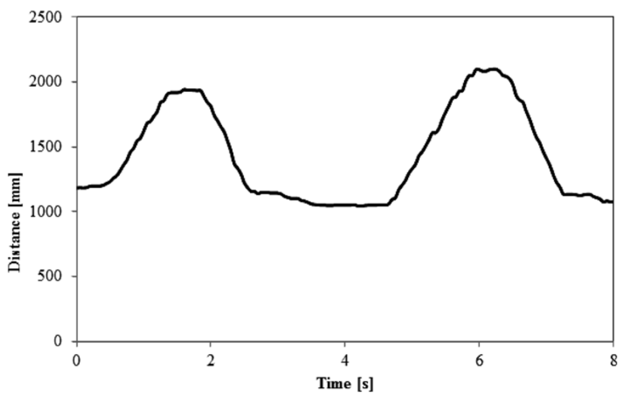

Fig. 8 Detection of object position through disturbance rejection filter

Conclusions

A filter to reject the influence of disturbances such as rain and snow has been developed for a sensor installed on an excavator and used for acquiring information on the surrounding area in an outdoor environment. This filter is configured to judge and reject disturbances, using the velocity, acceleration, and angle of disturbance candidate points in measurement frames, and its ability to detect the positions of objects even in the rain has been confirmed. In the future, this technique will be used for sensors to acquire distance information in the surrounding area, which will lead to the new functional development of excavators.

References

1) N. Mitsuyanagi. *Kensetsu no sekō kikaku*. 2009, No. 709, pp. 52-57.
2) C. Shike el al. *Komatsu technical report*. 2015, Vol. 61, No.168, pp. 2-6.
3) *Japan Construction Machinery and Construction Association Standard*. JCMAS H017, 2003.
4) M. Kumai el al. *Journal of the Meteorological Society of Japan*. 1954, Vol. 32, No. 3, pp. 69-76.
5) R. P. Ray el al. *Nature Communications*. 2016 Vol. 7, No. 10851.