Sensor applications

Development of a Bathing Accident Monitoring System Using a Depth Sensor

Yoshiaki Endo[1] and Chinthaka Premachandra[2*]

[1]Department of Electronic Engineering, School of Engineering, Shibaura Institute of Technology, Tokyo 135-8548, Japan
[2]Department of Electronic Engineering, School of Engineering/Graduate School of Engineering and Science, Shibaura Institute of Technology, Tokyo 135-8548, Japan
*Senior Member, IEEE

Manuscript received December 18, 2021; accepted December 28, 2021. Date of publication December 31, 2021; date of current version January 27, 2022.

Abstract— Among the domestic accidents that occur globally, a few percent are due to accidental drowning, mostly related to bathing. This letter examines countermeasures against bathing accidents and proposes a bathing accident monitoring system to prevent accidental drowning due to loss of consciousness during bathing. This system considers the user's privacy and uses only the depth information acquired by a depth sensor installed in the bathroom. This system grasps the movement of the bather with a depth sensor and informs others, such as the bather's family, when drowning might be occurring. In this letter, we mainly analyzed depth data from depth sensors and developed automatic detection of drowning conditions. Automatic detection of the drowning state was experimentally evaluated in an actual bathroom. The scenario for the experiment was the natural flow of a series of general bathing movements (e.g., normal bathing, wiping the face, and touching the shoulders) and reproduction of the drowning state. As a result, it was shown that the automatic detection rate of the drowning state was at the applicable level.

Index Terms—Sensor applications, Bathing accident prevention, depth sensor, drowning detection, monitoring system, skeleton point analysis.

I. INTRODUCTION

Fatal domestic accidents occur all over the world. For example, in Japan, out of the approximately 1.4 million people who die annually, 1% die due to domestic accidents. In addition, 40% of domestic accidents in Japan are caused by accidental drowning, and most of which are caused by bathing accidents [1]. In addition, the mortality rate during respiratory arrest increases with the passage of time [2], making prompt lifesaving important. In long-term care and similar facilities, witnessed bathing may be performed as a measure to prevent such bathing accidents, but it is not realistic from the viewpoint of implementation at home and when privacy is required. One of the authors has personally experienced the loss of a relative in a bathing accident. From this experience, we started this research with the hope of decreasing the number of similar accidents as much as possible. Three main types of conventional research focus on the prevention of bathing accidents. The first type detects the movement of physical sensors connected with the bathwater level and bathers. For example, Isonaga *et al.* detected movement of the water level with an acoustic sensor installed in the drain pipe [3]. This approach has the drawbacks of decreased bathing quality by submerging the device in a bath, which also complicates the cleaning of the sensors. The second type directly monitors the condition of the bather using electromagnetic waves. Examples are motion detection using gigahertz-band millimeter-wave radar [4] and a bathing monitoring system using a high-resolution radar [5], such as UWB-IR. A similar approach is the estimation of the waving movement of the bather using the cubic higher order local autocorrelation method [6].

However, this method has drawbacks, including the high cost of equipment for handling millimeter-wave radar and the fact that the detection of drowning may be delayed by the movement of only hands. The third type indirectly monitors the condition of bathers using electromagnetic waves, an example of which is a care recipient monitoring system using RFID tags [7]. In this RFID tag-based method, the RFID tags and antennas have to be installed on both sides of doors and other equipment in the bathroom, so the installation of the system is complicated. Furthermore, some of the above ToF sensors make outliers during the data acquisition compared to depth sensors. On the other hand, the depth sensors are able to generate accurate depth information of a certain area, so the sensing accuracy and range are comparatively higher compared to above mentioned other sensors. Therefore, in this research, we aim to develop a new bathing accident monitoring system using a depth sensor in order to address these problems.

The main causes of drowning during bathing are the loss of consciousness of the bather. Therefore, in this letter, we try to automatically detect the drowning of bathers using depth data acquired by a depth sensor. Specifically, skeleton detection is performed on the depth information obtained from a RealSense depth sensor, and the bathing person's head is detected by tracking the position of the nose. Based on the obtained spatial coordinates of the nose, the altitude of the head is monitored. The drowning condition is judged by comparing the altitude of the nose with the height of the bathtub. The proposed drowning detection algorithm is low-weighted and can be implemented with a normal computer or small type computer (Raspberry pi) in real time. The overall hardware environment is simple and can easily be applied in a normal bathroom. This proposed automatic detection method was implemented in the real world, and its effectiveness was confirmed by experiments.

II. SYSTEM CONFIGURATION AND DETAILS

To detect unconscious bathers in danger of drowning, in this letter, we developed a system using a relatively inexpensive Intel depth sensor. Fig. 1 shows a schematic diagram of the system configuration. The variables in the schematic diagram of Fig. 1 have the following meanings.

1) θc: Installation angle between the central axis of the depth sensor and the ceiling.

Corresponding author: Chinthaka Premachandra e-mail: (chintaka@shibaura-it.sc.jp).
Yoshiaki Endo contributed equally to this work.
Associate Editor: J. M. Corres.
Digital Object Identifier 10.1109/LSENS.2021.3139636

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

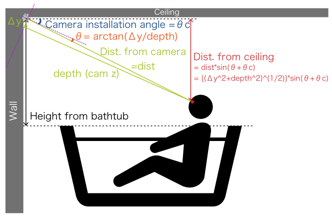

Fig. 1. Outline diagram of the monitoring system.

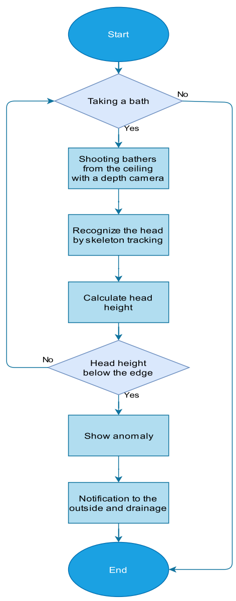

Fig. 2. Data processing flow in the proposed system.

2) θ: Angle between the straight line connecting the camera and the nose and the central axis of the camera, calculated from the depth information acquired by the camera.
3) *Dist.*: Z-axis coordinates obtained from the depth information acquired by the camera, corrected by adding the deviation in the Y-axis direction (straight line distance from the camera to the nose).
4) $Depth$: Z-axis coordinates obtained from the depth information acquired by the camera.
5) Δy: Y-axis coordinates obtained from the depth information acquired by the camera.
6) $Distancefromceiling$: Distance from the ceiling to the nose.
7) *Height from bathtub*: Height from the edge of the bathtub to the camera.

Fig. 2 shows the processing flow of the proposed automatic drowning detection method based on the schematic diagram of Fig. 1. Here, the head position of the bather is measured by analysis of data from the depth sensor, and the drowning state is automatically detected by comparing the nose altitude with the height of the bathtub. This method is described in detail in the following sections.

A. Depth Sensor Application

In this letter, we used an Intel RealSense D415 depth sensor, as shown in Fig. 3, which is already used to study consumer products [8]–[10]. It can easily be connected with a computer and is compatible with software such as skeleton generation software. This camera is equipped with two infrared cameras, an infrared pattern irradiator, and one RGB camera and can measure a range from 0.3 to 10 m in units of 0.1 mm and connect to a PC via a USB port. Generally, two-dimensional (2-D) cameras are used to study these kinds of detection purposes [11]–[13]. Depending on the application, omnidirectional cameras are also applied to develop consumer-level products [14]–[16]. However, the usage of depth sensors leads to protect the privacy of the bathing person rather than 2-D or omnidirectional cameras.

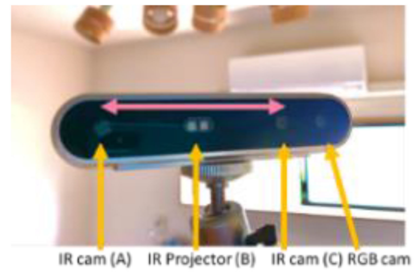

Fig. 3. Intel RealSense D415 depth sensor.

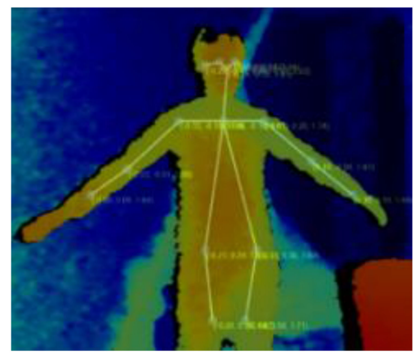

Fig. 4 Actual use of the SDK.

The RealSense D415 measures distance by the active stereo method. The active stereo method measures distance by irradiating the measurement target with an infrared pattern having a specific feature that represents information, such as coordinates, and triangulating the distance to the pattern using two infrared cameras. Because the source of the irradiation pattern in the active stereo method is the camera, it is rarely affected by the brightness of the imaging environment, and it is not necessary to detect the position by the feature value. This is very effective for applying this system to various types of bathrooms.

B. Skeleton Tracking

In this letter, the spatial coordinates of the nose are acquired using skeleton detection and used to monitor the head altitude. For this purpose, we used Skeleton Tracking SDK by Cubemos, Germany, which is a skeleton detection software development kit (SDK) [17], [18]. In combination with a general programming language such as Python or C++, this SDK detects the key body monitoring points from real-time streams, images, and video files acquired from the camera. Key features of this SDK include labeling processing, coordinate acquisition, and assignment of key points to the skeleton, which can be combined with the original data and used as variables in the software.

Skeleton detection was performed and the key points were labeled, the coordinates displayed, and the skeleton depicted on the depth image acquired by the RealSense depth sensor. The detection of these key points by the SDK is shown in Fig. 4. In this letter, we mainly used the skull for altitude detection. The drowning detection algorithm has been completely developed following the skeleton information on the depth sensor images.

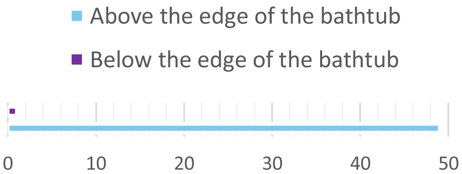

Fig. 5. Survey results on head position during normal bathing.

Fig. 6. Obtained 2-D RGB image.

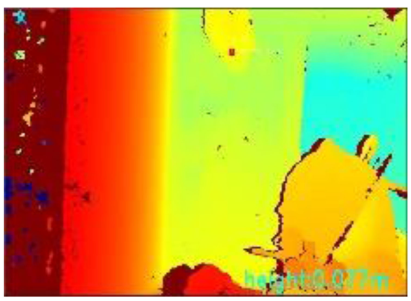

Fig. 7. Obtained 2-D depth image.

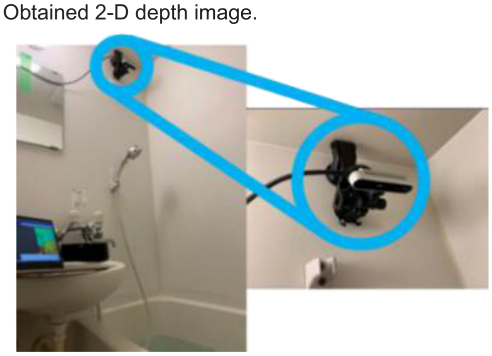

Fig. 8. Equipment installation location.

III. DROWNING DETECTION BY DEPTH SENSOR

A. Drowning Definition and Head Position Measurement

In this letter, the drowning state is defined as a numerical value based on the altitude of the head of the bather. As part of a survey, we asked 50 men and women in their teens to 70s about the typical position of their head relative to the edge of the bathtub during normal bathing. The survey results are shown in Fig. 5. According to this survey, 49 respondents (98%) typically held their heads above the edge of the bathtub. Based on this result, we decided to define the state where the nose is below the edge of the bathtub as drowning.

We aimed to create a drowning detection system that does not require the user to make complicated settings and has the potential for practical use with various types of bathtubs installed in general homes and nursing care facilities. In this system, the installation angle (θc) and altitude of the camera are positioned with respect to the upper edge of the tub, as shown in Figs. 1 and 8. The altitude ($Height from bathtub$) refers to the difference in height between the camera and the edge of the bathtub rather than between the camera and bottom of the bathtub and is measured by the installer after initial installation.

To detect drowning, the distance from the ceiling to the nose (Dist. from ceiling) is first calculated as follows:

$$\text{Dist. from ceiling} = \text{Dist.} \times \sin(\theta + \theta_C) \quad (1)$$

where Dist. is the Z-axis coordinate obtained from the depth information acquired by the depth sensor, corrected by adding the deviation in the Y-axis direction (i.e., the straight-line distance from the sensor to the nose), and θ is the angle between the straight line connecting the camera and the nose and the central axis of the camera, calculated from the depth information obtained by the depth sensor.

Using the position of the nose obtained from (1), the state is considered as drowning when the following inequality is true:

$$\text{Height from bathtub} \leq \text{Dist. from ceiling.} \quad (2)$$

B. Determining Drowning State Using Skeleton Detection

In the skeleton tracking SDK used in this study, 2-D RGB images are generally used for skeleton detection, and the result of motion capture is displayed using the Unity engine. However, because this research assumes that the system will be used in a private space such as a bathroom, acquisition of a 2-D RGB stream is not appropriate. Therefore, we instead use a color map of a 2-D depth image, created using depth information acquired by the depth sensor.

Fig. 6 shows a 2-D RGB image obtained from the RealSense depth sensor. Fig. 7 shows the 2-D depth image obtained from the 2-D RGB image in Fig. 6. The position of the nose was determined using skeleton detection and is represented by a red dot. The *height* in the lower right of Fig. 7 represents the difference in height between the edge of the bathtub and the nose calculated from the result of (1) in the previous section. Based on this height information, the drowning state is determined using (2).

IV. EXPERIMENTS

A. Experimental Environment

In this letter, we conducted many evaluation experiments and confirmed the effectiveness of the proposed automatic drowning detection system. Table 1 illustrates the bathroom environment in which the experiment was conducted.

TABLE 1. Experimental Environment.

Item	Value
Room temperature	22°C
Water temperature	40°C
Camera installation angle (θ_c)	65°
Height from bathtub	1.35 m

As shown in Fig. 8, we installed the equipment in a bathroom and filled the bathtub with hot water (water temperature, ∼40 °C). The installation of the camera was done with an angle-adjustable camera holder. Therefore, preferred angles can easily be set with this holder. The altitude of the nose was determined using skeleton detection and depth information acquired by the depth sensor. In the experiment, a series of typical bathing behaviors were performed (e.g., normal bathing, wiping the face, and touching the shoulder), as was the simulation of the drowning state. In more detail, these experiments were conducted using ten subjects, with the 6000 frames under the drowning situation and 6000 frames under the nondrowning (normal bathing) situation. The position of the nose was monitored during all these activities, and an evaluation of the drowning detection system was conducted.

B. Experimental Results

The example of the detection situation is shown in Figs. 9 and 10. The red dot in Fig. 10 is the nose as detected using skeleton detection,

Fig. 9. State of drowning.

Fig. 10. Drowning detection.

TABLE 2. Detection Result.

	Positive	False	Undetected
Normal bathing	88.7%	3.2%	8.1%
Drowning	94.1%	5.9%	0.0%

the light blue letters show the distance with respect to the edge of the bathtub calculated by (1), and the pink text represents the result of (2). The drowning states are judged from these. The RGB image displayed in Fig. 9 is used only for verifying the experimental results, and the detection system processes only the depth images during actual use. The results of the system can further be confirmed through the submitted video with this letter.

Table 2 lists the results of multiple experiments with the proposed method. In the table, "False" refers to false positives detected by the system (i.e., a judgment of drowning during normal bathing or a judgment of normal bathing during drowning simulations), and "Undetected" refers to instances when the nose could not be detected.

As it can be seen in Table 2, the rate of drowning detection rate in this letter is high. The accuracy following the confusion matrix is 91.4%. The most common error, instances where the nose could not be detected during normal bathing, is thought to have been caused by touching the face or turning the head sideways. As Table 2 lists a minor number of false detections and undetections occurred at the normal bathing situation. Undetections refer to the situation in which the nose is not detected. These false and undetections occurred when the bather touches face by hand.

On the other hand, a minor number of false detections also occurred during drowning situations. This means that the drowning situations were detected as normal bathing situations. However, according to our observation, these minor false detections did not occur in the consecutive frames and drowning was correctly detected from the nearby frames of the falsely detected frames. Following the correct detections from the nearby frames, the system can inform the drowning situation to the user's family or to another party.

One problem with the current system is that the nose is sometimes temporarily hidden and the coordinate data fluctuate. This is thought to be caused by differences in individual bathing styles, and it may be impossible to completely account for these differences. In addition, automated response actions such as notification alerts and automatic bathtub drainage were not implemented in this study and remained as future work.

According to the experiments, the system showed almost similar results under the incandescent light condition, fluorescent light, and LED light conditions.

V. CONCLUSION

In this letter, we proposed a system to prevent accidental drowning during bathing using the processing of information acquired by a depth sensor. According to the operational experiments of the system, highly accurate results were obtained for the detection of drowning. In the future, we plan to further reduce the false positives during drowning. In addition to that, we plan to develop automated response actions (automatic drainage and notification to family members) when drowning is detected.

REFERENCES

[1] Ministry of Health, Labor and Welfare, "Vital statistics vital statistics confirmed number of deaths 5-35 number of deaths and percentages by age by type of major unexpected accidents at home," 2017.

[2] Fire and Disaster Management Agency, "Ministry of internal affairs and communications," I want to save a life that can be saved," Accessed: Dec. 10, 2020. [Online] Available: https://www.fdma.go.jp/en/items/en_03.pdf

[3] S. Isonaga, S. Hattori, M. Okamoto, and S. Tanaka, "Measurement of water level in a monitoring system of a bathroom," in *Proc. SICE Annu. Conf.*, Aug. 2005, pp. 1730–1734.

[4] S. Matsuguma and A. Kajiwara, "Bathroom accident detection with 79GHz-bandmillimeter wave sensor," in *Proc. IEEE Sensors Appl. Symp.*, Mar. 2019, pp. 1–5.

[5] K. Jimi, H. Seto, and A. Kajiwara, "Bathroom monitoring with fast-chirp modulation millimeter-wave UWB radar," in *Proc. IEEE Radio Wireless Symp.*, Mar. 2020, pp. 134–137.

[6] K. Kashima, R. Nakamura, and A. Kajiwara, "Bathroom movements monitoring UWB sensor with feature extraction algorithm," in *Proc. IEEE Sensors Appl. Symp.*, Feb. 2013, pp. 118–122.

[7] D. Chen, B. Zeng, Z. Sun, L. Zhao, Z. Huang, and M. Wang, "An off-bed detection and bathroom accident monitor system for nursing home," in *Proc. Int. Conf. Adv. Robot. Mechatronics*, Aug. 2016, pp. 53–58.

[8] Y. Ito, C. Premachandra, S. Sumathipala, H. W. H. Premachandra, and B. S. Sudantha, "Tactile paving detection by dynamic thresholding based on HSV space analysis for developing a walking support system," *IEEE Access*, vol. 9, pp. 20358–20367, Jan. 2021.

[9] S. Sasaki and C. Premachandra, "Head posture estimation by deep learning using 3D point cloud data from a depth sensor," *IEEE Sensors Lett.*, vol. 5, no. 7, pp. 1–4, Jul. 2021.

[10] C. Y. Chih, Y. C. Wan, Y. C. Hsu, and L. G. Chen, "Interactive sticker system with Intel realsense," in *Proc. IEEE Int. Conf. Consum. Electron.*, 2017, pp. 174–175.

[11] M. Muštra and A. Štajduhar, "Segmentation masks for the mini-mammographic image analysis society (mini-MIAS) database," *IEEE Consum. Electron. Mag.*, vol. 9, no. 5, pp. 28–33, Sep. 2020.

[12] Q. M. U. Haq, M. A. Haq, S. J. Ruan, P. J. Liang, and D. Q. Gao, "3D Object detection based on proposal generation network utilizing monocular images," *IEEE Consum. Electron. Mag.*, to be published, doi: 10.1109/MCE.2021.3059565.

[13] E. A. P. J. Prawiro, N. K. Chou, M. W. Lee, and Y. H. Lin, "A wearable system that detects posture and heart rate: Designing an integrated device with multiparameter measurements for better health care," *IEEE Consum. Electron. Mag.*, vol. 8, no. 2, pp. 78–83, Mar. 2019.

[14] S. Ono and C. Premachandra, "Generation of panoramic images by two hemispherical cameras independent of installation location," *IEEE Consum. Electron. Mag.*, vol. 11, no. 1, pp. 17–25, Jan. 2022.

[15] C. Premachandra, S. Ueda, and Y. Suzuki, "Detection and tracking of moving objects at road intersections using a 360-Degree camera for driver assistance and automated driving," *IEEE Access*, vol. 8, pp. 135652–135660, Jul. 2020.

[16] C. Premachandra and M. Tamaki, "A hybrid camera system for high-resolutionization of target objects in omnidirectional images," *IEEE Sensors J.*, vol. 21, no. 9, pp. 10752–10760, May 2021.

[17] Intel, "Skeleton tracking SDK for Intel realsense^{TM} depth cameras," Accessed: Dec. 10, 2020. [Online]. Available: https://www.intelrealsense.com/skeleton-tracking/

[18] J. V. Patil and P. Bailke, "Real time facial expression recognition using realsense camera and ANN," in *Proc. Int. Conf. Inventive Comput. Technol.*, 2016, vol. 2, pp. 1–6.