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Economic Floating Waste Detectionfor Surface Cleaning Robots

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Abstract. Removing waste out of water surface is a routine task and can be operated by using autonomous surface cleaning robots. This paper presents amethodoflaser-based floating waste detection for surface robot guidance when waste positions are unknown beforehand. Basing on concept of refraction and reflection of laser ray, the proposed laser-based technique is proven to be applicable on floating waste detection. The economic waste detector is constructed and mounted on the robot. Five DOF equations of motion are formulated for calculation of waste position incorporating distance measured by the laser and also the robot motion caused by external wind force as well as water surface tension. Experiments were conducted on a pond with calm water and results show that the presented economic waste detection successfully identify and locate position of plastic bottles floating on water surface within the range of 5 meters.

1 Introducion

In developing countries, accumulation of floating waste such as plastic scraps, foam scraps or tree leaves on city canals or ponds can block water drainage and also cause pollutions. Cleaning water surface is therefore an essential routine task.

Surface cleaning robots on lake, pond, or reservoirs gained interests from researchers and issues were addressed such as motion control and autonomous driving. Motion of the robot was represented by hydrodynamic model and maneuver ability performance was predictable [1]. The asymptotic stabilizaion control was also theoretically validated for motion control of the surface robot [2]. As for autonomous driving, bank following algorithm with obstacle avoidance was implemented by using ultrasonic sensors [3]. Later, a low cost robot structure design was presented and simulation of multi robot system for lake cleaning was proposed [4]. The strategy of waste removal in a large area was presented whereas waste is assumed to be randomly distributed but waste position is known. On the other hand, the problem of waste detectionwhen waste position is unknown had not yet been investigated.

Laser range finder showed high performance on ocean navigation of unmanned surface vehicles. LIDAR was utilized for obstacle detection and avoidance of obstacle above ocean level for autonomous driving [5-6].The laser scanner is also used for 3D surface reconstruction in which both below and above water level structure were scanned[7].Along with the performance, cost of the laser scanner is high.

This work presents a method for identifying and locating waste floating on calm water surface by using a low cost laser system before the cleaning robot starts navigation. A Pan-Tilt laser unit is utilized as a waste detector heading into water surface and scanning for floating waste. When the waste detector is mounted on the robot floating on water surface, external wind force causes three dimensional rotations. Accordingly, waste position can be obtained from five degree of freedom equations of motion.

This paper is organized as follows: In section 2, the Floating Waste Removal Robot and the waste detector are introduced. Next, the method to identify floating waste is explained and equations for waste position are formulated in section 3. Section 4 presents experimental results. Finally, conclusions and future works are given.

2 Floating waste removal robot

2.1 The robot structure

As shown in Fig. 1, the floating waste removal robot was developed for cleaning on calm water surface such as on city canal, lake, pond, pool, etc.The robot structure is apontoondriven by two paddle wheels and a rudder. The robot has two types of waste collectors and a waste container. The front waste collector is a flight conveyor with half-cylindrical fin developed in [8] and side collectors are net basket lifted by arms. Performances of the waste collectors were evaluated in [9]. Plastic bottles were used in experimentsas floating waste and the best waste collecting performance was at 1.71 kg/minute.

The robot is controlled by Arduinos interfacing with sensors and motor driver modules. The GPS and IMU sensorsprovide information about robot position and inertia. Encodersmeasurerobot driving speed and

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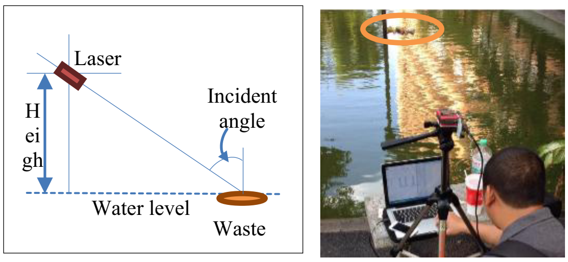
conveyor belt speed.The robot is tele-operated control by using joystick and keyboard whereasan operator can manually control the robot speed andthe flight conveyor belt speed. Thoughthe operator cansee floating waste from video taken via a wireless camera onboard, it is hard to estimate distance to the waste floating.

Figure 1. The floating waste removal robot and the waste detector mounted on the top.

Figure 2. The wastedetector.



Side view (b) Configuration

Figure 3. Test of laser tilt range.

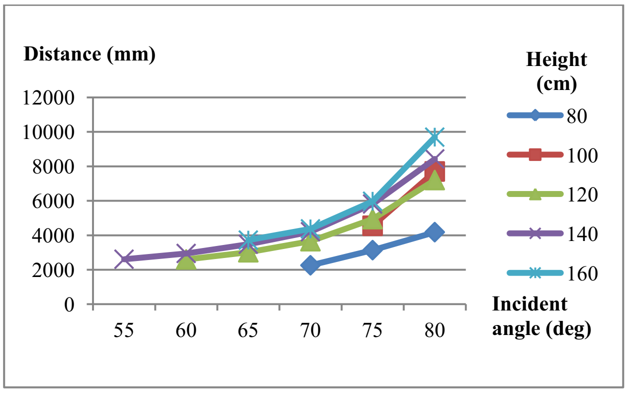


Figure 4. Tilt range test results.

2.2 The waste detector

The waste detector is mounted on the top of the robot as shown in Fig. 1 marked as a red circle.Fig. 2 shows the waste detectorconsisting of a Pan-Tiltlaser unitanda digital distance meter UNI-T-UT-390B mounted on the top. The meter is selected since it is a low cost laser device. Arduino Mega 2560interfaces with the digital distance meter and two Turnigy620DMG servo motors controlling pan and tilt angle. In order to detect the robot motion,CMPS10 sensoris also mounted at the center of robot's base for measuring roll, pitch, and yaw angle.

3 Laser based waste detection

3.1 Background

Laser system has been recently developed for water level measurement [10]. A pulse laser rangefinder sensor using phase method was pointing perpendicularly to calm and sloshing water surface for water level detection.

When laser ray is non-perpendicular to water surface, refraction occurs at interface between air and water where the refractive index depends on density of medium [11]. The refracted ray always point to the denser medium. In this case, the refracted ray points into water. As a result, distance to water surface is not measurable. On the other hand, when there is waste floating such as plastic bottles, the incident ray is reflected on the waste back to the digital meter and distance to the waste is measurable.

A simple test isdone to provethe conceptabove by holding the digital meterabove water level andreadvaluedisplayed on the meter. By several trials, the sameresultisobtained. That iswhen the meterpoints non-perpendicularlyinto water,measured value is not obtainedfrom the digital distance metersince the distance meter shows error message.Whenthe meter points perpendicularlyinto water, the meter shows water level.

3.2 Range of laser scan

Before mounting the waste detector on the robot, several tests were conductedin order to obtain appropriate mounting configuration.

The first step isfinding the range of maximum and minimum incident anglethat can identify waste on water surface. As shown in Fig. 3a, the height and the incident angle are adjustable. During the test, the waste detector is mounted on a camera stand as shown in Fig. 3b andplastic bottles are marked as an orange oval. By varying the height of the waste detector from 80 to 160 cm above water level and varying the incident angle from 50 to 85 degrees, the distance to the waste is measured by laser. Fig. 4 shows the measured distance at each height and incident angle.It is shown that different range of incident angle is obtained for each height level. At 160 cm above water level and 80 degree of incident angle, the waste can be detected at nearly 10 meters.The widest range of incident angle, from55 to80 degrees,is obtained at 140 cm.

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The secondstep is to ensurethe appropriate height for mounting the waste detector on the robot. The plastic bottlesare fixed at 4 meters away from the camera stand. For each height, the incident angle is varied until the waste is detected. As shown in Table 1, when the laser unit is higher, the incident angle is smaller.At 160 cmheight, the error is large.Therefore, the appropriate height for mounting on the robot is up to 140 cm above water level. This complies with the results in Fig. 4 showing that the 120 cm and 140 cm height yields wide range of measurement.

Table 1. Distance tothe floating plastic bottles (mm)

Height (cm) / Incident angle (degree)	80	100	120	140	160
80	4180	-	-	-	-
75	-	4099	-	-	-
72	-	-	4091	4188	
70	-	-	-	-	4495

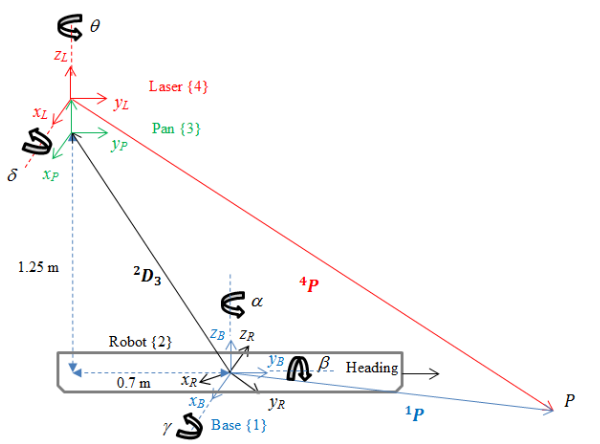

Figure 5. Sideview of the robot illustratingrelationshipamong frames.

3.3 Calculation for waste position

Four reference frames are defined as the Base frame, the Robot frame, the Pan frame, and the Laser frame, respectively.Assume the robot is stand still and represented by the Base frame as in Fig. 5. The robot is heading along y-axis. The waste detector motion is represented as the Pan and the Laser frame on the top.Based on the composite transformation of frames [12], neglecting linear motion, rotation from frame 2 to frame 1 is the rotation of robot caused by external wind force and surface tension can be written as

$$
{}^{1}\boldsymbol{R}_2(\boldsymbol{\alpha},\boldsymbol{\beta},\boldsymbol{\gamma}) = \begin{bmatrix} cos\alpha & -sin\alpha & 0 \\ sin\alpha & cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} cos\beta & 0 & sin\beta \\ 0 & 1 & 0 \\ -sin\beta & 0 & cos\beta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\gamma & -sin\gamma \\ 0 & sin\gamma & cos\gamma \end{bmatrix}. \tag{1}
$$

where α, β, and γ, are roll, pitch, and yaw angle, respectively. There is no translation from frame 2 to frame 1, therefore the translation vector ${}^{1}\boldsymbol{D}_2$ is zero.The transformation matrix from frame 2 to frame 1 can be written as

$$
{}^{1}\boldsymbol{T}_2 = \left[\begin{array}{c:c} {}^{1}\boldsymbol{R}_2(\boldsymbol{\alpha},\boldsymbol{\beta},\boldsymbol{\gamma}) & {}^{1}\boldsymbol{D}_2 \\ \hdashline 0 & 1 \end{array}\right]. \tag{2}
$$

Frame 3 is rotated by the pan angle, θ. The rotation matrix from frame 3 to frame 2 is

$$
{}^{2}\boldsymbol{R}_3(\boldsymbol{\theta}) = \begin{bmatrix} cos\theta & -sin\theta & 0 \\ sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{3}
$$

Frame 3 is 1.25 m above and 0.7 m behind Frame 2. Thus, the translation vector from frame 3 to frame 2 is

$$
{}^{2}\boldsymbol{D}_3 = [0 - 0.7\ 1.25]^T. \tag{4}
$$

According to Eq. (3) and (4), the transformation matrix from frame 3 to frame 2 is

$$
{}^{2}\boldsymbol{T}_3 = \left[\begin{array}{c:c} {}^{2}\boldsymbol{R}_3(\boldsymbol{\theta}) & {}^{2}\boldsymbol{D}_3 \\ \hdashline 0 & 1 \end{array}\right]. \tag{5}
$$

Frame 4 is rotated by the tilt angle, δ. The rotation matrix from frame 4 to frame 3 is

$$
{}^{3}\boldsymbol{R}_4(\boldsymbol{\delta}) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\delta & -sin\delta \\ 0 & sin\delta & cos\delta \end{bmatrix}. \tag{6}
$$

Frame 4 is 4.25 cm above frame 3. Thus, the translation vector from frame 4 to frame 3 is

$$
{}^{3}\boldsymbol{D}_4 = [0 \quad 0 \quad 0.00425]^T. \tag{7}
$$

According to Eqs. (6) and (7), the transformation matrix from frame4 to frame3 is

$$
{}^{3}\boldsymbol{T}_4 = \left[\begin{array}{c:c} {}^{3}\boldsymbol{R}_4(\boldsymbol{\delta}) & {}^{3}\boldsymbol{D}_4 \\ \hdashline 0 & 1 \end{array}\right]. \tag{8}
$$

Finally, the waste position P referred to frame 1 can be calculated by

$$
{}^{1}\boldsymbol{P} = {}^{1}\boldsymbol{T}_2\, {}^{2}\boldsymbol{T}_3\, {}^{3}\boldsymbol{T}_4\, {}^{4}\boldsymbol{P}. \tag{9}
$$

The vector ${}^{1}\boldsymbol{P}$ is a vector to point P on frame 1, $[x\ y\ z\ 1]^T$. The vector ${}^{4}\boldsymbol{P}$ is a vector to point P on frame 4, $[0\ d\ 0\ 1]^T$ and d is distance from frame 4 to point P and is measured by the digital meter.

4 Experimental results

The waste detection istested on a pond under no sway, no surge, and no heave. During the experiment, the robot is standstill and the water is calm. Due to the external wind force and surface tension, the robot motion is slightly rotated in the roll, pitch, and yaw direction. Plastic bottles

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are used as floating waste since it is often found waste in city canals and river.

Figure 6. Test environment.

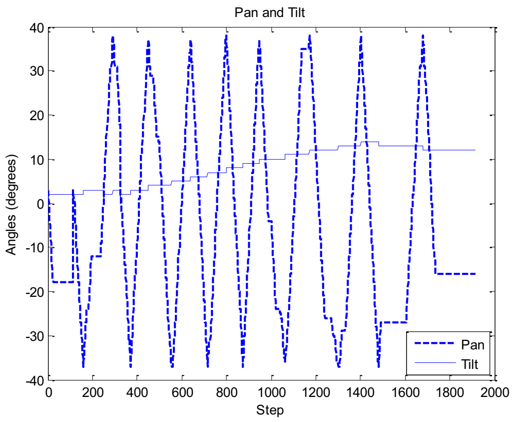

Figure 7. Pan and tilt angles.

The coordinate of the robot is at (0,0). As shown in Fig. 6, in the front of the robot are plastic bottles floating on water surface at coordinate(250,400) referred to the robot position. The size of the plastic bottles is 0.5 m radius.

During the waste detection, the laser scan is stepped by servomotor command as shown in Fig. 7. The results are analysed by using MATLAB. Range of the pan angle is from -38 to +38 degrees and range of the tilt angle is from 2 to 14 degrees. For each tilt angle step, the pan angle is varied from the minimum to the maximum angle. The scan stops when both the maximum pan and tilt angle are reached. At each scan step, the roll, pitch, and yaw angle, as well as the distance are measured.

Fig. 8 shows the yaw angle at each step during the scan. At the beginning, the yaw angle swings in the range of 141.5 to 145 degrees due to surface tension and external wind force. After a while, the yaw angle lies between 141.5 to 142 degrees. Meanwhile, both the roll and the pitch angle are quite still. Both of them lie between 0 and 1 degree.

The laser measurement returns two types of output, zero and distance value. When there is no waste found on water surface, measured distance is set to zero as the incident ray is refracted into water and the meter returns no value. When the waste is found, measured distance is obtained as the laser ray reflects on plastic bottles back to the meter and the meter returns a valid distance value. The raw data of measured distance is plotted in Fig. 9. From the beginning, between steps 1 to 400, the distance values are zero. Later, between steps 400 and 505, some distance values are slightly obtained. After that the distance value is again zero in the range of steps 505 to 1015. Between steps 1015 and 1085, distance values are densely obtained since the plastic bottles are foundand the distance is at approximately480 cmaway. After step 1085, the distance values are again zero with some values until the last step.

In total there are 1915 scanned points, in which only 85 points contains distance value. Fig. 10 shows the plot of waste positions on xy plane using the distance value of those 85 points and eq. (9). Out of 85 points, 61 points are the plastic bottles and 24 points are unknown objects. The density of those 61 points verifies that the plastic bottles are successfully detected. The center of the detected waste points is closed to (250,400).

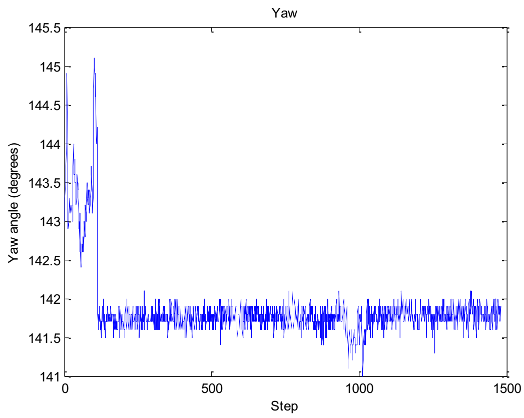

Figure 8. Yaw angle on the Base frame.

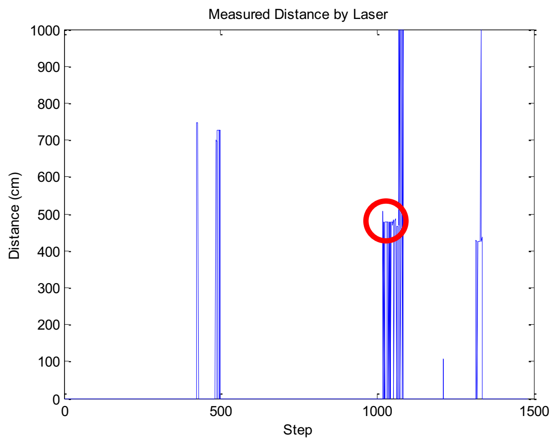

Figure 9. Distance measured by laser.

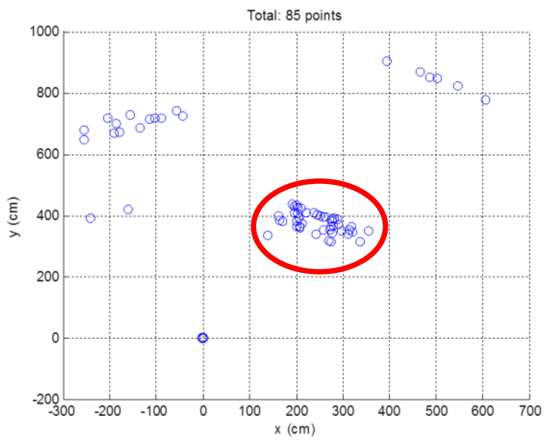

Figure 10. Waste detection result.

Please note that the floating waste in Fig. 6 is also marked in Figs. 9 and 10 accordingly. From the experiments, it is found that brightness of sunlight on water surface can cause error on distance measurement of the laser. When the sun light is too bright such as at noon or too dark at night, the digital distance meter returns no value.

5 Conclusions and future works

The presentedlaser-basedwastedetection technique wassuccessfullyvalidated on a pond.The experimentalresultsshowedthatthe constructedlow-cost waste detector is able to identify and locate position of plastic bottlesfloatingon calm water within the range of 5 metersawayfrom the surface robot. This technique is applicable for autonomousrobot guidance in unknownenvironmentunder medium sunlight illuminationwherewaste position ispriori unknown.

Future workisimprovement ofthe wastedetectionperformance and integrationwith GPS data in order tolocatewaste position in global coordinate.

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