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Identification for Recycling Polyethylene Terephthalate (PET) Plastic Bottles by Polarization Vision

ZHIYING TAN[1,2], ZHONGWEN FEI[1,2], BAOLAI ZHAO[1,2], JIAN YANG[3], XIAOBIN XU[1,2], AND ZILONG WANG[1,2]

[1]College of Mechanical and Electrical Engineering, Hohai University, Changzhou 213022, China
[2]Jiangsu Key Laboratory of Special Robot Technology, Hohai University, Changzhou 213022, China
[3]College of Mechanical Engineering, Yangzhou University, Yangzhou 225127, China

Corresponding author: Zhiying Tan (zytan@hhu.edu.cn)

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ABSTRACT The recycling of disposed PET plastic bottles has significant meaning for environmental pollution control and resource recycling. The reuse value heavily depends on the purity of the recycled PET. In order to improve the purity of PET recycling, a new means of material identification of PET plastic bottle based on polarization vision is proposed. To identify PET plastic bottles on conveyor belt, an effective region segmentation method for plastic bottle location and feature extraction has been put forward. The polarization of the scattered light on the surface of the object contains the information of its material. To obtain robust material characteristics of the PET plastic bottle, an approximate refractive index calculation method based on the degree of polarization and phase angle is introduced. The mean, standard deviation and coefficient of variation of the approximate refractive index and intensity distribution are used to construct the feature vector. The support vector machine (SVM) algorithm was used for PET identification. The experimental results show that the mean accuracy of PET plastic bottles material identification of recycled bottles is up to 92.06%.

INDEX TERMS Plastic recycling, polarization vision, refractive index.

I. INTRODUCTION

Due to the strong barrier property, PET has become one of the most important packaging material for almost all kinds of beverages, including juice, milk and its products, tea, mineral water and some foods. At present, the majority of PET plastic bottles are made of raw pet materials extracted from fossil oil [1]. The annual production of PET plastic bottles, of 3 million tons consumes more than 18 million tons of petroleum, which causes great environmental pressure. The recycling of PET not only conserves resources, but also creates wealth for the society [2]. The recycled PET can be reused to produce staple fiber, filament, packing belt, sheet and food grade slice according to different quality grades [3], [4]. The quality of the recycling highly depends on the purity of the sorted raw materials.

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The methods for PET separation are divided into gravity, electrostatic, and magnetic density separation, flotation, and sensor-based sorting [5]. Common plastic bottles are mainly made of PET, polyvinyl chloride (PVC), polyethylene (PE), polypropylene (PP) and polystyrene (PS). The purity of the recycled PET depends on the identification rate of PET bottles out of many different plastic products. A wet shaking table was used to separate PET from cleaned PVC and PS [6]. Three stage sink–float method and selective flotation, were used for separation PET from PVC [7]. For the cleaning packaging plastics, the 97.2% PET purity can be attained by the combination of alkaline treatment and froth flotation [8].

Although the magnitude and polarity of the generated charge depends on the contacted polymers material can be used sorting plastics into PP, PET/PS, PVC and HDPE, it is difficult to distinguish PET from PS [9]. The triboelectrostatic separation of PVC, PET, and ABS has been performed successfully in the two-stage process [10].

A 200-800nm spectral window was generated by using laser-induced plasma spectroscopy (LIPS) to act on the consumer plastics. The collected plasma emission spectral data compared with reference spectral libraries stored in computer. The linear and rank correlations statistical correlation methods were used to distinguish plastic materials [11], [12]. Laser-Induced Breakdown Spectroscopy (LIBS) was applied for the identification six kinds recyclable polymers by focusing a Nd:YAG laser radiation at wavelength 1064nm having laser energy = 40 mJ [13]. Using LIBS together with discriminant function analysis (DFA) has the ability to correctly classify 99% of the polymers [14]. The best conditions were proposed with laser and the helium buffer gas, which can efficiently identify the four groups of plastics PS, PP, ABS and ABS/PC [15].

Near infrared (NIR) reflectance measurements are used to identify bottle composition class. The classification accuracy reached 94.14% by the dipwavelength and average values of the reflective NIR spectrum [16]. For identification and separation among containers and bottles made of PET, HDPE, PVC, PP and PS, a "Two-Filter" identification method was proposed based on NIR reflectance spectroscopy [17]. An approach combining mid infrared (MIR) spectroscopy with independent components analysis (ICA), which gave 100% discrimination rates in the separation of all studied plastics: PET, PE, PP, PS and PLA [18]. However, the discrimination rates decreased to the surface contaminations of plastics wastes. Two near-infrared wavelength operator and hyperspectral images has been used for achieving 100% identification accuracy of PET and PVC [19].

Hyperspectral imaging (HSI) in the near infrared (NIR) range (1000 – 1700 nm) was evaluated to discriminate PET from PLA provided a prediction efficiency higher than 98% [20]. Raman spectroscopy was used to identification of common household plastics PET, high-density PE, low-density PE, PC, PP and PS for recycling purposes [21]. The identification of black polymers and recognition of biopolymers in plastic recycling can be solved by HSI, as separation of polyolefins, in conventional plastic recycled streams [22].

Combining euclidean distance, neural network and self-organized mapping techniques together, the success rate reached almost 100% for the plastic type [23]. The accuracy of color recognition of recycled bottles reach 94.7% by the improvement of SVM [24]. However, its recognition rate was greatly affected by the light. Polarization vision takes the degree of polarization and the angle of polarization of the reflected light on the surface of the object as the research object, which is little affected by the light thus the data is stable.

Most of the lights in nature, create partially polarized light that may be regarded as a mixture of unpolarized and linearly polarized light [25]. Analogous to color vision system, the polarization can be characterized by the parameters the intensity, angle and degree of polarization [26], [27]. Polarization-based methods have been used to segment material surfaces according to varying levels of relative electrical conductivity, in particular distinguishing dielectrics, which are non-conducting and metals [28], [29]. However, few studies have been conducted on the application of polarization vision to PET identification.

In order to obtain a higher identification accuracy of recycling PET plastic bottles, a method combining polarization vision and support vector machine (SVM) algorithm is proposed. In this paper, the segmentation method of effective area of recycled plastic bottle is given. Then, a method to calculate the approximate refractive index of recycled plastic bottle based on the degree of polarization and azimuth is introduced. Afterwards, the feature vector is constructed by the mean, standard deviation and coefficient of variation of the approximate refractive index and intensity distribution. Finally, SVM is used to train and learn the feature vector, and the recognition model is obtained, which is verified by experiments.

II. SCHEMATIC OF PET IDENTIFICATION FOR PLASTIC BOTTLES

Common recycling plastic bottles can be divided into four categories: PET, PE, PP and PS. In terms of the market share of all beverages in the world, PET plastic bottles account for more than 70%. In this paper, a new method of recognition of recyclable PET in pipeline by using polarization vision technology is proposed. The PET plastic bottles identification system is based on polarization vision, as shown in Fig.1.

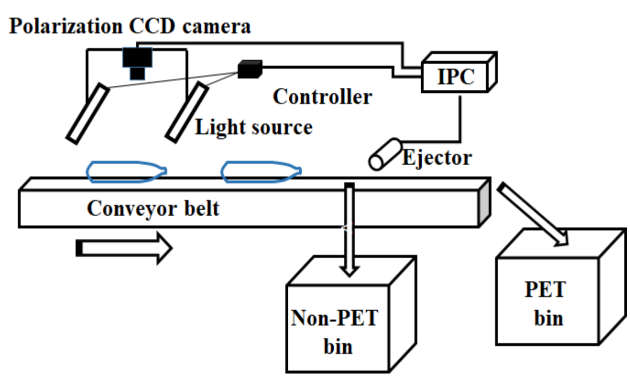


FIGURE 1. The whole PET bottles sorting system.

Flow chart of PET plastic bottles identification using polarization is shown in Fig.2. Firstly, the polarization intensity images were collected, the polarization degree and phase angle were obtained. Then the refractive index was approximately calculated by mirror reflection refractive index equation [28]. Finally, SVM is used to train the extracted features and set the judgment criteria.

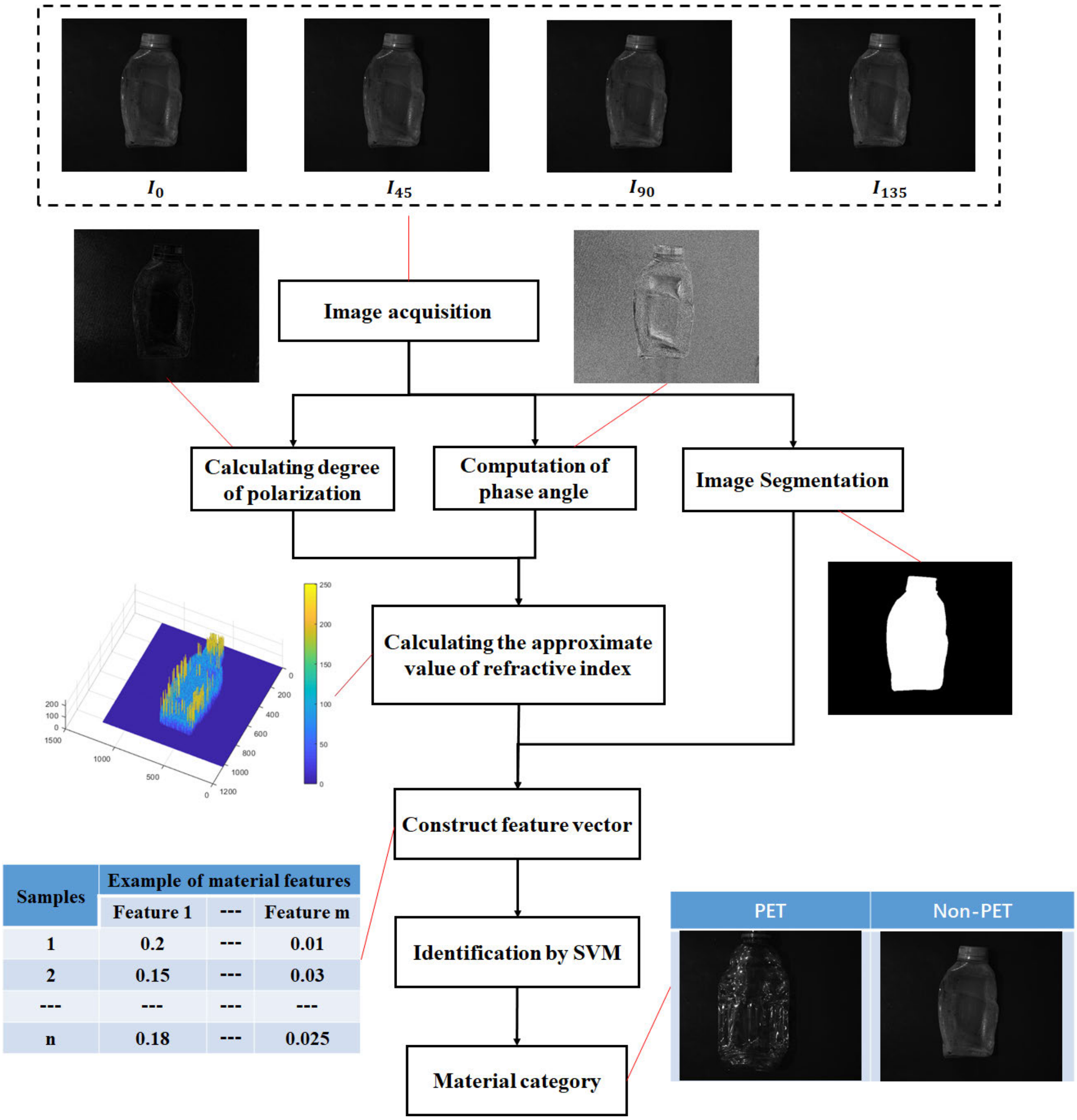


FIGURE 2. The identification process of recycled plastic bottles.

III. CALCULATION OF THE APPROXIMATE VALUE OF REFRACTIVE INDEX

According to Fresnel reflection theory, polarized reflected light can be parameterized by three values: the intensity I, phase angle ϕ and degree of polarization ρ. Using the Stoke's parameters, I, ϕ and ρ can be calculated from the intensity images I_0, I_{45}, I_{90} and I_{135} in four polarization directions of 0°, 45°, 90° and 135° degrees.

$$I = (I_0 + I_{45} + I_{90} + I_{135})/2 \tag{1}$$

$$\phi = \frac{1}{2}\arctan_2(I_{45} - I_{135}, I_0 - I_{90}) \tag{2}$$

$$\rho = \frac{\sqrt{(I_0 - I_{90})^2 + (I_{45} - I_{135})^2}}{I} \tag{3}$$

The degree of polarization of specular reflected light can be expressed by refractive index:

$$\rho = \frac{2\sin^2\theta\cos\theta\sqrt{n^2 - \sin^2\theta}}{n^2 - \sin^2\theta - n^2\sin^2\theta + 2\sin^4\theta} \tag{4}$$

According to formula (3), the refractive index n can be expressed by zenith angle θ and degree of polarization ρ [30]:

$$n = \sqrt{\frac{-b + \sqrt{b^2 - 4ac}}{2a}} \tag{5}$$

where

$$a = \rho^2\cos^4\theta \tag{6}$$

$$b = 2\rho^2\cos^2\theta(2\sin^4\theta - \sin^2\theta) - 4\sin^4\theta\cos^2\theta \tag{7}$$

$$c = \rho^2(2\sin^4\theta - \sin^2\theta)^2 + 4\sin^6\theta\cos^2\theta \tag{8}$$

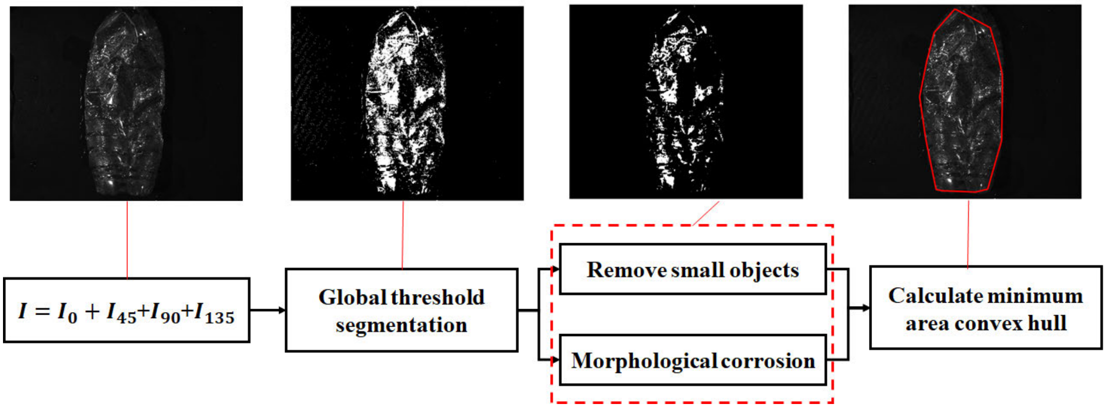


FIGURE 3. The segmentation process of recycling plastic bottles.

IV. IDENTIFICATION OF PET PLASTIC BOTTLES BASED ON SVM

A. SEGMENTATION OF PLASTIC BOTTLES

Intensity image I was binarized by global fixed threshold segmentation. In this experiment, the threshold value 51 is used to segment the plastic bottles from images. The noise in the binary image is filtered by morphological corrosion operation and area restriction, which mainly includes foreign matters and water stains on the conveyor belt. Then, convex hull of the whole region obtained by merging the remaining regions in the binary image was calculated, as shown in Fig.3, where the inner region of the convex hull is denoted as Ω.

B. EXTRACTION OF FEATURES

To some extent, the approximate refractive index represents the material of plastic bottle. However, influenced by the ambient light and the noise introduced by the sensor, there is some noise in the calculated approximate refractive index of the plastic bottle.

Therefore, the mean, standard deviation, coefficient of variation of the approximate refractive index and intensity distribution are used to construct the feature vector.

The feature vector used to identify PET plastic bottles is defined as:

$$F = \left[R_D, Std_R, \frac{Std_R}{R_D}, I_D, Std_I, \frac{Std_I}{I_D} \right] \tag{9}$$

where R_D and Std_R are the mean and standard deviation of dataset D, respectively, and I_D and Std_I are the mean and standard deviation of dataset I, respectively.

The dataset D and I are defined as

$$\mathrm{D} = \{R_{ij}, (i,j) \in \Omega\} \tag{10}$$

$$\mathrm{I} = \{I_{ij}, (i,j) \in \Omega\} \tag{11}$$

where R_{ij} is the approximate refractive index at the position (i, j). Although there is no linear relationship between zenith angle and phase angle, its value has obvious effect on distinguishing the material of plastic bottle. In this paper, the phase angle ϕ is used instead of zenith angle θ to obtain the approximate refractive index R_{ij}. I is the light intensity at the position (i, j), which is characterized by the gray value.

C. TRAINING AND EVALUATION OF THE MATERIAL IDENTIFICATION MODEL

Support vector machine (SVM) has significant advantages in solving two kinds of supervised classification problems [31]–[35]. In this paper, combined with SVM algorithm, 20 groups of randomly selected training sets of the same size were used for model learning and testing to verify the influence of the training set on the learning results.

In the process of training and learning, the labels of PET, PE, PP and PS were set as 1, 2, 3 and 4 respectively. Three binary models PET-PE, PET-PP and PET-PS were trained by SVM. Using the training models to classify the test sample, three labels L1, L2 and L3 were obtained. When all the three labels were 1, it was determined as PET, otherwise it was determined as non-PET.

In this paper, considering the fact that PET plastic bottles account for a large proportion of the market, the numbers of the training and the testing PET bottles account for a large proportion. The total number of plastic bottles used for training and testing is 507, including 240 PET, 48 PE, 179 PP and 40 PS. The training set samples are randomly selected from the data set. The training set was randomly selected from 507 plastic samples, which consisted of 100 pet, 30 PE, 80 PP and 20 PS.

V. EXPERIMENTAL RESULTS AND DISCUSSION

The method of identifying material of plastic bottle described was verified by experimentally. In order to verify the practical application ability of this method, the field of view of the camera is 500mm * 418mm. Since the features used to identify plastic bottle material contain noise, polarizing camera MER-502-79U3M POL with resolution of 2048 × 2448 fitted with an industrial lens MVL-MF1220M-5MP is selected for polarization images acquisition. The camera uses a globally exposed Sony IMX250MZR CMOS polarization

FIGURE 4. Different forms of plastic bottles in sample collection.

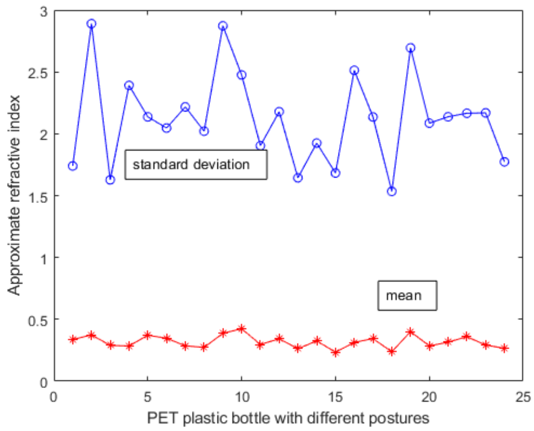


FIGURE 5. The mean and standard deviation of the approximate refractive index.

photosensitive chip, which can simultaneously collect images at four angles of 45°, 90°, 135° and 0°.

In order to test the practicability of the proposed method, the shapes and the positions of the samples in the tests are different. In Fig.4 shows a part of the attitudes of the samples in the experiment.

Fig.5 shows the statistical characteristic distribution of a plastic bottle after different positions and different forms of compression. A plastic bottle was extruded into 24 shapes and placed in the camera field of view for detection. The standard deviation and mean value of each posture are calculated. The x-coordinate indicates the serial number of the 24 postures of the plastic bottle. The results shows that the proposed feature extraction method is less affected by the shape of plastic bottle and the algorithm is stable and accurate.

Figs.6 − 9 show the approximate refractive index of pet, PE, PP and PS. The mean values of approximate refractive indices of PET, PE, PP and PS bottles were 0.3363, 0.0757, 0.2062 and 0.1989 respectively, and the variances were 1.7398, 0.2880, 1.0045 and 1.2820, respectively. It can be found that the mean value and standard deviation of the approximate refractive index of the four materials are quite different.

In order to verify the effectiveness of the method, samples are randomly selected from the data set to form the training set, then features are obtained by image segmentation and approximate index statistics. SVM is used for model

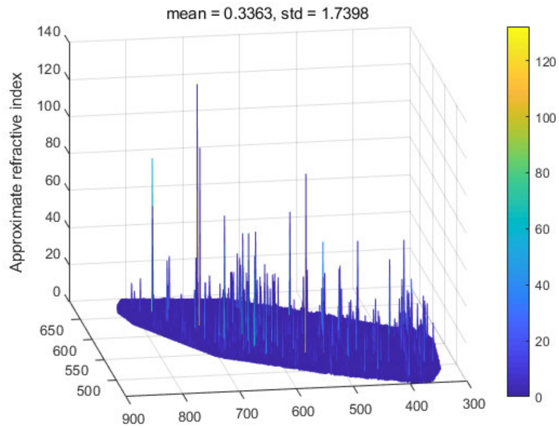


FIGURE 6. Approximate refractive index distribution of PET.

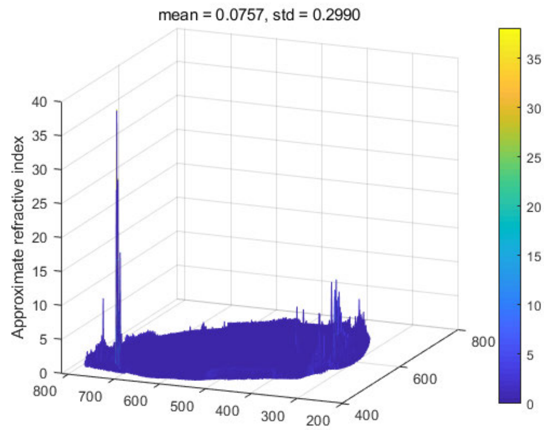


FIGURE 7. Approximate refractive index distribution of PE.

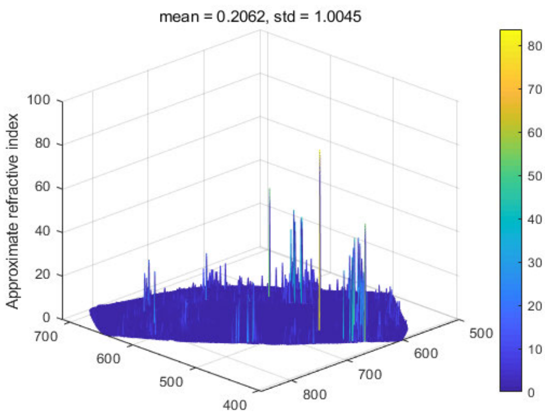


FIGURE 8. Approximate refractive index distribution of PP.

training, and the data set is identified and tested. The results of 20 random training tests are shown in Table 1, it can be seen that although different training sets have some impacts on the results, most recognition rates are more than 90%. So practically, a merely one simple sample selection can achieve high accuracy.

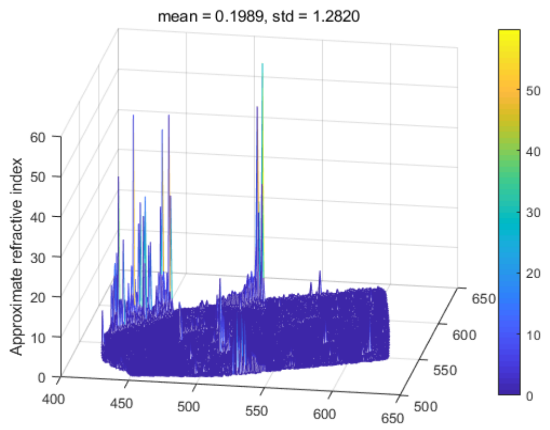


FIGURE 9. Approximate refractive index distribution of PS.

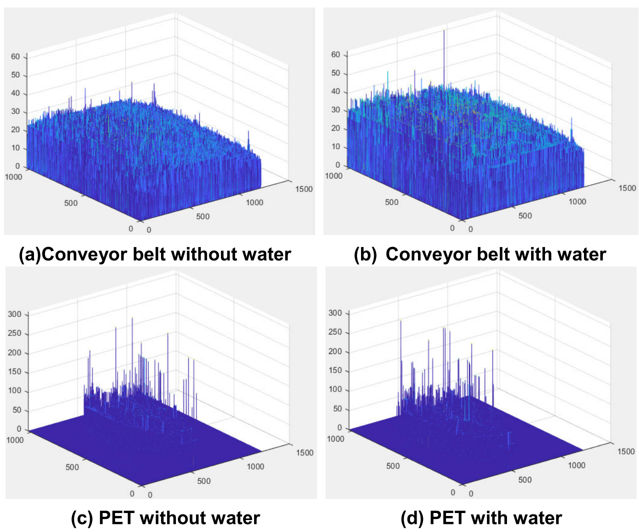


FIGURE 10. Approximate refractive index distribution.

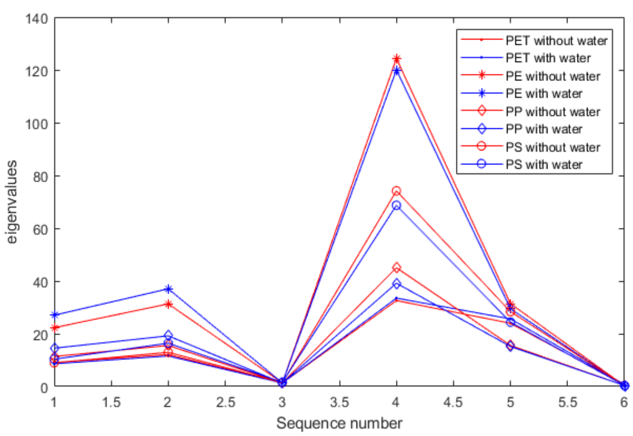


FIGURE 11. Comparison of eigenvalues with and without water.

Efficiency and accuracy of the system are the two main performances that need to be continuously improved. There are various affecting factors. In addition to hardware improvements, such as illumination conditions and the processor, the choice of algorithm is also important [34].

TABLE 1. Plastic bottle recognition success rate.

Serial number	Recognition accuracy of PET	Missing rate of non-PET(%)	Mistake sentencing rate of PET(%)
1	93.10%	4.14%	2.76%
2	93.69%	4.14%	2.17%
3	89.55%	7.30%	3.16%
4	91.12%	3.35%	5.52%
5	91.91%	5.52%	2.56%
6	93.49%	3.94%	2.56%
7	92.31%	4.54%	3.16%
8	90.14%	7.10%	2.76%
9	92.90%	4.34%	2.76%
10	92.31%	1.18%	6.51%
11	92.11%	3.55%	4.34%
12	89.15%	5.52%	5.33%
13	90.34%	7.89%	1.78%
14	94.08%	3.16%	2.76%
15	93.89%	4.14%	1.97%
16	91.91%	3.16%	4.93%
17	92.90%	4.14%	2.96%
18	93.10%	4.54%	2.37%
19	92.50%	3.75%	3.75%
20	90.73%	4.34%	4.93%
mean	92.06%	4.14%	2.76%

In the actual sorting of recycled plastic bottles, after the front-end cleaning and de labeling process, there will be some water stains on the inner and outer surfaces of plastic bottles and on the conveyor belt. In order to analyze the influence of water on sorting results, a comparative experiment was carried out.

Fig.10 shows the approximate refractive index of conveyor belt and PET plastic bottle with and without water. From the distribution results, the influence of water logging on the approximate refractive index distribution was small. The approximate refractive index characteristics of PET, PE and PP with and without water were extracted. The numerical results were shown in Fig.11. From the extraction results of water and no water eigenvalues, the proposed material recognition algorithm was less affected by water stains, and can be used in the actual recycling environment.

The data and code involved in this experiment can be downloaded from the web page *https://github.com/zytanhhu/vision*.

VI. CONCLUSION

This study proposed a new method to identification the PET plastic bottles from three kinds of plastic bottles with different materials of PE, PP and PS for the purpose of the recycling. The image segmentation method is used to calculate a convex hull in the area where the plastic bottle is located. The polarization degree and polarization angle in the convex hull of plastic bottle are used to calculate the approximate refractive index array. The SVM method is used to learn the identification model for PET plastic bottle. The results demonstrated that the recognition accuracy of PET could reach 92.06%, missing rate of non-PET is 4.14% and mistake sentencing rate of PET is 2.76%.

Although LIPS, LIBS, NIR, MIR, HSI and other methods have achieved higher recognition rate in PET recognition, they are severely affected by environmental light, and the cost of sensor is high. The new method of PET plastic bottle identification based on polarization vision proposed in this paper is hardly affected by the light environment. It only requires a single polarization camera to satisfy the sorting demand for the production line, which is promising in applications in the recycling market.

In our future work, better material features and recognition algorithms will be adopted to provide classification of PET, PE, PP and PS plastic bottles with more accuracy. In addition, the light source is another means for the improvement of the system.

REFERENCES

[1] W. Kou, "Possibilities of utilizing polyethene terephthalate (PET) bottle deposit-refund system in China," Ph.D. dissertation, Dept. Environ. Technol., Lappeenranta-Lahti Univ., Lappeenranta, Finland, 2019.

[2] M. Sulyman, J. Haponiuk, and K. Formela, "Utilization of recycled polyethylene terephthalate (PET) in engineering materials: A review," *Int. J. Environ. Sci. Develop.*, vol. 7, no. 2, pp. 100–108, Jan. 2016.

[3] L. Gu and T. Ozbakkaloglu, "Use of recycled plastics in concrete: A critical review," *Waste Manage.*, vol. 51, no. 51, pp. 19–42, May 2016.

[4] R. Zhang, X. Ma, X. Shen, Y. Zhai, T. Zhang, C. Ji, and J. Hong, "PET bottles recycling in China: An LCA coupled with LCC case study of blanket production made of waste PET bottles," *J. Environ. Manage.*, vol. 260, Apr. 2020, Art. no. 110062.

[5] S. Serranti and G. Bonifazi, "Techniques for separation of plastic wastes," in *Use of Recycled Plastics in Eco-Efficient Concrete*. Cambridge, U.K.: Woodhead, 2019, pp. 9–37.

[6] M. T. Carvalho, E. Agante, and F. Durão, "Recovery of PET from packaging plastics mixtures by wet shaking table," *Waste Manage.*, vol. 27, no. 12, pp. 1747–1754, Jan. 2007.

[7] S. Pongstabodee, N. Kunachitpimol, and S. Damronglerd, "Combination of three-stage sink–float method and selective flotation technique for separation of mixed post-consumer plastic waste," *Waste Manage.*, vol. 28, no. 3, pp. 475–483, Jan. 2008.

[8] T. Carvalho, F. Durão, and C. Ferreira, "Separation of packaging plastics by froth flotation in a continuous pilot plant," *Waste Manage.*, vol. 30, no. 11, pp. 2209–2215, Nov. 2010.

[9] G. L. Hearn and J. R. Ballard, "The use of electrostatic techniques for the identification and sorting of waste packaging materials," *Resour., Conservation Recycling*, vol. 44, no. 1, pp. 91–98, Apr. 2005.

[10] C.-H. Park, H.-S. Jeon, H.-S. Yu, O.-H. Han, and J.-K. Park, "Application of electrostatic separation to the recycling of plastic wastes: Separation of PVC, PET, and ABS," *Environ. Sci. Technol.*, vol. 42, no. 1, pp. 249–255, Jan. 2008.

[11] J. M. Anzano, I. B. Gornushkin, B. W. Smith, and J. D. Winefordner, "Laser-induced plasma spectroscopy for plastic identification," *Polym. Eng.*, vol. 40, no. 11, pp. 2423–2429, 2000.

[12] J. Anzano, M.-E. Casanova, M.-S. Bermúdez, and R.-J. Lasheras, "Rapid characterization of plastics using laser-induced plasma spectroscopy (LIPS)," *Polym. Test.*, vol. 25, no. 5, pp. 623–627, Aug. 2006.

[13] M. A. Gondal and M. N. Siddiqui, "Identification of different kinds of plastics using laser-induced breakdown spectroscopy for waste management," *J. Environ. Sci. Health A*, vol. 42, no. 13, pp. 1989–1997, Nov. 2007.

[14] M. Banaee and S. H. Tavassoli, "Discrimination of polymers by laser induced breakdown spectroscopy together with the DFA method," *Polym. Test.*, vol. 31, no. 6, pp. 759–764, Sep. 2012.

[15] S. Barbier, S. Perrier, P. Freyermuth, D. Perrin, B. Gallard, and N. Gilon, "Plastic identification based on molecular and elemental information from laser induced breakdown spectra: A comparison of plasma conditions in view of efficient sorting," *Spectrochim. Acta B, At. Spectrosc.*, vol. 88, pp. 167–173, Oct. 2013.

[16] Y. Tachwali, Y. Al-Assaf, and A. R. Al-Ali, "Automatic multistage classification system for plastic bottles recycling," *Resour., Conservation Recycling*, vol. 52, no. 2, pp. 266–285, Dec. 2007.

[17] H. Masoumi, S. M. Safavi, and Z. Khani, "Identification and classification of plastic resins using near infrared reflectance," *Int. J. Mech. Aerosp. Ind. Mech. Manuf. Eng.*, vol. 6, no. 5, pp. 213–220, Jan. 2012.

[18] A. Kassouf, J. Maalouly, D. N. Rutledge, H. Chebib, and V. Ducruet, "Rapid discrimination of plastic packaging materials using MIR spectroscopy coupled with independent components analysis (ICA)," *Waste Manage.*, vol. 34, no. 11, pp. 2131–2138, Nov. 2014.

[19] M. Moroni, A. Mei, A. Leonardi, E. Lupo, and F. Marca, "PET and PVC separation with hyperspectral imagery," *Sensors*, vol. 15, no. 1, pp. 2205–2227, Jan. 2015.

[20] A. Ulrici, S. Serranti, C. Ferrari, D. Cesare, G. Foca, and G. Bonifazi, "Efficient chemometric strategies for PET–PLA discrimination in recycling plants using hyperspectral imaging," *Chemometric Intell. Lab. Syst.*, vol. 122, pp. 31–39, Mar. 2013.

[21] V. Allen, J. H. Kalivas, and R. G. Rodriguez, "Post-consumer plastic identification using Raman spectroscopy," *Appl. Spectrosc.*, vol. 53, no. 6, pp. 672–681, Jun. 1999.

[22] S. Serranti, "Plastic waste monitoring and recycling by hyperspectral imaging technology," *Proc. SPIE*, vol. 11197, pp. 1119706-1–1119706-5, Nov. 2019.

[23] E. Scavino, D. A. Wahab, A. Hussain, H. Basri, and M. M. Mustafa, "Application of automated image analysis to the identification and extraction of recyclable plastic bottles," *J. Zhejiang Univ.-Sci. A*, vol. 10, no. 6, pp. 794–799, Jun. 2009.

[24] Z. Wang, B. Peng, Y. Huang, and G. Sun, "Classification for plastic bottles recycling based on image recognition," *Waste Manage.*, vol. 88, pp. 170–181, Apr. 2019.

[25] M. Born, E. Wolf, and E. Hecht, "Principles of optics: Electromagnetic theory of propagation, interference and diffraction of light," *Phys. Today*, vol. 53, no. 10, pp. 77–78, 1999.

[26] N. W. Roberts, M. J. How, M. L. Porter, S. E. Temple, R. L. Caldwell, S. B. Powell, V. Gruev, N. J. Marshall, and T. W. Cronin, "Animal polarization imaging and implications for optical processing," *Proc. IEEE*, vol. 102, no. 10, pp. 1427–1434, Oct. 2014.

[27] S. B. Powell, R. Garnett, J. Marshall, C. Rizk, and V. Gruev, "Bioinspired polarization vision enables underwater geolocalization," *Sci. Adv.*, vol. 4, no. 4, Apr. 2018, Art. no. eaao6841.

[28] L. B. Wolff and T. E. Boult, "Constraining object features using a polarization reflectance model," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 13, no. 7, pp. 635–657, Jul. 1991.

[29] L. Zhang, F. Yang, and L. Ji, "Multi-scale fusion algorithm based on structure similarity index constraint for infrared polarization and intensity images," *IEEE Access*, vol. 5, pp. 24646–24655, 2017.

[30] Z. Tan, B. Zhao, X. Xu, Z. Fei, and M. Luo, "Object segmentation based on refractive index estimated by polarization of specular reflection," *Optik*, vol. 208, Apr. 2020, Art. no. 163918.

[31] S. Shahbudin, A. Hussain, D. A. Wahab, M. M. Marzuki, and S. Ramli, "Support vector machines for automated classification of plastic bottles," in *Proc. 6th Int. Colloq. Signal Process. Appl. Committee Conf. (CSPA)*, Malacca, Malaysia, May 2010, pp. 345–348.

[32] J. Cao, G. Lv, C. Chang, and H. Li, "A feature selection based serial SVM ensemble classifier," *IEEE Access*, vol. 7, pp. 144516–144523, 2019.

[33] W. Shu and K. Cai, "A SVM multi-class image classification method based on DE and KNN in smart city management," *IEEE Access*, vol. 7, pp. 132775–132785, 2019.

[34] N. Zeng, Z. Wang, B. Zineddin, Y. Li, M. Du, L. Xiao, X. Liu, and T. Young, "Image-based quantitative analysis of gold immunochromatographic strip via cellular neural network approach," *IEEE Trans. Med. Imag.*, vol. 33, no. 5, pp. 1129–1136, May 2014.

[35] D. Drungilas, M. Kurmis, Z. Lukosius, S. Jakovlev, and M. Voznak, "An adaptive method for inspecting illumination of color intensity in transparent polyethylene terephthalate preforms," *IEEE Access*, vol. 8, pp. 83189–83198, 2020.

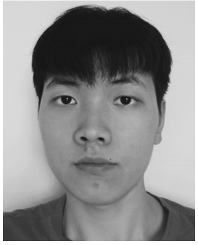
ZHIYING TAN received the B.E. degree in information and computing science from Shandong Agricultural University, China, in 2007, the M.E. degree in computational mathematics from Jilin University, China, in 2009, and the Dr.Eng. degree in computer software and theory from the University of Electronic Science and Technology of China, China, in 2013. From 2012 to 2017, she studied machine vision detection technology with the Hefei Institute of Material Science, Chinese Academy of Sciences. She is currently a Lecturer with Hohai University. Her major research interests include numerical analysis, image processing, and machine vision.

ZHONGWEN FEI received the B.S. degree in mechanical engineering from the University of Hohai, in 2018, where he is currently pursuing the M.S. degree in mechanical engineering. His current research interests include 3D laser measurement and embedded vision.

BAOLAI ZHAO received the B.S. degree in mechanical engineering from Hohai University, in 2019, where he is currently pursuing the M.S. degree in mechanical engineering. His current research interests include image processing and polarization vision technology.

JIAN YANG received the B.S. and Ph.D. degrees from the School of Mechanical Engineering, Nanjing University of Science and Technology, in 2005 and 2016, respectively. He is currently a Lecturer with the College of Mechanical Engineering, Yangzhou University. His current research interests include signal processing, neural networks, and compressed sensing.

XIAOBIN XU received the B.E. and Ph.D. degrees from the Nanjing University of Science and Technology, China, in 2012 and 2017, respectively. His current research interests include optical imaging, point cloud processing, and signal processing.



ZILONG WANG is currently pursuing the bachelor's degree with Hohai University. From 2019 to 2020, he was a Research Assistant with the Jiangsu Special Robotics Laboratory, Hohai University, Changzhou Campus, China. His research interests include machine learning, computer vision, and image processing.