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Multi-material classification of dry recyclables from municipal solid waste based on thermal imaging

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A B S T R A C T

There has been a significant rise in municipal solid waste (MSW) generation in the last few decades due to rapid urbanization and industrialization. Due to the lack of source segregation practice, a need for automated segregation of recyclables from MSW exists in the developing countries. This paper reports a thermal imaging based system for classifying useful recyclables from simulated MSW sample. Experimental results have demonstrated the possibility to use thermal imaging technique for classification and a robotic system for sorting of recyclables in a single process step. The reported classification system yields an accuracy in the range of 85–96% and is comparable with the existing single-material recyclable classification techniques. We believe that the reported thermal imaging based system can emerge as a viable and inexpensive large-scale classification-cum-sorting technology in recycling plants for processing MSW in developing countries.

1. Introduction

Municipal solid waste is being generated at a rapid pace and is expected to reach about 2.2 billion tonnes globally by 2025 due to urbanization and industrialization (Hoornweg and Bhada-Tata, 2012; Kawai and Tasaki, 2016). MSW management has, thus, become an acute concern for the municipal authorities worldwide. The problem of MSW management is relatively more complex in the developing countries due to the limited door-to-door collection, inefficient treatment and inadequate disposal facilities. Developing countries like India, China and Brazil, accommodating about 87% of world human population, do not follow source segregation of waste that results into large piles of mixed waste in their dump yards/landfills (see Fig. 1(a)). It is unlike in developed countries like the USA, UK and Canada wherein every household and other establishments separate their waste into the bins of various categories right at the source and often utilize curbside recycling programs (see Fig. 1(b)). Developing countries, on the other hand, use the social sector called rag pickers, which have very low income, collect recyclables from dumpsites and then sell to the recycling shops, middlemen, or exporters. The job of recovering recyclables like metal, glass, paper and plastic from MSW by rag pickers is often dangerous and prone to pathogenic infections. The motivation behind this paper is to develop an automated approach to sort dry recyclables from MSW stream to reduce human drudgery and improve the sorting efficiency.

A large proportion of MSW is bio-waste which is segregated using various techniques involving: waste separation presses or screw presses, disc screens, optical sorters and shredders (Bernstad et al., 2013; Gundupalli et al., 2017; Hansen et al., 2007; Jank et al., 2016, 2015; Romero-Güiza et al., 2014). We consider the outcome from these techniques as dry recyclable, which is further utilized as the input fraction for our developed technique from which the recyclables are classified and sorted. Performing multi-material classification/sorting on dried MSW involves two main technical challenges namely, (i) the large computational burden on the classifier due to the presence of uneven surfaces and a wide range of geometries of the recyclable objects present in MSW and (ii) a need for rugged/robust sensors in order to handle the dried MSW that present a dusty and harsh environment.

In this paper, we propose the use of thermal imaging technique as a possible solution to identify/classify recyclables from the MSW. Although sufficiently rich in information pertaining to material properties, the thermal intensity images are a single channel and thereby have modest computational processing requirements. The thermal imaging cameras are relatively inexpensive than other equipment used in material detection for MSW like hyperspectral imaging technology (HSI) (Picon et al., 2010, 2009; Picón et al.,

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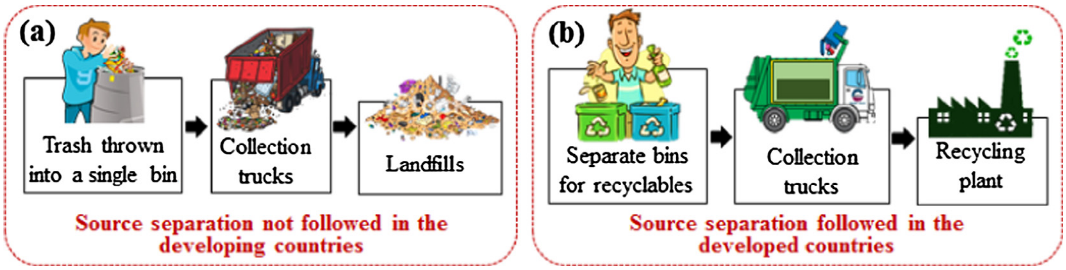

Fig. 1. (a) Source separation not followed in developing countries, (b) Source separation in developed countries.

2012; Tatzer et al., 2005), spectroscopy analysis (Kassouf et al., 2014; Safavi et al., 2010; Serranti et al., 2011, 2010), laser induced breakdown spectroscopy (LIBS) (Anzano et al., 2008, 2006; Gondal et al., 2007; Gornushkin et al., 2000; Grzegorzek et al., 2011; Gurell et al., 2012) and optical sorting technology (Huang et al., 2010; Koyanaka and Kobayashi, 2011, 2010; Kutila et al., 2005).

The developed system based on thermal imaging sorts the recyclables into broad categories namely, iron, plastic, paper, stainless steel, aluminum and wood. The sorted fractions obtained from the developed technique may further be subjected to finer sorting using LIBS, HSI, optical sorting technology and spectroscopy analysis. Thus, the developed approach specifically targets on the use of low-cost thermal imaging to perform multi-materials classification of dry recyclables in MSW into the broad categories of iron, paper, plastic, aluminum, stainless steel and wood for automated sorting. Aforementioned sorting is performed manually in developing countries while it is often not required in the developed countries due to the well-established source-segregation programs. The main difference between the developed thermal imaging approach and the existing advanced material classification technologies is that the radiation intensity property instead of physical-chemical properties like electrical conductivity, density, surface and magnetic susceptibility are used for material classification.

A comprehensive summary of state of the art is reported within the field of automated sorting of source-separated MSW for recycling (Gundupalli et al., 2017). To the best of our knowledge, there has been no work reported specifically in the area of multi-material classification using thermal imaging for sorting recyclables from MSW stream using a robotic system. This paper focuses on identifying/recognizing broad categories of recyclable materials, such as metal, wood, plastic and glass by explicitly estimating the radiation intensity properties. For example, a glass plate with an emissivity of 0.92 (Holst, 2000) will radiate more compared to an aluminum plate with an emissivity of 0.04 and will thus have a comparatively brighter thermal image (Incropera et al., 2006; Maldague, 2001; Modest, 2003). The emissivity values of various metallic and non-metallic materials are available in the literature (Holst, 2000; Incropera et al., 2006; Maldague, 2001; Modest, 2003).

In the past, a multi-robot system for sorting construction and demolition waste (C&D) was developed (Lukka et al., 2014) that comprised of a manipulator, a conveyor, multiple sensing elements like 3D sensor, metal detector, RGB camera and near-infrared camera (NIR) for sorting C&D waste. A supervised machine learning approach for material classification and reinforcement machine learning was developed for grasping task (Kujala et al., 2015; Lukka et al., 2014).

Extensive research efforts are made for local invariant feature detector applied to RGB images (Tuytelaars et al., 2008). Object detection technique developed by Viola and Jones is robust to variations in image backgrounds (Viola and Jones, 2001). Keypoint feature is detected using techniques like SURF (speeded up robust feature) (Bay et al., 2008, 2006), SIFT (scale invariance feature transform) (Lowe, 2004) and PCA-SIFT (principal component analysis-SIFT) (Ke and Sukthankar, 2004). For raw image formats, keypoint features can be utilized for direct matching (Zhao et al., 2006). The main limitation of visual object sorting are the requirements for controlled illumination and a confined workspace.

The acquisition from an RGB camera can produce rich data like color, shape and texture. However, this may not be robust in recognizing the recyclable materials due to a lack of material specific information in an RGB image. The information about the thermal properties is provided by the infrared (IR) imaging and extensively used in the area of human detection, mine detection, defects in material and thermal leak detection (Khanafer et al., 2003; Li et al., 1995; Muscio and Corticelli, 2004).

Thermal imaging-based technique integrated with vacuum-based grippers for sorting of MSW has been reported (Thomas, 1997). However, the classification accuracy of such system has not been reported yet. Further, the vacuum-based approach may not be suitable for handling arbitrary shaped objects which are commonly found in MSW. The thermal imaging based technique integrated with robotic manipulation can handle arbitrary shaped objects. In this paper, we provide a classification-cum-sorting framework that performs determination of the precise location of recyclables in addition to multi-material classification of MSW.

The main contributions of this paper are: (i) use of comparatively inexpensive and robust thermal imaging sensor for multi-material classification of dry recyclables from MSW into broad categories for further processing using more sophisticated approaches and (ii) use of radiation property of various recyclable materials as a basis for material classification. The scope of this paper is restricted to post-consumer dry recyclable materials and encompasses recovery of commingled recyclable streams and mixed MSW.

2. Thermal imaging technique

Thermal imaging or infrared imaging often detects radiation in the long infrared range (7–13 μm) and generates intensity images known as thermograms. The emissivities of materials are different, and thus the thermograms of each material have separate intensities. Thus, variation in intensity can be used as a basis for materials classification. Fig. 2 illustrates a five-step overview of automated sorting based on thermal imaging.

In the first step, MSW fractions are continuously fed into the inspection chamber (see Fig. 2(a)). In the second phase, automatic inspection of the MSW is performed. A stream of thermograms of the MSW is acquired using the thermal imager that is mounted in the inspection chamber (see Fig. 2(b)). After this, the thermograms are processed to classify the recyclable objects present in the inspection chamber and subsequently the locations of each recyclable objects are also determined. Third, the conveyor system transports the MSW from the inspection chamber to the sorting area (see Fig. 2(c)). Fourth, the identified recyclable objects are

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