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An investigation of the usability of sound recognition for source separation of packaging wastes in reverse vending machines

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ABSTRACT

In this study, we investigate the usability of sound recognition for source separation of packaging wastes in reverse vending machines (RVMs). For this purpose, an experimental setup equipped with a sound recording mechanism was prepared. Packaging waste sounds generated by three physical impacts such as free falling, pneumatic hitting and hydraulic crushing were separately recorded using two different microphones. To classify the waste types and sizes based on sound features of the wastes, a support vector machine (SVM) and a hidden Markov model (HMM) based sound classification systems were developed. In the basic experimental setup in which only free falling impact type was considered, SVM and HMM systems provided 100% classification accuracy for both microphones. In the expanded experimental setup which includes all three impact types, material type classification accuracies were 96.5% for dynamic microphone and 97.7% for condenser microphone. When both the material type and the size of the wastes were classified, the accuracy was 88.6% for the microphones. The modeling studies indicated that hydraulic crushing impact type recordings were very noisy for an effective sound recognition application. In the detailed analysis of the recognition errors, it was observed that most of the errors occurred in the hitting impact type. According to the experimental results, it can be said that the proposed novel approach for the separation of packaging wastes could provide a high classification performance for RVMs.

1. Introduction

Municipal solid waste (MSW) management is a multidisciplinary activity that includes generation, source separation, collection, transportation, treatment, and disposal (Rada et al., 2013; Das and Bhattacharyya, 2015). One of the most important objectives of MSW management applications is the separation of recyclable packaging wastes at source with a high efficiency. For example, Turkey government recently set a 60% target value for the separate collection of the packaging wastes (LCPW, 2011). This target has not been realized in Turkey, yet. On the other hand, some European countries have accomplished 80% efficiency ratio for the separate collection of all waste fractions (Rada et al., 2013).

Source separation of MSWs refers to the separate collection of different waste fractions such as metal, glass, plastic, and cardboard, in the place where they are generated (Rousta et al., 2015). Nowadays, the source separation of recyclable wastes is accomplished via deposit applications (e.g. the discount tickets for empty bottles, etc.), colored bags and separate collection containers (Dahlén et al., 2007; Larsen et al., 2010; Gallardo et al., 2012; Lavee and Nardiya, 2013; Groot et al., 2014; Rigamonti et al., 2014; Zhang and Wen, 2014). However, there is always a risk of consumer misuse in these conventional applications: The consumer can throw the waste to a wrong bag and/or an incorrect part of the container.

Reverse vending machine (RVM) is a device used for the separate collection of packaging wastes automatically. These devices can successfully disable human factors in the source separation. They prevent aforementioned human misuse substantially, reward the users directly, and punish misuse when necessary. Working principles of RVMs can be listed as; 1 – proximity sensors (Van Den Broek et al., 1997, 1998), 2 – image processing (Ramli et al., 2007), 3 – barcode reading (Wyld, 2010), and 4 – radio frequency identification (RFID) (Thomas, 2008; Glouche and Couderc, 2013). The first three techniques are inefficient in waste management applications due to the vast variety of packaging wastes in terms of fullness, deformation conditions, shape, structure and mass. Tagging all the packaging materials with an RFID tag during the

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manufacturing phase might seem to be an efficient solution. However, this tagging process significantly increases the costs (Binder et al., 2008; Thomas, 2009: 0.05–0.10 $/tag) and the tags are harmful to the environment. For example, if the RFID technology is started to be used worldwide today, approximately two trillion products per year should be tagged (Thomas, 2008). These tags could contain toxic or valuable materials (Abdoli, 2009). The possibility of releasing the toxic tags to the environment, the damage they cause in the separation automats (Wager et al., 2005) and the operational problems (Aliaga et al., 2011) restrict the wide usage of the RFID technique. Consequently, it is obvious that a new efficient and cheap source separation technique for RVMs should be developed to overcome the weaknesses of the current technologies.

In this study, we investigate the use of sound recognition for source separation of packaging wastes in RVMs and present the initial experimental results. In the experiments, sounds were generated from packaging wastes via free falling, pneumatic hitting and hydraulic crushing impact types. The sounds were recorded with two different microphones. A support vector machine (SVM) and a hidden Markov model (HMM) based classification systems were trained using the sound recordings. The systems were tested with packaging wastes in different material type and size. In the experiments, it was observed that the classification systems provide high classification accuracies (between 82% and 100%) for the separation of packaging wastes.

2. Theory, material and methods

2.1. Theory

It is possible to identify the type (glass, metal, plastic, etc.) and/or shape of a solid material using the sounds reflected from it or generated by it. Zhao et al. (2003), Ohtani and Baba (2006a,b), Gonzalez et al. (2011, 2012) and Zhang et al. (2013). Characteristic of a sound reflected or generated from a solid material is affected by factors such as the shape and type of the material, and the type of the physical impact (Avanzini and Rocchesso, 2001).

It has been proven that sound generator objects could be identified from their shapes (Kunkler-Peck and Turvey, 2000), sizes (Giordano and McAdams, 2006) and material structures (Giordano, 2003; McAdams et al., 2004, 2010) by humans. According to Tucker and Brown (2002), the most distinguishing feature of a sound generator is its material structure for a human listener. In Rocchesso and Fontana (2003), it is stated that the research on identifying an object from its sound feature started in the 1970s and many algorithms have been developed in this research area. For example, Wildes and Richards (1988) developed two theoretical statements namely "bandwidth" and "decay" to identify the material structure of non-elastic materials. Lutfi and Oh (1997) and Klatzky et al. (2000) performed experiments using the collision sounds to assess the material identification capacity of human listeners. Avanzini and Rocchesso (2001) used a hammer to generate a sound.

Besides the above researches; sound/speech processing technologies has evolved significantly. Today, it is an accomplished technological achievement to classify an object using the sound signals generated and/or reflected from it (Madisetti, 2009; Lyons, 2010; Ingle and Proakis, 2011). Various algorithms and computer tools have been developed for this purpose (Young et al., 2006; Sphinx, 2009). It could be found in the studies of Haff and Pearson (2007), Ocak (2009), Chang and Lai (2010), Madain et al. (2010), Subha et al. (2010), Tran and Li (2011), El-Alfi et al. (2013), Guyot et al. (2013), Yuan and Ramli (2013) and Theodorou et al. (2015) that various feature types and classification methods can be used to classify the sounds with different characteristics.

Just like the other solid materials, packaging wastes generate different sounds under a physical impact. However, to the best knowledge of the authors, there is no previous study in the literature that uses sound recognition to identify the packaging wastes. In this study, we focus on using sound recognition approach for separate collection of the packaging materials in RVMs. The main steps of the methodological approach used in this study can be found in Fig. 1.

2.2. Experimental setup and sound recording procedure

An open-top cubic structured steel chamber with 50 cm $\times$ 50 cm $\times$ 50 cm dimensions was designed for the sound recording experiments. The chamber was isolated with rock wool panels. The thickness of the isolation was 10 cm. All the waste sound recordings were taken inside this chamber. The recordings were obtained with the help of the free falling (FF), pneumatic hitting (H) and hydraulic crushing (C) physical impact types. Pneumatic and hydraulic cylinders were used for the H and C type impacts, respectively. The maximum allowable pressure of the hydraulic system was 40 bars. On the other hand, the pneumatic system was operated under a constant pressure of four bars. A pressure regulator was used to maintain the constant pressure. The experimental setup and some of the packaging wastes used in this study can be seen in Fig. 2.

Packaging wastes used in this study were collected from student canteens in Kocaeli University and shopping malls in Kocaeli city center. All the collected wastes were empty and they had been consumed and dumped to trash bins by consumers. The wastes were categorized into four groups according to the material type; metal (M), plastic (P), glass (G), and cardboard (CB). As mentioned earlier, RVMs are high-tech machines which classify the waste given by the consumer and reward the consumer according to the waste type. Therefore, the size of the wastes should also be considered for the rewarding mechanism in the real world waste management applications. For this reason, the wastes were collected in three different sizes for every waste category above, namely big (B), medium (MS) and small (S). The sounds were obtained for the three physical impact types; free falling (FF), pneumatic hitting (H) and hydraulic crushing (C). Sound recordings were taken with two different microphones. One of the microphones is a dynamic (D) and the other is a condenser (CN) microphone. Technical specifications of the dynamic microphone are 40 Hz–15 kHz frequency response, 600 ohm impedance, and -54 dB re one V/Pa sensitivity for MXL LSM-5GR. Technical specifications of the condenser microphone are 20 Hz–20 kHz frequency response, 150 ohm impedance, and -30 dB re one V/Pa sensitivity for MXL CR89. The sounds were recorded on a computer via a sound card using Cubase5 software. Also a video recording was taken for possible future research.

The sound recordings were taken for every waste type-waste size-impact type combination, individually. A coding scheme was developed in order to present the experimental results more clearly. In the coding scheme, the following order was used: "waste type _waste size_impact type_experiment number_microphone type".

The total number of the waste types used in this study was 11 due to the absence of medium size metal waste. These waste types and their specifications can be found in Table 1. Some of the experimental conditions are also presented in the table for a better understanding of the coding scheme. In this study, different brands and various deformation conditions of waste types were taken into account in order to make a more realistic research. In real world applications, the compositions of the waste types might differ from one brand to another and they might be deformed when dumped to the trash bins. As a result, five different brands and three