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An exploratory study on the automated sorting of commingled recyclable domestic waste

Dilan Bonello, Michael A. Saliba *, Kenneth P. Camilleri

University of Malta, Msida MSD 2080, Malta

Abstract

In material recovery facilities (MRFs) the sorting of waste is typically carried out predominantly manually. In this work, the MRF in Marsaskala, Malta is used as a case study to explore ways in which more automation can be employed to the sorting of commingled recyclable domestic waste. The work addresses first the conceptual design of the process layout and methods. This is followed by the detailed design and development of a universal gripper to replace the human sorter, aimed at removing contaminants from a stream of already sorted material, increasing the purity of the baled material and thereby increasing profits.

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Keywords: Material recovery facility; automation; universal gripper

1. Introduction

Domestic waste, or municipal solid waste (MSW), is waste that includes organic material, recyclable material, electrical and electronic waste (WEE) together with other waste. Traditionally this waste has been wholly and directly disposed in landfills [1, 2]. Recyclable domestic waste on the other hand is that part of the domestic waste that can be recycled and reused after the termination of the product function [3, 4]. Recyclable domestic waste can typically be extracted from MSW in a material recovery facility (MRF). A clean, or dry, MRF is one that processes

* Corresponding author. Tel.: +356 2340-2924.
E-mail address: michael.saliba@um.edu.mt

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unsorted recyclable waste that has already been separated at source from the non-recyclable waste. Typically, such waste consists of glass, ferrous and non-ferrous metals, plastics, paper and cardboard. The material is first sorted to meet the requirements of the plant, and then further processed (e.g. baled or compacted) for shipment to the applicable markets.

In Malta there is currently only one facility that performs the sorting of recyclable domestic waste. It is a dry MRF that receives about forty tonnes of material per day. The unsorted waste, known as commingled waste, that comes to the facility contains material that is categorized into three main classes, these being the target materials, the non-target materials and the rejects. The target materials are those materials that the MRF is able to process and are sorted out into a number of different categories: polyethylene terephthalate (PET) clear, PET colour, high-density polyethylene (HDPE), low density polyethylene (LDPE), paper, cardboard, ferrous and non-ferrous metals. The non-target materials are recyclable materials that this particular plant cannot process but that are still recyclable and therefore are still collected from households, such as polystyrene (PS), polypropylene (PP), tetrapak, milk cartons and jablo. The materials which should not be present in the received mix make up the reject materials class.

The sorting system present at this MRF is predominantly manual, with human sorters present at the side of conveyor belts that transfer the materials, to manually grasp the assignment material category. The only semi-automated part is the sortation of ferrous and non-ferrous materials, whereby electromagnets and eddy current separation machines are used respectively.

Some common problems of MRFs such as the one under consideration is the fact that it relies almost solely on visual inspection of the commingled waste passing on the conveyor. Material surge could occur, thus not giving time for a sorter to grasp all the materials assigned. The conveyor belt has to move at a slow rate to allow time for materials to be visually identified. Fatigue of sorters is also present due to having a 12 hour shift, together with the fact that their job is really repetitive and boring. Health issues such as skin problems are inevitable in these facilities [4]. Given these problems, it is natural to consider the application of some of the various modern automated material handling and sensing technologies to material recovery. Indeed, most long-term cost analyses indicate that the use of automation in MRF is more cost effective than the use of manual sorting [5].

The objectives of this work are to review existing material sensing and sorting technologies and to propose an integrated sensing and sorting system for a dry MRF; as well as to develop a first prototype of an innovative robot-based material handling system to be applied as a final stage for each category of recyclable material, to remove contaminants that still remain within the sorted streams.

2. Literature review

In manual sorting of recyclable waste, the materials are all identified through the use of human visual inspection by the sorters. The size of the material to be grasped, the depth of the commingled waste on the conveyor belt, and the speed of the conveyor belt all play a role in the identification of materials [6]. All material handling is done manually.

In the automated sorting of recyclable waste, various sensing and material handling technologies can be applied, depending in many cases on the particular materials involved. A common technology used for the identification of paper and cardboard is near infrared (NIR) spectroscopy, involving the measurement and analysis of reflectance for incident wavelengths in the range of 0.78 to 2.5 μm [7]. Air jets can then be used to extract this material [2]. Ballistic machines can also be used to “sense” (as well as separate) the thin two-dimensional (2D) material such as paper and cardboard – in these systems the input stream is directed to a conveyor that is relatively steeply inclined, so that bulky (three dimensional, or 3D) objects topple backwards while 2D items move upwards on the conveyor [8]. Large volume cardboard can be separated using disc screening technology [9].

Metallic objects can be identified, and also recognized as ferrous or non-ferrous, through the use of inductive technology and NIR. Ferrous materials can be extracted using magnets or electromagnets, while non-ferrous materials can be extracted using eddy current separation technology [2]. NIR can also be used to identify non-target materials and rejects, with the only limitation being that of black materials, such as black LDPE bags, due to absorption of the electromagnetic waves [8]. In order to separate large components, sieves with large perforations are used along the transmission route, so that large materials keep on moving forward whilst the smaller materials pass through the sieve. For small components, sieves with smaller perforations are used [2].

NIR technology can also be used to identify LDPE, HDPE and PET, coupled with a visual imaging sensor to differentiate between PET clear and PET colour [8, 10, 11]. Small LDPE items (e.g. thin films) can be separated using an air stabilization system that pins the material to a conveyor and allows it to exit through a dedicated outlet, e.g. [12]. Large LDPE items can be extracted manually, and then released into overhead suction tubes, e.g. [13]. HDPE and PET items can be extracted using air jets [11].

Large components are removed from the commingled waste through the use of trommels, inclined or horizontal shaking screens and disc screens [2]. The transfer of commingled waste is carried out through the use of conveyor belts, using methods of levelling to create constant material flow rates throughout the system. There are four main types of levelling systems, these being, the feeding of materials in a slow manner, the use of a series of conveyor belts of progressively increasing speeds, the metering drum and the gates or curtains [14]. The compressing and densification of the individual sorted material and the material that does not get sorted is usually done through the use of a horizontal baler [2]. Material perforation is employed for plastic bottles in order to create holes to allow air to escape with ease from the bottles [11]. Notwithstanding the level of automation used in the MRF, the review of the literature indicates that the removal of contaminants from the already separated waste is always done by the human sorter.

Bag openers are normally utilized in automated facilities. The trommel type of bag opener have blades inside the trommel to slit open the bags. Rotating drum/s type bag shredders make use of rotating teeth to open up the bags. The configuration can be either horizontal or vertical [14].

There are various layouts for the sorting of recyclable domestic waste depending primarily on the targeted material of the MRF. In systems that employ automation there are usually four primary processes: pre-sorting whereby materials that are large are screened; papers and cardboard are then collected together with LDPE; PET clear, PET colour and HDPE are also grouped together; and this is followed by the grouping and sorting of ferrous and non-ferrous materials [15].

The handling / sorting of commingled waste is a relatively new application of robotics. Early studies involved the automated sorting of paper objects [16], and the semi-automated disassembly and subcomponent sorting of electrical and electronic equipment for recycling [17], and utilized vacuum grippers for material handling. Since 2014, the specific problem of waste sorting has been addressed as a variation of the more general, and more studied, problems of bin picking and of object sorting in unstructured environments, and the robotic sorting of waste has been applied in a commercial setting (see [18,19] and references therein). In [19], as well as in other robotic waste sorting systems (e.g. [20]), handling is carried out using two-jaw grippers. Further progress in this area will require the development of highly versatile but conceptually simple grippers that can pick up a very wide variety in shape, size and type of object. Some examples of such devices, from outside the material recovery industry, include grippers based on telescoping pins [21], electrorheological fluid [22], memory foams [23], heavily under-actuated multi-finger / multi-joint systems [24], granular jamming [25], and electroadhesion / electrostatic actuation [26].

3. Conceptual design of the process

Design specifications of the process were set based on discussions with the MRF plant manager and engineers. This resulted in the following list: i) sort out the eight target materials; ii) output target baled material in the range of 90 – 100 % purity (high hit rate); iii) be a highly efficient process; iv) be a fully automated process; v) sort target material in the lowest number of operations; vi) sort the largest materials at the initial stages of the process to prevent any machine damage at later stages; vii) cater for all the commingled recyclable domestic waste in Malta which is around 260 tonnes per week; viii) be able to sort out more than 40 tonnes a day if required; ix) have robust machines where possible requiring little maintenance; x) take input commingled waste via a wheel loader; xi) output sorted waste in a densified form; xii) be able to work seven days a week, one shift (12 hours) per day; xiii) be bought at a reasonable price; and xiv) sort materials in a safe manner. A quality function deployment chart was drawn up in order to relate the customer requirements to the design requirements and thus come up with importance ratings for the design requirements. This resulted in efficiency of process given the highest importance, followed by safety, automation level, cost and throughput.

Morphological charts were drawn up in order to identify the potential candidate solutions/means for each sub-function in the process e.g. the opening of bags, the detection of large LDPE etc., based on the literature review. Advanced digital logic was used in order to generate relative weights for each criterion, derived from the quality function deployment chart. This resulted in a relative weight of 0.25 for efficiency and safety, of 0.20 for automation level, and of 0.15 for cost and speed of operation. Decision matrices were drawn up to identify the particular mean for each sub-function in the morphological chart. Three conceptual solutions were generated for the general layout of the facility, and a decision matrix was used to select the best solution. The selected proposal for the facility, showing the schematic layout and the various selected means, is shown in Fig. 1.

4. Design and development of the universal gripper

4.1. Design specifications

The overall objective of the device is to be able to grasp various contaminant material having different shapes, sizes and weights. The general objectives were to develop a gripper that is: i) as light as possible, in order to maximize payload capacity of the robot; ii) as small as possible, to attain maximum access within the workspace; iii) as rigid as possible, in order to be accurate and repeatable; iv) as safe as possible, both in the operating condition and even in the event of overload or collision; v) produced / available at a reasonable cost; vi) able to pick up a very wide variety of objects; and vii) able to be used by all the robots in the facility required to pick up any contaminant material available in any of the already separated target materials.

It was assumed that the end-effector would only be required to pick up objects of major dimension between 40 mm and 110 mm, and of weight below 0.5 kg, since other processes would have taken care of material size and weight extremities beyond these values. It was also assumed that the sorted materials on the conveyor would be reasonably spread out, and that the gripper would only encounter contaminants of the target and non-target type.

The specific design specifications were formulated based on the literature review and on discussion with the plant engineers. These involved specifications related to performance (autonomous and fast actuation); operating environment (contact with dry materials of the target or non-target type; resistant to water and dust; ambient temperature 0 – 70 ^{o}C); serviceability (easy to clean and lubricate, and to replace components; low frequency of maintenance); life span (about 10 million cycles); cost (less than €1000); size (as detailed above); materials (lightweight, non-toxic, fire retardant, odourless, impact resistant); weight (maximum 4 kg); and safety (no sharp edges; can be set up easily with gloved hands). A quality function deployment chart was drawn up in order to identify the relative importance of the design requirements criteria.

4.2. Conceptual design

A morphological chart was drawn up in order to identify potential candidate solutions for each individual kind of object to be picked up. Advanced digital logic was used in order to generate relative weights for each criterion, derived from the quality function deployment chart. This resulted in a relative weight of 0.20 for efficiency and speed, of 0.17 for cost, of 0.14 for strength and rigidity, and of 0.10 for weight, size and safety. Six conceptual solutions for the gripper design were generated, and a decision matrix was used to select the best solution.

The selected design concept consisted of a combination pinch-type and vacuum gripper, and is shown in Fig. 2. The vacuum cup is located between two jaws, and attached to a freely retractable tube member which is normally in the fully extended position due to gravity. The gripper is mounted on an industrial robot and moves to a location offset vertically above the object to be grasped, whose positon and orientation would have been identified by optical sensors. Due to the tracking function of the robot, this offset position moves at the speed of the conveyor belt and tracks the object from above. The gripper then moves down to its minimum height above the conveyor (such that the tips of the gripper jaws are clear of the conveyor belt by about 1 cm), while still tracking the object, and both the vacuum and the jaws are actuated. Should flat paper or cardboard be present, these will be beyond the reach of the closing jaws but will be grasped by the vacuum cup. For 3D objects such as a small HDPE container, both the jaws and the vacuum

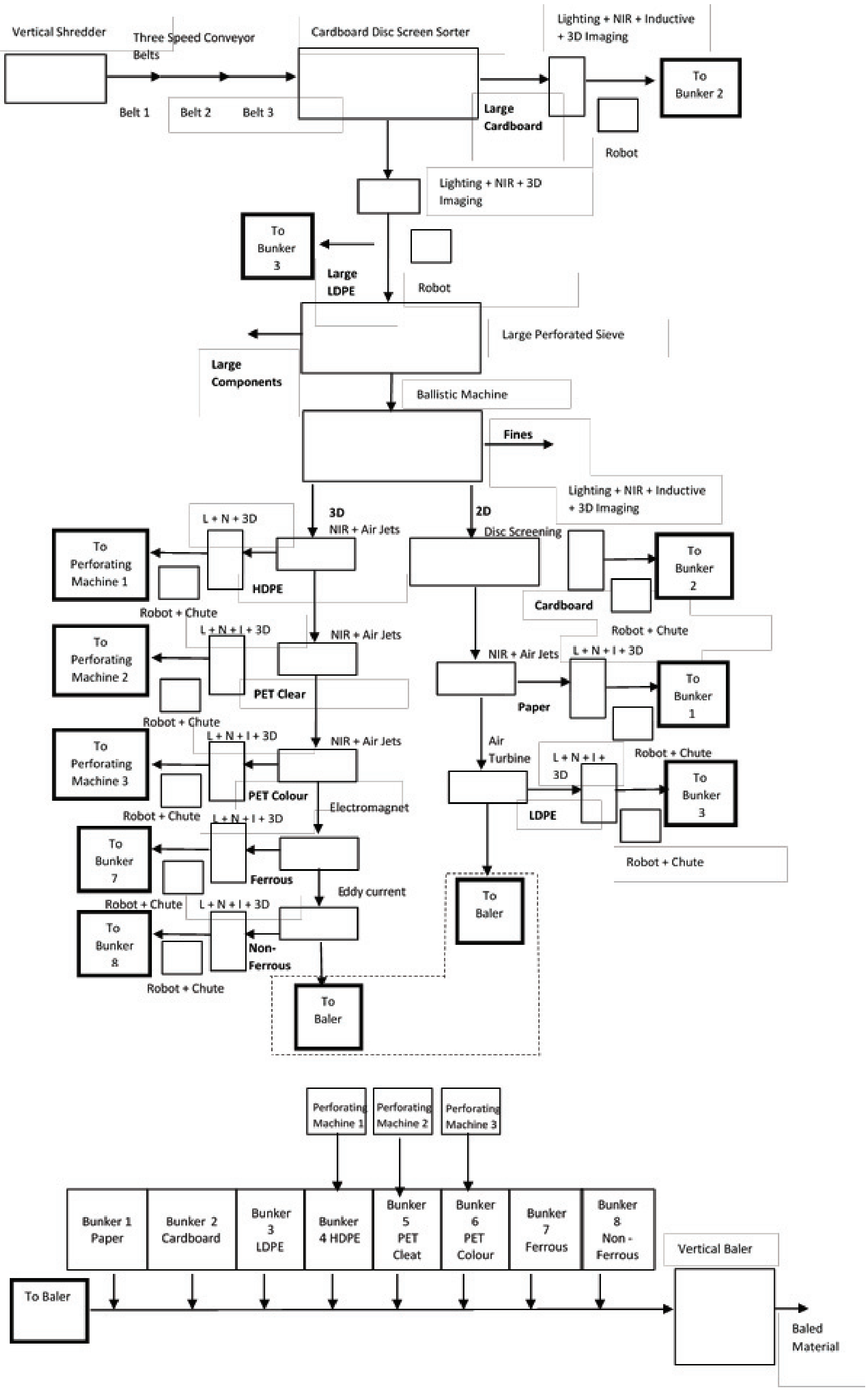

Fig. 1. Schematic diagram of the proposed MRF layout.

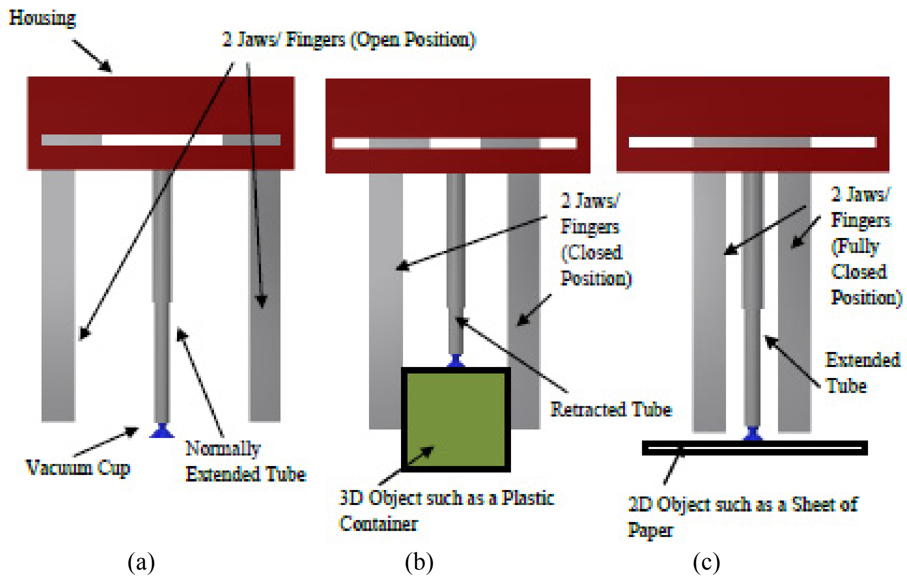

Fig. 2. (a) gripper normally open with extended vacuum tube; (b) gripper grasping 3D object using jaws, aided by vacuum cup held by partially retracted tube; (c) gripper grasping a 2D object using the vacuum cup.

cup will contribute to the grasping. In some cases the vacuum cup will not contribute to the grasp due to high porosity (e.g. holes) of the object, or due to a highly curved surface of the object. In these cases, the object is grasped by the jaws alone. This gripper is therefore able to grasp a very wide variety of object types within the design limitations in size and weight.

4.3. Embodiment design

Since the gripper is to be used in a system requiring high speeds and payloads but low levels of accuracy, control and adjustability, as well as low cost, the clear choice for the jaw actuation system was to use a pneumatic drive. In this way also, the same power source is used for both the moving jaws and the vacuum cup. In order to have a consistent force that does not depend on object size, a double acting cylinder is used to actuate the gripper jaws. Due to the large range in object size, it was opted to use a parallel jaw, rather than a rotary jaw, gripper. Due to the requirements for high speed, high payloads, large stroke length, and compactness, it was opted to use a gripper based on two opposed cylinders to provide large forces from a compact housing, with a rack and pinion mechanism to provide synchronous motion [27].

A thorough materials selection exercise was carried out to select the most appropriate materials for the critical parts of the end effector. The selected materials are shown in Table 1. In order to take advantage of the deformable nature of many of the objects to be grasped, ridges were machined onto the gripper jaws to increase the probability of attaining form closure during grasping. Chamfers were machined at the exterior lower sides of the jaws to help displace any materials close to the object to be grasped. The selected vacuum cup was of the single bellow type in order to enable effective grasping even of uneven, curved and / or non-horizontal surfaces. The diameter of the suction cup was of 35 mm, in order to have clearance from the jaws when these are in the fully closed position.

The required grasping force of the gripper jaws was estimated using Engelberger's equation, for a payload of 0.5 kg, using a g-factor of 3, a worst case coefficient of friction $\mu = 0.19$ (between aluminium and Teflon), and a factor of safety of 2, and was found to be about 75 N. The required vacuum pressure for the suction cup was estimated also for an object weight of 0.5 kg with a g-factor of 3, and was found to be about 70 kPa. From this calculation it was also concluded that the venturi type of vacuum generator would be sufficient for this application.

4.4. Detailed design

The final design of the gripper was based primarily on the synchronous double acting pneumatic gripper that was required. The selected gripper that meets all the design criteria is the MHL2-20D1 from SMC Pneumatics [28], a 40 mm stroke per jaw gripper having a 20 mm piston bore and generating a 74 N gripping force. The rest of the parts were custom manufactured, and the final detail model can be seen in Fig. 3. Failure mode and effect analysis was carried out throughout the entire exercise even in the testing of the prototype. Finite element analysis was also carried out on the jaw design in order to find the Von Mises stresses, the maximum displacement and the maximum and minimum safety factors present.

4.5. Preliminary evaluation and discussion

The gripper was mounted onto a Mitsubishi RV-6SL (6-DOF, revolute geometry) robot. In the first test, various materials taken from a typical domestic commingled waste recycling bag were placed at a known position and orientation onto a stationary conveyor belt to be grasped, see Fig. 4(a). In the second test the robot was used in conjunction with a variable speed conveyor, incorporating a diffuse photoelectric proximity sensor for object detection and provision of a trigger signal to the robot, and a digital encoder giving an input to a tracking interface card installed in the controller. Various 3D objects from the recycling bag were fed (in a known position along the conveyor width, and in a known orientation) onto the moving conveyor belt, and the success of the robot in tracking and picking the objects was monitored, see Fig. 4(b). Conveyor speed was varied between 0.10 and 0.15 m/s.

All of the objects tested could be grasped successfully. The results of the first test are given in Table 2. The results for the second test were generally successful as proofs of concept, with the proximity sensor needing some setting adjustment according to the object to be sensed and its position across the conveyor. It is noted that in the

Table 1. The chosen materials for the different parts.

Part	Chosen material
Jaws	Al 6061-T6
Telescopic tubing	Al 6061-T6
Vacuum cup	Nitrile Butadiene Rubber (NBR)
Rings in Telescopic Tubing System (Bushings)	Nylon 6/6

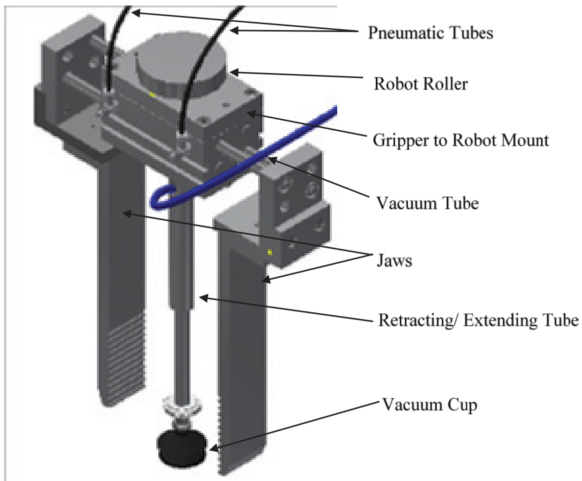

Fig. 3. A CAD model representation of the developed gripper

(a) (b)

Fig. 4. (a) Setup for first test: various items to be grasped; (b) Setup for second test: HDPE container to be grasped while moving on the conveyor belt.

Table 2. Results of first test.

Material	Form	Product	Weight	Performance			Remarks
			(g)	Run 1	Run 2	Run 3	
Paper	Ball	newspaper	21	G	G	G	Vacuum cannot handle uneven surface
		white paper	6	G	G + V	G	Vacuum cannot handle uneven surface
		grey board	31	V	G	G + V	Vacuum cup deforms board
	Flat	newspaper	4	V	V	V	Easily handled
		white paper	4	V	V	V	
		grey board	41	V	V	V	
Cardboard	Container	cardboard box	45	G + V	G + V	G + V	
	Flat	cardboard sheet	29	V	V	V	
LDPE	Container	bottle	90	G + V	G + V	V	
	Flat	plastic bag	1	V	V	V	Longer delay needed after release
HDPE	Container	shampoo bottle	62	G + V	G + V	G + V	Easily handled
PET	Bottle	bottle	57	G + V	G + V	G + V	
	Bag	plastic bag	6	V	V	V	
Ferrous	Container	tomatoes can	46	G + V	G + V	G + V	
	Flattened	tomatoes can	46	V	V	V	
Non-ferrous	Container	soft drink can	11	G + V	G + V	G + V	
	Flattened	soft drink can	12	G + V	V	V	
Carton	Container	milk carton	27	G + V	G + V	G + V	
	Flattened	milk carton	26	V	V	V	
Polystyrene	Container	food container	28	G + V	G + V	G + V	
	Flattened	food container	13	V	V	V	
Polypropylene	Container	liquid soap	32	G + V	G + V	G + V	
		tomato paste	77	G + V	G + V	G + V	
	Flat	lunch box lid	15	V	V	V	

Legend: G – grasped with jaws; V – grasped with vacuum cup

actual application, the position and orientation of objects would be detected using automated imaging systems such as NIR and/or machine vision, and that the proximity sensor (that in any case cannot detect 2D objects) would not be needed. Occasionally, uncrushed cans lying on their side can roll sideways on first contact and jam between the telescopic tube and a gripper jaw. The gripper design and approach strategy are being improved to address this issue. Other general limitations of the present design include some constraints on maximum and minimum object size due to the open and closed position limits of the two jaw gripper (for the cases where grasping cannot be effected by the suction cup); the possibility of interference with the grasping process by other items that are close by; and potential issues with items that are too porous or perforated to be grasped using vacuum (for the cases where grasping cannot be effected by the jaws). These are issues to be addressed in future work. In general however, the simultaneous use of two different grasping methodologies allows for one to compensate for the other in most cases.

5. Conclusion

The results indicate that manual dry recycling systems can be partially, or potentially even fully automated through the use of robust machines, laid out in specific sequences as suggested by an extensive literature review and based on stakeholder consultation and on a detailed design process, in order to sort out the various materials into their respective fractions. In addition, robots can be utilized in various parts of the process in order to replace the manual sorters. Versatile universal grippers such as the one developed here can be used to grasp materials having different shapes, sizes and weights. Grasping performance can be optimized through the accurate determination of the approach position and orientation of the gripper above the object to be handled, based on 3D vision, NIR sensing and artificial intelligence. The overall approach is relevant to potential applications on a global scale, at a time of increasing awareness and regulation of the need to recover recyclable material from domestic waste.

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