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Robotic Pick-and-Toss Facilitates Urban Waste Sorting*

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Abstract— **Incorporating robots into industrial settings is not a new concept, but their use in the waste recycling industry is critical. Recently AI-assisted robots are used to support waste sorting and improve the quantity and quality of recovered materials. This article aims to study and apply a new transfer paradigm for recyclable sorting using Delta robots, which is based on replacing the usual Pick-and-Place process with the much faster Pick-and-Toss process. Current robotic sorting systems can sort one item per second, Pick-and-Toss intends to significantly advance this score. We quantitatively and qualitatively assess the tossing approach by comparing it to Pick-and-Place, in terms of accuracy and robustness, both in simulation and on a real waste sorting lab-setup equipped with an ABB-IRB360 Delta robot. Overall, the Pick-and-Toss approach proves to be a powerful mechanism that succeeds faster sorting of waste streams in comparison to the standard Pick-and-Place procedure.**

I. INTRODUCTION

In recent years there has been an increasing demand for new robotics applications that focus on solving real-life problems. One area that can be significantly enhanced by modern robotic technology is waste management. In particular, the need for separating recyclables into bins dedicated to different material types so that they can be used as a second-order resource, can be significantly enhanced by robotic technology.

Recently we developed a robotic system for material sorting that works effectively on mixed recyclables flows [1]. The system combines (i) machine learning technology to categorize recyclables transferred on a conveyor belt into a set of predefined material classes, (ii) vacuum gripping to pick recyclable items and (iii) a delta robot to quickly transfer recyclables to the corresponding material bin.

The implemented robotic system outperforms human quality-control workers who pick out about 30 to 40 items per minute, on a daily average. In contrast, our robot picks on average 60 items per minute which is similar to the processing rate of commercial systems.

Besides the significant advancement already achieved by robots, recyclable sorting is a task that has to be done as fast and accurately, as possible. This is the only way to effectively manage the ever increasing volume of waste created by people following the modern life style.

To this end, the present work investigates methods to speed up the processing of recyclables. In particular, this study focuses on substituting the ordinary "Pick-and-Place" procedure with a much faster "Pick-and-Toss" which can significantly improve the rate of recyclables separation. In short, the Pick-and-Toss (PnT) approach exhibits important advancements in comparison to Pick-and-Place (PnP). These are shortly summarized bellow:

- PnT expands the scope of the robot, enabling it to reach bins located far beyond its normal operating range and therefore, increases not only the maximum allowed number of installed bins but also the number of different material types that can be handled by a single robotic unit.
- PnT reduces the time of processing recyclable items by 15.3% in comparison to PnP, thus making recyclable sorting more energy efficient.
- PnT increases the processing capacity of the robotic unit by 18%, without sacrificing the quality of the result, thus enabling more waste to be processed in a given amount of time.

Following the above summarized results, the present work puts forward an essential advancement for industrial robots undertaking recyclables sorting, which may lead to significant economic and environmental benefits.

The rest of the paper is organized as follows. Section II provides a summary of previous works most relevant to the present study. The following section presents the individual parts of the robotic system that has been developed for sorting recyclable waste. Then, Section IV studies the two waste sorting approaches, namely Pick-and-Place and Pick-and-Toss. Experimental scenarios and assessment results obtained for each one of the two approaches are presented in Section V. Finally, the last section discusses the obtained results and highlights directions for future work.

II. RELATED WORK

To date, industrial waste sorting is mostly based on the optical separator technology which achieves a recovery rate of about $93-95\%$ [2]. Optical sorters are typically based on user-defined accept/reject criteria to binary separate between objects of different type transferred on conveyor belts. Due to the binary separation, an increased number of conveyor belts must be used to separate materials into many classes. As a result, the use of optical separators assumes high-cost and large-volume industrial installations.

During the last decade robotic technology introduced an alternative to the above described approach. Incorporating robots into industrial settings is not a new concept but their use in the recycling industry is more challenging due to the need of using tough enough equipment to withstand a beating

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in harsh recycling environments.Working with robotic fingered hands limit the speed and the stability of the gripping process and at the same time arise significant restrictions regarding the materials shapes that can be processed [3], [4].

Further to that, fast and effective gripping of materials without potential slips during transfer, is highly desirable in waste sorting. In industrial applications, where reliable, fast and effective gripping is necessary, the use of vacuum grippers is very common [5], [6]. Vacuum provides particularly powerful gripping properties [7] and has been one of the key enabling technologies that facilitated the use of robots in recyclable sorting industrial applications.

Currently, there is already a number of commercial AI-driven robots that have been applied in industrial environments to pick out recyclable materials. Some of the most well known systems are: Sadako [8], samurAI [9], AMP Robotics [10] and ZenRobotics (considering also the management of construction waste) [11]. The majority of existing systems capitalize on the particularly speedy motion of Delta robots to achieve fast transfer of recyclables from the conveyor belt to the sorting bin. The benefit of the Delta robot kinematic profile is that it reduces the weight within the arms and therefore provides very high acceleration capability [12].

Recently, Max-AI in collaboration with Bulk Handling Systems (BHS) released a new sorting solution that employs two collaborating robotic arms to sort recyclables following a material tossing approach [13]. This system has been presented as the main competitor of the commonly used delta-robot approach. Other relevant works examining object tossing by robots have also appeared in the literature during the last years [14], [15], [16], focusing however on application domains very different than recyclable sorting.

The present work investigates for the first time the combination of the particularly fast Delta robot technology with the concept of material tossing. Following this approach, the current study seeks to create new improved and quicker processing of recyclables and, at the same time, inspire new applications beyond the waste management sector.

III. ROBOTIC WASTE SORTING

We develop an integrated robotic system for recyclable sorting that is composed by three parts, namely: (i) a vision-based material detection and classification, (ii) a robotic waste sorting and (iii) a vacuum gripping system.

A. Vision-based Material Classification

The present work capitalizes on recent advances on Deep Learning based computer vision to develop a visual classifier of recyclables. In particular, we have collected 1000 images of recyclables which are used to train a randomly initialized Mask R-CNN following a procedure with 100 epochs, with 100 steps per epoch and 100 validation steps. The trained network can separate between different types of recyclables as shown in Fig 1. The identified object locations are forwarded to the robot, which implements their physical separation into different bins.

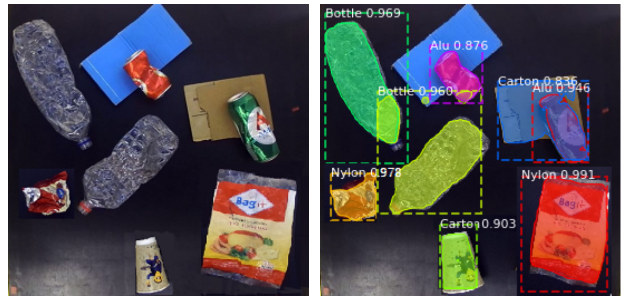


Fig. 1: Material classification using Mask R-CNN. A dotted bounding box and a corresponding colored filled mask is assigned for every predicted material. The name of the class and the predicted confidence is also depicted for each classified material. Colors are randomly selected.

B. Robotic System

The proposed system consists of an ABB IRB360 delta robot. This type of robot is ideal for applications assuming repetitive labour tasks.

A key benefit of delta robots is that the heavy motors are fixed on the frame, allowing the moving parts of the robot to be very light. This is in contrast to typical articulated robot arms in which each motor carries the weight of all the successive motors. Given that delta robots assume the motion of a limited part of the robot mass, the delivered motor torque is effectively dedicated to the transfer of the payload. Accordingly delta robots provide a very efficient way of x, y, and limited z transactions.

C. Vacuum Gripper

Many industrial applications assuming the low cost, reliable and fast picking of materials without any need for fine manipulations, rely on vacuum gripping. In this direction, we have designed and manufactured a vacuum gripping system which is attached to the end-effector of the robot that undertakes the sorting of recyclable materials [1]. In short, the vacuum gripping system is composed by:

- A suction cup consisting of flexible and compliant materials that pathetically adjust their shape to the unstructured surface of the contacting material to improve sealing and thus enable vacuum gripping.
- A vacuum generator namely the PIAB-piCLASSIC Xi40-3 which is powered by compressed air to generate vacuum based on the Venturi's principle. The device generates high-speed flow between the vacuum cup and the material's surface, thus creating vacuum able to pick and hold the selected materials.
- A custom made shock absorber attached at the end of the robotic arm. The shock absorber has a two fold functionality. First, it gradually presses the suction cup on the material to facilitate sealing. Second, it absorb vibrations along the z axis, that could potentially hurtle materials, thus make impossible their picking.

IV. MATERIAL SELECTION AND TRANSFER

An essential part of the sorting process is the selection and manipulation of the recyclables. Typically, recyclables are transferred on a conveyor-belt with a constant velocity and random distribution. Technically, the steps that are followed by the system while the materials are moving on the conveyor, are: (i) material classification, (i) material selection, (iii) robot picking of the selected material, and (iv) transfer of material to the proper bin.

The market-value of recyclables may be a key parameter to prioritize the order that recyclables are sorted. The present work assumes that all materials share the same value and focuses on the study of the trajectory followed by the robot in order to (i) minimize the time spent on material sorting and (ii) increase the processing capacity of the robotic unit.

This trajectory is defined as a two-step process, i.e. (i) pick the item and (ii) throw it to the bin. In the following, we refer to the picking optimization process, and we present two alternative approaches for the throwing part.

A. Pick-and-Place Activity

The majority of robotic systems used in the industry for sorting recyclable waste follow a Pick-and-Place (PnP) procedure. Recently we developed a system that accomplishes waste sorting following the contemporary PnP approach [1]. For this system, the processing cycle of the individual materials is separated into 5 sub-actions as described bellow:

- s-i Horizontal translation from the current position to the target-waste position.
- s-ii Vertical translation towards the waste with the pathetic involvement of the shock absorber which ensures good contact of the suction cup with the material surface, and activation of the vacuum to implement gripping.
- s-iii Follow the material transferred on the conveyor belt for a short period of time to improve sealing.
- s-iv Vertical translation upwards for 150mm moving away from the conveyor belt, with the requested material grasped by the suction cup.
- s-v Horizontal translation towards the bin that corresponds to the waste material, where vacuum is deactivated for the disposal of the waste.

Following the above summarized, ordinary PnP approach, the separation of each material takes approximately 800-1060 msec. The time is split to the individual actions as follows:

$$t_{s-i} = [230, 410]ms \qquad t_{s-ii} = 50ms \qquad (1)$$
$$t_{s-iii} = 120ms \qquad t_{s-iv} = 70ms$$
$$t_{s-v} = [230 - 410]ms$$

As can be seen from the above, the steps s-ii, s-iii and s-iv are implemented in constant times. In contrast to these three actions, the s-i and s-v are implemented at varying times. This is because the distance between their start and end point is not fixed but is determined by (a) the bin that the previously separated material has been placed, (b) the position of the current material on the conveyor belt and (c) the location of the bin that the current material must be placed. This is illustrated graphically in Fig 2a, where 5 indicative pick-and-place movements are shown, with the s-i represented by dashed lines and s-v represented by solid lines.

B. Pick-and-Toss for Waste Sorting

The large amount of waste that must be treated daily at the sorting plants creates a strong need to reduce the time required to separate the materials. In contrast to the commonly used PnP procedure that approximately achieves the sorting of one material per second, the present work studies its replacement with a new "Pick-and-Toss" (PnT) process, which offers new possibilities for much faster sorting of waste flows.

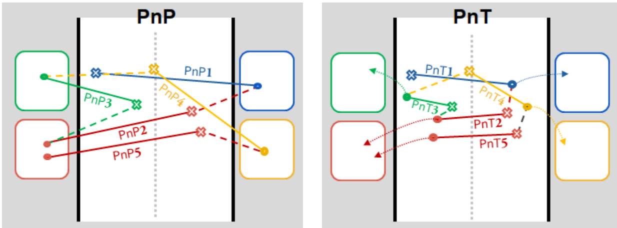
As indicated by the action-times mentioned in the previous section, the most available space for reducing the total time of the materials' sorting cycle is on actions "s-i" and "s-v". Interestingly, one way to save time for both s-i and s-v, is to substitute the full transfer of items from the picking location to the disposal location, with the alternative "throwing" of the materials to the target bin. This approach saves time for action s-i, which assumes that the robot has just processed an item and goes for the next one. In that case, the robot's starting location is not one of the bins (as in PnP), but a location much closer to the center of the conveyor belt. As a result, the robot travels a much sorter distance to pick the next material for sorting. Moreover, time is additionally saved for action s-v. This is because, the robot does not travel the whole distance from the picking location to the bin, but only a percentage of it and then the material is tossed to the bin. The s-i and s-v distances covered by the robot in the case of PnT are illustrated in Fig 2b.

By comparing parts (a) and (b) of Fig 2, the reader can obtain an intuitive but clear explanation of the differences between PnP and PnT. There are significant differences between the two approaches in the distances covered by the robot and consequently the time needed by the robot to complete the physical separation of materials.

In practice, what is necessary to change in order to transfer the PnP implementation into a PnT implementation, is only the execution of action s-v. This is described bellow. For the shake of explanation, we assume that the robot has just picked a new material (i.e. it has completed action s-iii). Then the robot starts traveling its way to the bin, but after completing a percentage of this transfer, the suction is deactivated and the robot stops moving. This makes the material to brake vacuum -due to the inertia of the material's motion- which ends up with the material tossing towards the bin. The fact that the robot covers only a percentage of the original s-v action indirectly saves also time for s-i, as already discussed above.

V. EXPERIMENTAL RESULTS

The proposed sorting scheme has been implemented and experimentally validated in both simulated and real robot



(a) (b)

Fig. 2: An example of the robot trajectories executed for sorting 5 items following either the PnP (a), or the PnT (b) approach. Different colors used for different classes of items. Crosses denote the location of picked items, dots show the points of placing (a) and tossing (b) the item. The dashed lines show robot trajectories toward the next item to pick (i.e. actions s-i) and filled lines show the robot trajectories for sorting the item to the respective bin (i.e. actions s-v). In the case of PnT, colored dotted parabolic lines represent the items flying toward the bins. The example assumes that four types of items shown in green, red, blue and yellow have to be separated in to the respective bins. The sorting process starts with picking the blue item, and proceeds with the rest as shown by the lines. Overall, the trajectory followed by the robot when following the PnT approach is significantly shorter than the corresponding PnP trajectory.

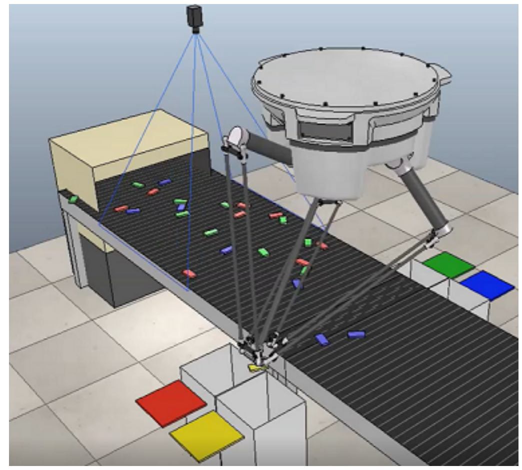


Fig. 3: The V-REP simulation environment showing the conveyor belt carrying items of four different colors/types, which are sorted by the robot to the corresponding bin.

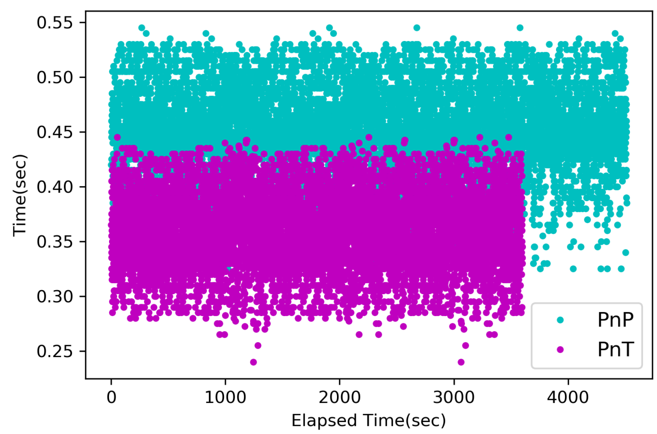


Fig. 4: An overview of the time needed to perform 10000 sortings following either the PnP or the PnT approach. The task completes faster with the adoption of PnT. The y-axis depicts the time spent in implementing the individual sortings, which are represented with dots in the plot.

environments. In the current section we present first quantitative results that demonstrate the accuracy and robustness of the proposed PnT sorting scheme in simulation, comparing it to the typical PnP scheme. Further to that, evaluation results are outlined for the case of a lab sorting system using the ABB-IRB360 delta robot that sorts four different types of materials i.e. bottle, aluminum, carton, nylon.

A. Simulation Experiments Comparing PnP vs PnT

In order to compare the performance of the PnP and PnT approaches in the recyclables sorting task, the ABB-IRB360 delta robot is simulated in the open-source V-REP environment provided by Coppelia Robotics (Fig.3). The environment facilitates also the simulation of conveyor-belt and vacuum gripping, thus being particularly appropriate for studying the task at hand.

The recyclable items to be sorted are represented by cuboids, which, for the given study, share the same size and adhesion properties. The cuboids are placed on a conveyor-belt that moves with a constant velocity of 0.2 m/s. The different types of items are represented by cuboids of different colors. The item classification is based on a color detection functionality that is already available in V-REP library. The number of bins is the same with the number of items' colors. Accordingly, the task of the robot is to place the cuboids into the bin that corresponds to their color.

To compare the PnT against the PnP approach we examine the performance of the system in a tasks that assumes the sorting of 10000 items. The items are uniformly distributed into four different colors/types (i.e. approx. 2500 items per color) and four different bins are used for their separation. For both cases, we assume rich-enough item flows, that keep the robot always busy. It is noted here that the ideal conditions of the simulation environment allow the reduction of times spent on the actions s-ii, s-iii and s-iv, which are set to $t_{s-ii} = 30ms$, $t_{s-iii} = 50ms$, $t_{s-iv} = 30ms$ for the case of the simulated experiments.

Figure 4 summarizes the obtained results when adopting either the PnP or the PnT approach. Clearly, the sorting of 10000 materials is accomplished significantly faster with the use of the PnT approach. On average, the processing rate of PnT is 166 items per minute, when in contrast, the processing rate of PnP is 133 items per minute. This is interpreted as improving the productivity of the *simulated* system by 24.8% within a predefined working period.

We elaborate further on the obtained results to study the characteristics of the dynamic actions s-i and s-v as they are

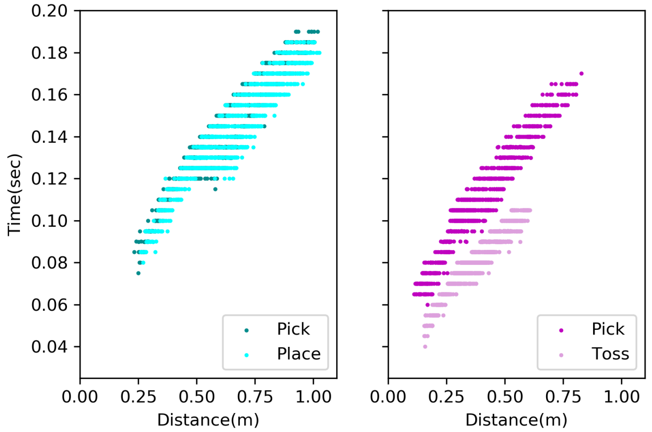


Fig. 5: The spatio-temporal characteristics of horizontal (s-i and s-v) robot movements during PnP and PnT sorting.

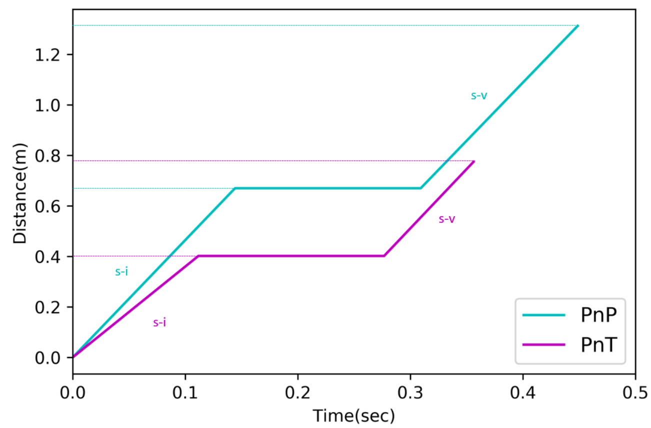


Fig. 6: The time averages of the robot actions s-i to s-v, for the case of PnP and PnT.

implemented in each sorting case by the robot. The spatio-temporal characteristics of s-i and s-v for the case of PnP and PnT are illustrated in Fig 5. Clearly, for PnP, both actions take more time since they assume a longer travel of the robot in comparison to PnT. However, it is interesting to note that besides the PnT s-v actions assuming shorter distances in comparison to PnP s-v, they are also executed in less time. This is because the velocity profile of the action s-v is very different among PnP and PnT. More specifically, in the case of PnP the robot starts the action at zero velocity, then it accelerates and ends up again with a zero velocity. However, in the case of PnT the robot start at zero velocity, it accelerates as above, but there is no need to decelerate back to zero. While on travel, vacuum is deactivated and the robot makes an upwards U-Turn (to go get the next item), which makes the item toss towards the bin. The time spent on the U-turn is counted in the s-i activity, which explains why s-i is shown less different between the PnP and PnT case.

Another point of interest regards how PnT reduces the processing time in relation to the distance between the item's conveyor location and the target bin. Time reduction is affected by the amounts of the constant-length activities implemented by the robot in each processing cycle. The constant length activities are the s-ii and s-iii actions, plus the U-turn mentioned above which is however counted as part of s-i. In total, the time-averages of the actions implemented by the robot in each processing cycle of the experiment discussed so far, are summarized in Fig 6. As shown in the figure, time reduction between PnP and PnT is accomplished only for s-i and s-v.

Finally, it is of particular interest to assess whether the toss activity expands the usability of the sorting robot rendering it capable of sorting items which are separated into a higher number of types. This is not possible with the contemporary PnP approach, because of the constrained working range of the robot which limits the number of bins the robot can reach. However, using the PnT approach, the robot is capable of tossing items in locations beyond its working range, and thus extend its scope. To asses this hypothesis, a simulated experiment is conducted which assumes the separation of 8 types of items into 8 different bins. Interestingly the robot could straightforwardly cope with the separation of 8 different types of items. In that case, the productivity of the robot (number of processed items in time) has reduced on average by 1.5%. However, it is worth noting that this small reduction is expected because of the longer distances that the robot has to travel in order to toss items in distant bins.

B. PnP vs PnT Evaluation in the Real Robot

Further experimentation is performed in real world conditions using an ABB-IRB360 robot. The experiments capitalize on the industry-like setup developed in our lab, which facilitates the study and assessment of alternative technologies and ideas on robot-powered recyclable waste sorting. The underlying setup consists of (i) a conveyor belt that transfers the recyclable wastes at a speed ranging between 135 and 277 mm/sec (ii) an ABB IRB-360 DELTA robot that is installed above the conveyor belt, (iii) an external camera for the visual detection and classification of recyclable materials, and (iv) the vacuum gripping system [1].

The present study considers the separation of four different types of recyclables, namely PET bottles, aluminum cans, cartons and nylons. The computational vision system summarized in section III-A is employed to successfully categorize the materials into the four available categories.

The composite system has been extensively tested in sorting recyclables following the PnP approach, as also described in [1]. In contrast to the ideal conditions of the simulated environment, several characteristics of the real world may affect the overall performance of the system and the effectiveness of vacuum gripping, such as dealing with deformable materials having unreconstructed shapes and unknown weights. As a result, the success rate of the robot in handling real recyclables has been estimated to approximately 87-94% depending on the type of materials.

In contrast to the previous study focusing on PnP, the

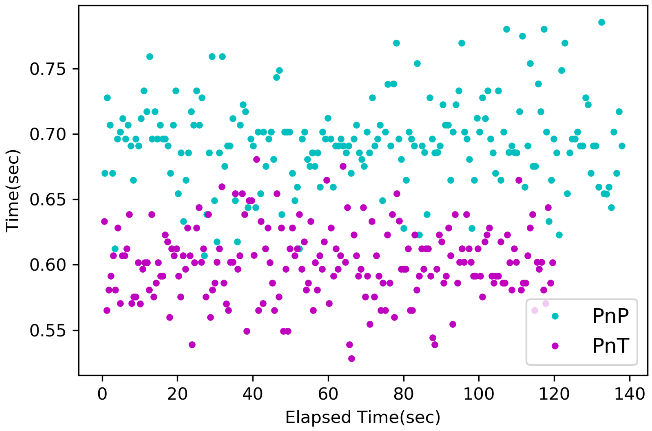


Fig. 7: An overview of the time needed to perform 200 picks in real conditions following either the PnP or the PnT approach. PnT tasks are completed faster. The y-axis depicts the time spent in implementing the individual sortings, which are represented with dots in the plot.

present work explores the performance of the system when the PnT approach is adopted. An indicative video that demonstrates PnP versus PnT performance is provided in the following link: https://youtu.be/JDhomgotdnA.

In order to compare the PnP and PnT approaches in the real world, we contrast the time each one needs to complete the sorting of 200 different materials. To this end, we manually fed the conveyor belt with 280 recyclables (to ensure that the requested number of 200 sortings is reached) and then the performance of each approach is examined. The timing of the individual sortings is shown in Fig. 7. According to the results, following the PnT approach the robot has been able to successfully complete the processing of 200 recyclables in 15.3% less time than PnP. Clearly this is almost half of the reduction observed in the simulated environment (see Fig 4). This is mainly for two reasons. First, the rate of failures during the transfer of materials has slightly differentiated for the cases, increasing from 8% in PnP to 13% in PnT. This means that in the case of PnT, the robot had to repeat the management of a material more often, to achieve a single successful sorting. Second, in the real experiments, the times spent on actions s-ii, s-iii, s-iv, all of them having static, predefined duration, are longer than the ones used in the simulation experiments (their values for the real experiments are shown in Eq. (1)). As a result, the percentage of time reduction per material management when comparing PnP and PnT, is slightly less for the real experiments, which accumulatively affects the total result.

VI. CONCLUSIONS

The present work puts forward a new approach to improve the effectiveness of robots undertaking recyclable-sorting tasks. This is based on the idea of substituting the ordinary Pick-and-Place (PnP) activity with a new, more efficient Pick-and-Toss (PnT) operation. The current study attests to the validity of the proposed approach.

Fig. 8: Indicative snapsots from the integrated robotic sorting system in action.

Overall, PnT (i) enhances the productivity of the robots used in recyclable waste sorting (i.e. more recyclable items processed per time unit), and (ii) extends the effective range of robots by making reachable bins located outside their original operational scope. The combination of the two, makes more effective the PnT-following robotic systems applied in recyclable sorting, thus offering not only significant economic benefits to the relevant sorting plants, but also major environmental benefits to society as a whole.

In the future, we plan to elaborate on the static parameters of the real robotic system in order to reduce failures and assess the composite system on a significantly larger set of recyclables. The application of the Pick-and-Toss approach to a real industrial waste sorting environment is also in our future plans.

REFERENCES

[1] E. Papadakis, F. Raptopoulos, M. Koskinopoulou, , and M. Maniadakis, "On the use of vacuum technology for applied robotic systems," in *ICMRE 2020-IEEE 6th International Conference on Mechatronics and Robotics Engineering*, 2020.
[2] S. Gundupalli, S. Hait, and A. Thakur, "A review on automated sorting of source-separated municipal solid waste for recycling," *Waste Management*, vol. 60, pp. 56–74, 02 2017.
[3] J. Mahler, M. Matl, V. Satish, M. Danielczuk, B. DeRose, S. McKinley, and K. Goldberg, "Learning ambidextrous robot grasping policies," *Science Robotics*, vol. 4, no. 26, 2019.
[4] B. Sauvet, F. Lévesque, S. Park, P. Cardou, and C. Gosselin, "Model-based grasping of unknown objects from a random pile," *Robotics*, vol. 8, no. 3, 2019.
[5] J. R. Amend, E. Brown, N. Rodenberg, H. M. Jaeger, and H. Lipson, "A positive pressure universal gripper based on the jamming of granular material," *IEEE Transactions on Robotics*, vol. 28, no. 2, pp. 341–350, April 2012.
[6] P. Tuleja, "Unilateral gripping with active vacuum suction cup: Calculation of gripping force and number of suction cups," 2014.
[7] D. T. Pham and S. H. Yeo, "Strategies for gripper design and selection in robotic assembly," *International Journal of Production Research*, vol. 29, no. 2, pp. 303–316, 1991.
[8] Sadako:. [Online]. Available: http://www.sadako.es/max-ai/
[9] SAMURAI Robotic Sorting System. [Online]. Available: https://www.machinexrecycling.com/products/samurai-sorting-robot/
[10] AMP Robotics. [Online]. Available: https://www.amprobotics.com/
[11] Zen Robotics:. [Online]. Available: https://zenrobotics.com/
[12] V. Poppeova, J. Uricek, V. Bulej, and P. Sindler, "Delta robots - robots for high speed manipulation," *Tehnicki Vjesnik*, pp. 435–445, 2011.
[13] Url: https://www.youtube.com/watch?v=tEAr1w1Jxww.
[14] H. Frank, D. Barteit, and F. Kupzog, "Throwing or shooting - a new technology for logistic chains within production systems," in *IEEE Intern. Conf. on Tech. for Practical Robot Apps*, 2008, pp. 62–67.
[15] A. Zeng, S. Song, J. Lee, A. Rodriguez, and T. A. Funkhouser, "Tossingbot: Learning to throw arbitrary objects with residual physics," *CoRR*, 2019.
[16] J.-S. Hu, M.-C. Chien, Y.-J. Chang, S.-H. Su, and C.-Y. Kai, "A ball-throwing robot with visual feedback," *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 2511–2512, 2010.