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AI-powered Robotic Material Recovery in a Box

RECLAIM

D5.1: Early prMRF development based on available enabling technologies

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List of Abbreviations

Abbreviation	Definition
AI	Artificial Intelligence
DoA	Description of the Action
RDG	Recycling Data Game
prMRF	portable, robotic Material Recovery Facilities
RoReWo	Robotic Recycling Workers
RoReWo-T	Robotic Recycling Workers Team
HSI	Hyperspectral Imaging

Executive Summary

The RECLAIM project unites state of the art research results in robotics and grippers technology, artificial Intelligence, computer vision and hyperspectral imaging, and mature waste management technology to deliver a portable, robotic Material Recovery Facility (prMRF) capable of significantly enhancing local-scale waste sorting activities for material recovery. To achieve this goal, repeated integration and testing activities play a crucial role as they promote the unification of the research and innovation work done in RECLAIM. Indeed, while in WP3 different software modules on recyclable identification localization and categorization are conceived, designed and developed, and in WP4 low cost Robotic Recycling Workers (RoReWos) and robotic grippers are constructed, the WP5 considers the integration of the relevant technologies and their ongoing installation in a container-box for the synthesis of the prMRF.

This deliverable provides a summary of the integration activities implemented during the first months of the RECLAIM project, which aimed to evaluate the combined performance of the technologies tested in the project, in an attempt to reveal potential problems, highlight directions for fruitful research work and minimize risks to the developments targeted by RECLAIM.

This deliverable includes six (6) sections. After a brief introduction in section 1, the section 2 summarizes key components that are necessary for the implementation of the prMRF. Then, given that the container -box that will host the prMRF was not available in the first months of the project, section 3 presents the approach followed in RECLAIM for the pairwise integration of the prMRF components. This aims to ensure that existing and newly developed technologies are smoothly integrable and that no critical issues are expected to arise during the synthesis of the prMRF.

Then, section 4 summarizes our first attempt to develop a composite system that can successfully treat a waste stream, being capable to identify and recover the recyclable objects of a prespecified material type. Section 5 provides directions for future work summarizing how RECLAIM developments in robotics and grippers, artificial Intelligence, computer vision, and hyperspectral imaging will be accommodated in the prMRF.

Finally, the conclusions section summarizes the work done on prMRF component integration, discusses the innovation potential of the current developments and comments on how it links to the Recycling Data Games also considered in RECLAIM.

1 Introduction

The RECLAIM work is structured in three phases that aim to implement three incrementally enhanced versions of the prMRF and the targeted technology. The first is the Machinery Integration phase that aims to consider and test technology available by RECLAIM partners and to implement early prototypes of newly proposed waste processing components, to quickly verify that the infrastructure available at the end of phase 1 is suitable and adequate for the operation of the prMRF. Along this line, the present document summarizes preparatory RECLAIM activities towards the creation of the portable, robotic Material Recovery Facility (prMRF). Moreover, the developed prototypes will enable data collection to accelerate the training of the necessary AI modules and facilitate the design of environmental games targeting recycling and particular material recovery.

In the first months of the project, we have exploited the extensive expertise of ROBENSO and HERRCO in applied waste management solutions, that provided guidelines to technical partners for choosing, purchasing and implementing the hardware and software components that are necessary for the operation of the prMRF. The relevant components regard the container-box and the mechanical equipment that supports waste transfer and treatment, the computer vision module and the hyperspectral imaging module that together enable the identification, localization and categorization of recyclables, the newly introduced Robotic Recycling Workers and the grippers to be used for picking and sorting different materials. The first phase of RECLAIM aims at the early integration of the relevant components in order to promptly reveal/mitigate conflicts in the waste processing chain.

Considering the availability of the different components, we have proceeded with integration and interoperability tests in subgroups, in order to immediately reveal potential conflicts in the recyclable materials processing chain specified in Deliverable 2.1, early in the project lifecycle. In that way, we expected we would have sufficient time for conflict consideration and risk mitigation.

Interestingly, so far we have achieved a seamless conceptual and physical integration among the different hardware and software components that are planned to be integrated in the prMRF. As described below, RECLAIM current decisions for the development of the prMRF appear to be in the right direction, as early assemblies and subgroup integration tests have not identified any conflicts. On the contrary, using the early developments we have been able to develop the first version of a simple autonomous recyclable sorting mechanism, which verifies the validity of the RECLAIM approach and, to the extent possible, assures that the intended prMRF functionality will be fully accomplished.

1.1 Intended readership

The present report is a public (PU) document. Its readership is considered to be the European Commission, the RECLAIM Project Officer, the partners involved in the RECLAIM Consortium, beneficiaries of other European funded projects, and the general public.

1.2 Relationship with other RECLAIM deliverables

This deliverable is related to all follow-up technological deliverables in RECLAIM. The current document will serve as a basis for the developing future version of the components to be installed in the prMRF, and additionally as a guideline for their integration, communication and cooperative operation. In the coming months of the project this deliverable will serve as a reference point for RECLAIM partners that need to coordinate activities in order to achieve a smooth integration of the components they develop into the prMRF. Following the above, the Deliverable 5.1 is related with all following deliverables linked to prMRF construction and testing.

Table 1. Other RECLAIM deliverables related to Deliverable 5.1.

Del. No	Deliverable Name	WP	Month
3.1	Material recognition based on RGB and Hyperspectral imaging	WP 3	M18
3.2	prMRF operation monitoring and repeating advancement	WP 3	M30
4.1	Gripping mechanisms and RoReWo units for material recovery	WP 4	M18
4.2	Multi-robot / multi-gripper RoReWo-Team configuration	WP 4	M30
5.2	Preliminary assessment of prMRF performance	WP 5	M18
5.3	Final assessment of prMRF and sustainability plan	WP 5	M36
6.1	Waste Data for material recognition and Recycling Data Game	WP 6	M18
6.2	Algorithms and pipelines for Recycling Data Games	WP 6	M18 / M30
6.3	Assessment of the Recycling Data Game	WP 6	M18 / M36
1.3	Final Project Report	WP 1	M36

2 RECLAIM prMRF components

Following the prMRF architecture specified in Deliverable 2.1, we identify 5 key components of the prMRF that need to be explored and developed in a timely manner so that RECLAIM technology partners will be able to verify that their function is as intended and that they adequately fit into the prMRF synthesis plan. The relevant components include:

- The RECLAIM container-box that will host all the developed technologies and will actually operate as the prMRF, the main outcome of the project. The work in this direction regards making the necessary adjustments on the container to ensure proper fit of the mechanical waste processing equipment.
- The computer vision module that will process RGB images of the recyclables transported on a conveyor belt to detect and categorize them into material types and, in addition, to draw up a list of targets to be gripped and physically sorted by the RoReWos that will operate in the container.
- The hyperspectral imaging module that will process the spectrum of the transported recyclables as it is recorded by the HSI camera, to infer the material type at each location of the conveyor belt, based on prior knowledge on the reflection of light by each targeted material.
- The Robotic Recycling Workers (RoReWos) that will operate above the conveyor belt, grouped in two teams, to implement the physical sorting of the transported recyclables to material-specific bins.
- The grippers that will be mounted on RoReWos to accurately pick up the individual recyclable items, being specialized according to the different material properties and the different shapes that consumer packages can take.

3 Pairwise integration of the prMRF components

Different technology partners at RECLAIM have focused on the individual components mentioned in the previous section and have studied alternative technological solutions that can be adopted for implementing them. Each individual component is initially tested with synthetic or real data in an experimental environment before being integrated into the prMRF, which allows contrasting the performance of the component in question, with respect to the foreseen functionality.

The prMRF components that have been implemented and tested in the first phase of the project are shown in Figure 1. To confirm their proper function, the RECLAIM partners have connected them to modules similar to those that precede and follow the processing chain of recyclables within the prMRF, so that their functionality can be tested. In that way, we have examined groups of components that yield meaningful units, with concrete data flows which can be integrated and tested as partial assemblies, and at the same time can be used as potential demonstrations of the project.

Following this approach, the RECLAIM work has considered the early, sub-group integration of the developing components in smaller, partially overlapping subgroups. This is expected to facilitate the integration of partial developments in a unified fully functional system at the forthcoming stages of the project, as the investigation of each key component takes into account both the interfacing and the functional characteristics of the modules with which it directly interacts and the operational requirements of the process chain that the overall prMRF should implement.

In particular, the RECLAIM efforts have been organized in 6 parallel evolving subgroup integration activities that aim to assess the coupled and cooperative performance of key prMRF components, in order to assure that their future fully integrated operation will proceed with the minimum possible unexpected problems. The relevant subgroup integration activities are depicted with dashed rectangles in Figure 1 and are shortly described below:

- The first regards making the necessary adaptations to a shipping container to convert it into a prMRF, making it suitable to accept the installation of waste treatment equipment in a way that (a) ensures the efficient operation of all the cooperating mechanical units and (b) creates a suitable area for the installation of the robotic equipment that will undertake the autonomous and intelligent sorting of waste.
- The second concerns the camera that should be installed above the conveyor belt transporting the recyclables, to enable the monitoring of the continuously moving waste allowing their real-time identification, localization and categorization regardless of the particularities of the environment at the current processing time (e.g. day/night ambient light).

- The third relates to the use of the HSI camera in the field of recyclables sorting as well as its calibration and cooperative operation with the RGB camera, in a way that facilitates the correlation of the different but complementary information provided by the two cameras and creates the basis for the identification and categorization of materials with very high accuracy rates.
- The fourth concerns the development of Robotic Waste Worker (RoReWo) prototypes and in addition their installation on a waste conveyor belt in order to evaluate the simultaneous operation of these two prMRF components and make the necessary changes to ensure that they can operate cooperatively in an efficient manner.
- The fifth relates to the study and implementation of alternative gripping mechanisms that will be evaluated in the picking of recyclable materials in order to identify grippers that either specialize to certain types of packaging or can operate efficiently with a range of different recyclable materials.
- Finally, the sixth subgroup integration activity is related to the synergetic operation of multiple components to achieve an early early version of complete procedure accomplishing recyclable sorting that will be further elaborated and improved in the subsequent phases of the project.

The above summarized integration activities have actually started from the first months of the project, providing valuable insight during the specification of the prMRF and have already accomplished good progress as described in the following sections.

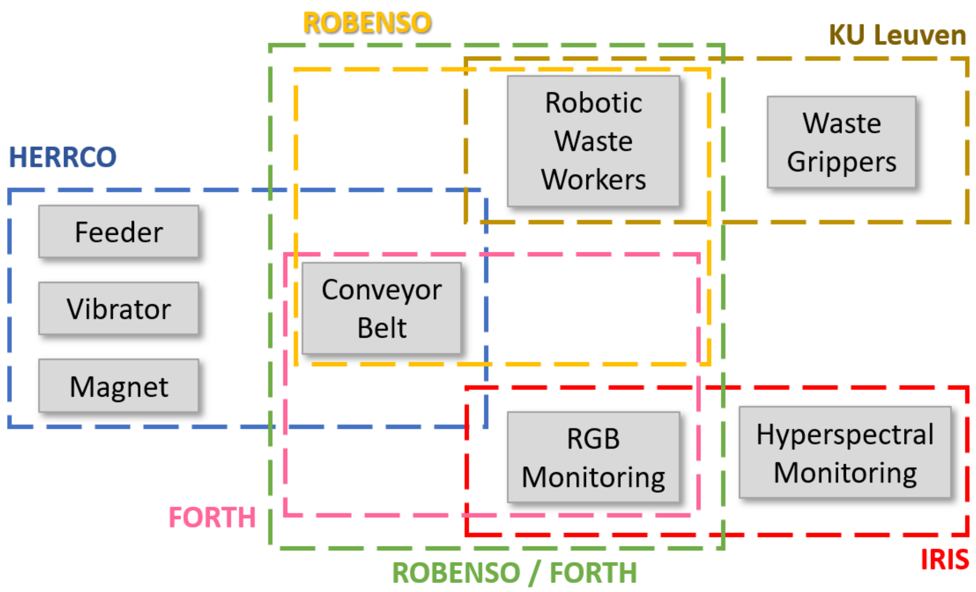

Figure 1. The sub-group integrations accomplished in the first phase of RECLAIM.

3.1 The prMRF mechanical equipment

Following the RECLAIM Grant Agreement, the main objective of what we call the "prMRF" is the implementation of a portable, fully automated mini Material Recycling Facility that can be easily transported to any location in the world to enable material recovery at a local scale.

The prMRF is constructed in a standard metal container which houses the basic sorting equipment (vibrator screen, conveyors, magnet, various assistive devices) as well as the smart autonomous sorting equipment including the RGB & Hyperspectral waste monitoring and the Robotic Recycling Workers. It is designed to host the relevant equipment in optimal utilization to ensure maximum project performance as well as easy service maintenance. The development of the prMRF started by specifying the size of the housing container, which is a standard 45' high-cube metal box. Immediately after clarifying the available space we worked on specifying the mechanical equipment necessary for recyclable waste feed and transporting within the container, as our intention is to build a fully automated, high-quality, portable sorting facility that could be the solution to a range of different recycling sorting scenarios.

A critical issue for the first months of RECLAIM has been the design and modification of the container so that it could host all the necessary mechanical equipment, also providing sufficient free and well-structured space for the subsequent installation of cameras and RoReWos. The main difficulty regards the fact that early decision and container modifications would be practically irreversible. At the same time, the prMRF is a highly unique construction without a standardized layout and all arrangements and cooperation details of the hosted equipment had to be explored and specified from scratch. This was a particularly complex and challenging problem, due to the variety of factors involved (technical limitations of the various components of the equipment, lack of data to model the problem and ultimately address it, several technical details in the operational characteristics of the components) and the fact that most parts of the equipment were not available at the time decisions were made.

Keeping in mind that in the next steps of the prMRF construction, unforeseen factors may arise (mostly related to the installation of the cameras and the robots) that could affect the operation of the prMPF, the container layout was designed with maximum flexibility for future decisions. This was tackled by an early and very active management which succeeded in collecting critical data on the operational requirements of prMRF components. In collaboration with all technical partners, HERRCO determined with relative safety the margins required for maximum permissible cooperation of equipment in the prespecified and rather limited space of the container, leaving space for partial adjustments.

The layout of the container has been specified in Deliverable 2.5 and is briefly repeated here for the sake of completeness of the present document, see also Figure 2. In short, the incoming stream of recyclables is received by a vibrator that distributes objects over the whole width of a forward moving belt that conveys recyclables along the entire length of the container. After the vibrator, the Hyperspecrtral Imaging (HSI) camera is installed, followed by the an RGB camera. The two cameras have complementary roles in object identification, localization, and categorization. Next, the group of 1.5Dof RoReWos is installed to perform material recovery and sorting. This is followed by a magnet that provides robust recovery of ferrous metals.

Then, a second RGB camera will be used to scan again the objects on the belt. This camera serves the two RoReWos that follow. The first is 2.5Dof area-picker and the last is a fully controllable 3.0Dof cartesian robot that will host the sophisticated grippers that will be designed and implemented in RECLAIM. Additionally, a backward moving belt is installed in the container to allow for an endless looping of recyclable materials, thus facilitating the demonstration of the prMRF to interested stakeholders and the wider public.

In this scheme, the weight and shape of the objects to be classified were considered, their position on the conveyor belt, the intention to avoid object overlapping, the operational requirements of the cameras and the processing time they need for material identification, the response time of the individual RoReWo types that perform recyclable sorting, how all the above are affected by the speed of the conveyor belt, and also, how supporting equipment like the air-compressor, blower, magnet, lights, PCs, looping belts would fit in the container. The actual internal view of the prMRF after container re-construction, is shown in Figure 3.

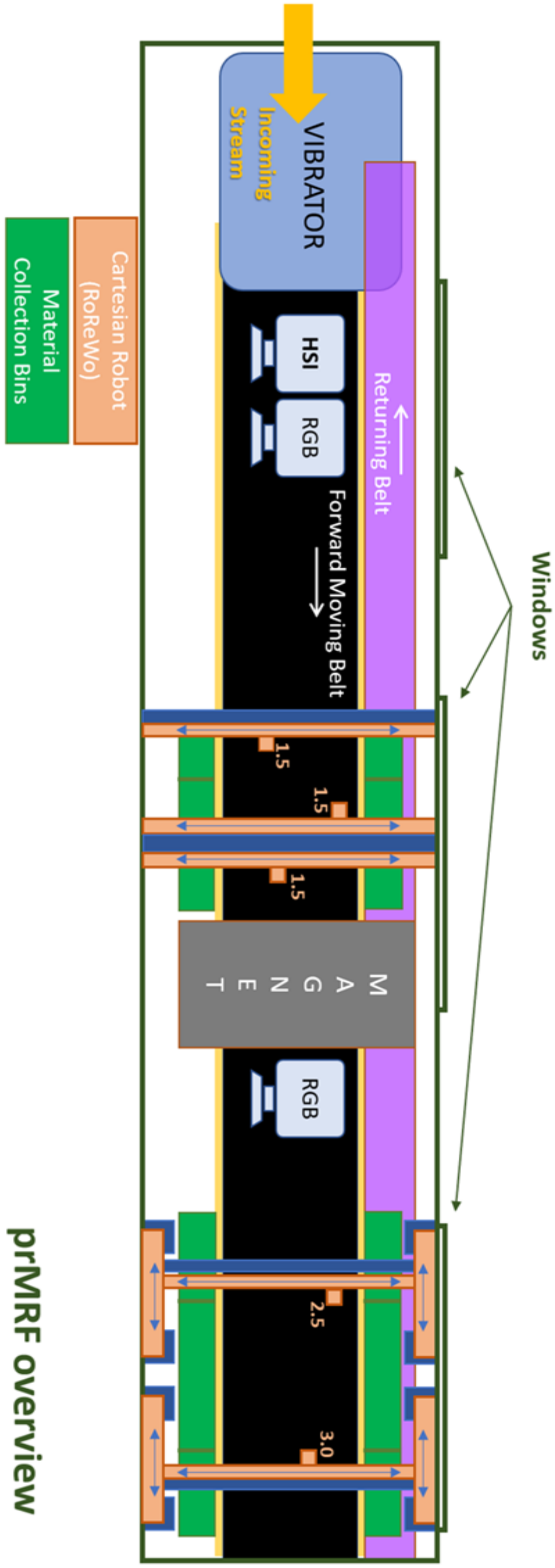

Figure 2. Overview of the equipment installation inside the prMRF, from a top view (see Deliverable 2.1 for details).

Figure 3. General internal views of the prMRF (as delivered from HERRCO to partners). The top image focuses on the vibrator, while the bottom image focuses on the magnet.

Complementary to the above, another issue that had to be addressed was the portability of the container itself and the mandatory use of additional special equipment (crane). This was arranged by including hydraulic cylinders, at each corner of the container, that would serve as adjustable lifting feet thus ensuring the portability of the prMRF, which could now be deployed on its own without the need for a crane to load/unload from the transport vehicle when moving from one place to another. Specifically, after the prMRF is raised by the hydraulic legs, the transport vehicle can drive the platform under it, then the legs are lowered and the prMRF will be on the transport platform.

To enhance the visibility and outreach of the project, it was decided that the prMRF should be capable of live demonstrations allowing the public to see the operation of the installed equipment. This meant that additional components should be installed in the prMRF, but more importantly, they had to be securely mounted on it to be transported safely inside the container that houses them. Therefore, to facilitate prMRF demonstrations, multiple adjustable slides are placed on each of the discharge hoppers (binary operation). Additionally we installed a set of backward moving conveyor belts collecting materials from the slides, which together with the main forward moving belt can transport the materials in an endless close loop, thus enabling the demonstration of prMRF performance for hours. Along with this it was obvious that windows were necessary to allow visitors to see inside prMRF from a safe distance.

Figure 4. General externa external view of the prMRF, showing side windows, the hydraulic legs for lifting and the static legs enabling the elevated operation of the container.

The mechanical equipment installed in the prMRF has gone under actual testing in the loop mode of operation for several hours (3 days with 2, 5 and 8 hours of continuous operation). Using this setup, we have been able to make experiment with varying vibrator and belt speeds, and get an idea of how they affect the distribution of materials on the forward moving conveyor belt. Overall, it was possible to easily achieve a good distribution of the materials on the conveyor belt, which is considered critical for autonomous, high performance recyclable sorting.

Figure 5. Views inside the prMRF container, during mechanical equipment testing.

The prMRF has been fed with sample recyclable material flows with very realistic characteristics that have been calculated according to the actual composition of the materials in the field, after estimating their weight, volume, and quantity and projecting them to the sample flow. The cooperation of the mechanical equipment installed in the prMRF was excellent, as the vibrator was able to evenly distribute the materials on the main forward moving conveyor belt, the magnet selected all the ferrous metals and the backward moving belt collecting all the recyclable materials initially fed into the prMRF transported them back to the vibrator to be redistributed to the main belt, and so on (see Figure 5).

3.2 Monitoring of waste in transit in the visible domain

In parallel with the implementation of the prMRF container and the completion of the internal adaptations which will allow the accommodation of the RGB and HSI cameras and, in addition, the team of Robotic Waste Workers (RoReWos), FORTH has examined the technical details and made several early tests that are relevant to the visual identification and categorization of recyclables in the visible domain (see pink box in Figure 1).

In particular FORTH has focused on the development of a waste monitoring module that will be applicable in challenging industrial environments to perform recyclable identification and categorization. This regards preparing a standalone mechanical base that will be used for hosting the necessary equipment and implementing the software that will actually identify the waste. Current developments have been extensively assessed in ROBENSO's laboratory, as well as the industrial Material Recovery facility operated by HERRCO in Heraklion, Crete, Greece, where we have been able to prove good fit with the environment and successful waste monitoring performance.

Similar to a typical industrial setup, we use a conveyor belt to transport recyclables in a continuous flow at an almost constant rate of transport. The speed of the belt specifies the context in which computer vision has to be applied to achieve waste identification and categorization. We use a Baumer VCXG.2-25C 2.3Mp camera to perceive waste flow at a rate up to 59 colored frames per second. The Baumer VCXG.2-25C is a global shutter camera that is appropriate for monitoring moving objects providing clear images without artifacts and motion blur.

The camera is mounted on a fixed yet adjustable base, approximately 80 cm above the conveyor belt, looking downward. The camera mount is properly adjusted so that the camera can observe the entire width of the belt and at the same time be close to recyclable objects to improve the quality of the images taken. The adjustable mount can be used to transfer and use the camera base to other conveyor belts different than the ones considered so far. This is expected to significantly facilitate the installation of the Baumer VCXG.2-25C camera above the forward moving belt installed in the prMRF container.

To ensure stable lighting conditions during system operation, the camera is placed inside a box that eliminates the effect of external lighting which changes during the day and may introduce unwanted artifacts in waste images. We have considered the use of such a mini dark-room critical for capturing recyclable images within the prMRF, because, for demonstration purposes, the container is equipped with four large windows (two on each side) and it is expected that the light in the prMRF will be largely affected by the sun light outside the container, which does not have constant direction and intensity.

To further minimize lighting variations and improve stability, we install a light panel at the top of the darkroom, which provides constant illumination to passing recyclables. Two different lighting modules have been examined. The first leverages the experience gained by HERRCO and ROBENSO from the installation of a robotic sorter at the material recovery facility in Heraklion, Crete, Greece. It consists of four LED light bars arranged in a way that they cover the whole width of the conveyor belt (Figure 6 (a)). To reduce uneven shiny effects, a satin diffuser is used to enable the close lighting of the belt without hot spots. Besides the proven effectiveness of this solution in a demanding industrial setup, it has been a rather expensive solution. Therefore, in the context of RECLAIM, we have been interested in exploring alternative solutions with significantly lower cost. To this end, ROBENSO in collaboration with FORTH has developed a custom lighting grid consisting of multiple low-cost lighting surfaces that together provide high brightness while enhancing lighting homogeneity (Figure 6 (b)). This solution was tested in the ROBENSO laboratory, providing very good results in terms of lighting the conveyor belt, and it was decided to use this lighting solution in RECLAIM.

(a)

(b)

Figure 6. Overview of the two lighting solutions examined in RECLAIM (a) using light bars, and (b) using low-cost lighting surfaces.

The above described installation has been used for data collection and the early development of a computer vision-based recyclable classifier. As already summarized in Deliverable 6.1, several datasets have been collected for both single type recyclable materials and mixed material streams. The collection of data has been significantly supported by HERRCO that provided bags of already sorted recyclables, which are then manually placed on ROBENSO's belt for the collection of type-specific data. Additionally, HEARRCO has provided images from the Heraklion material recovery facility depicting very realistic still challenging conditions where material identification and categorization algorithms have to be applied.

FORTH has manually processed the collected data to develop annotations that describe the content of the individual images. This is a hard and arduous task, which apart from requiring several hours of mind-numbing work, it also assumes good knowledge of the material types of product packaging. The annotated data are further employed to train recyclable classifiers that operate on new unseen data obtained by monitoring recyclables transferred by a conveyor belt.

To address the issue of separately identifying two same-type objects that are partially overlapping in the obtained images, we consider machine learning models that are able to solve the so-called instance segmentation problem. The Mask R-CNN model is a very popular solution that effectively accomplishes instance segmentation [1].

The collected data are used to develop Mask R-CNN models, so far trained to specialize on single material identification. This is an early attempt to develop computer vision modules with satisfactory performance on images depicting recyclable materials transported by conveyor belt, which will further allow testing the integrated performance of all modules necessary for prMRF synthesis. Indicative results are shown in Figure 7, where the performance of two separate models targeting PET and Aluminum identification in a real waste stream, is illustrated.

It is important to note that despite the fact that the computer employed for inferencing uses an NVIDIA GeForce RTX 2080 8GB graphics card, the processing rate achieved reaches an average of 5 fps, which is considered satisfactory for the given application, since the waste conveyor belt moves foward at approximately 30cm per second.

Future training attempts will focus on multiple material identification by a single computer vision module. It is noted that since the recyclable processing chain in the prMRF employes two RoReWo-Ts driven by two separate computer vision modules, extensive experimentation is necessary to assign roles to the individual RoReWos and thus specify the material types that need to be identified by each computer vision module (e.g. the first focuses on PET, HDPE, LDPE, and the second on Aluminum, Tetrapack, PP/PS). Clearly this has to be specified in the field, after considering the typical material composition of the mixed recyclable content of the blue bins in Kefallonia.

Figure 7. Identification of PET bottles (top) and aluminum cans (bottom)

To further improve the performance of the computer vision modules we have considered the generation of synthetic data, targeting the creation of large training datasets from a limited initial set of images [2]. In particular FORTH used grid-based elastic deformation to randomly deform segmented recyclable images, which allows to generate multiple new recyclable images that are partially differentiated from the original image (see Figure 8). The new instances are placed on top of real backgrounds to create synthetic images (see Figure 9). This process allows the generation of large artificial datasets used for training neural networks. We evaluate the usability of these datasets by studying the extent to which they can improve the performance of trained models when applied in unseen industrial images. The results obtained show that including small-scale object deformations in the artificial datasets can slightly improve the Accuracy and significantly improve the model Recall, while Precision of the model remains unchanged. In practice that means, more of the passing bottles were successfully identified, with approximately the same success at identifying the bottle boundaries.

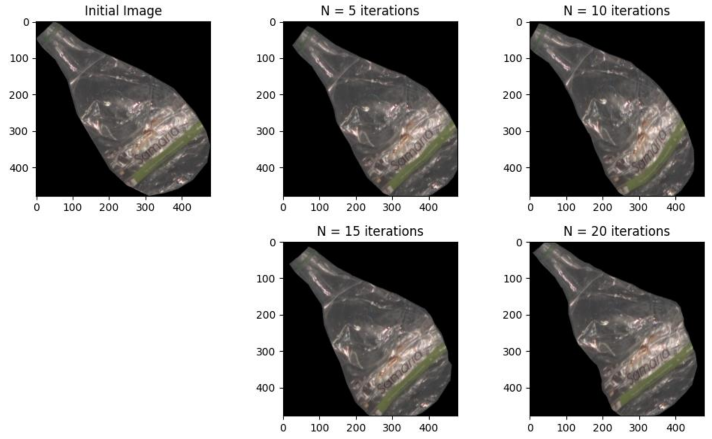

Figure 8. An initial object-image (left) undergoing multiple random distortions (right).

Figure 9. The original image (top) enriched with randomly deformed PET bottles (bottom).

3.3 Monitoring of waste in transit in the infrared domain

Hyperspectral Imaging System (HSI) comprises integrated hardware and software architecture that enables the acquisition and handling of spectral data as an image sequence. This sequence results from pre-defined alignment on a sample surface that is properly energized by a light source. In material recognition, the acquisition of hyperspectral images is performed by NIR spectroscopy which is widely used due to its ability to identify the chemical composition and spectral characteristics of a sample quickly and accurately without the need for sample preparation. Hence, spectroscopy techniques are widely implemented in terms of waste processing and material recovery for determining the consistency of objects. Real-time identification and quantification of composition with high classification accuracy for complex plastics is achievable through hyperspectral images in combination with chemometric models.

Complementary to hyperspectral cameras, in real world applications such as recyclable material sorting in the wild, the visual appearance of objects should be considered to separate/sort objects with the same consistency. In order to implement Deep Learning (DL) approach to successfully classify objects into predetermined material categories, mixed approach that combines waste imaging in both the visual and infrared domain, to achieve high accuracy material identification, localization and categorization in real, particularly challenging conditions is trialed.

In order to show the feasibility of the parallel imaging with both a RGB array and a hyperspectral imaging, some trials have been performed.

They took place on the same conveyor belt using both the HSI camera and the RGB camera which will be used in the final experimentation. As the tests were performed at IRIS, the only width available for the conveyor belt was 600mm. However, the resolution corresponding to a width of 1200mm was kept for both cameras. Hence, 30cm of lines on each side of the images are not used.

The 2 cameras used were:

- HSI: reference FX17 from Specim, spectral range of 900nm to 1700nm, distributed along 224 spectral bands. 640 pixels along the linear aperture. This camera is equipped with a lens with a focal length of 8mm. The size of the pixel on the conveyor belt is then 1.875mm, for a total width of 1200mm.
- RGB: reference VCXG.2-25C from BAUMER. The camera has a resolution of *1200 x 1920 pixels, with a pixel pitch of 4.8µm. The 1920 pixels are projected along the width of 1.2m, while the 1200 pixels are projected on a length of 750mm along the translation axis of the conveyor. This camera is equipped with a lens which has a 6mm focal length. Distance of the lens to the conveyor is then 781mm to obtain a projected pixel of 625µm on the conveyor. Acquisitions are performed by using the software provided by BAUMER.

Since the conveyor belt located at IRIS has a shorter size than the conveyor which will be installed in the Mobile unit, the part of the line seen by the HSI camera is limited to 600mm, while the RGB camera is looking at an area of 600mm * 500mm. We still keep the original field of view, but the images of the camera which are not on the conveyor are cropped.

To account for the moving part of the conveyor, the integration time of the RGB camera is limited to 25µs. During this integration time, the objects translates by a distance which corresponds to 1 pixel: as the conveyor is set at 0.25m/s, and each pixel represents . A distributed LED illumination set-up is illuminating the conveyor and the irradiance is measured and is in the range of 2400 lux.

Pictures of the set-up are shown below:

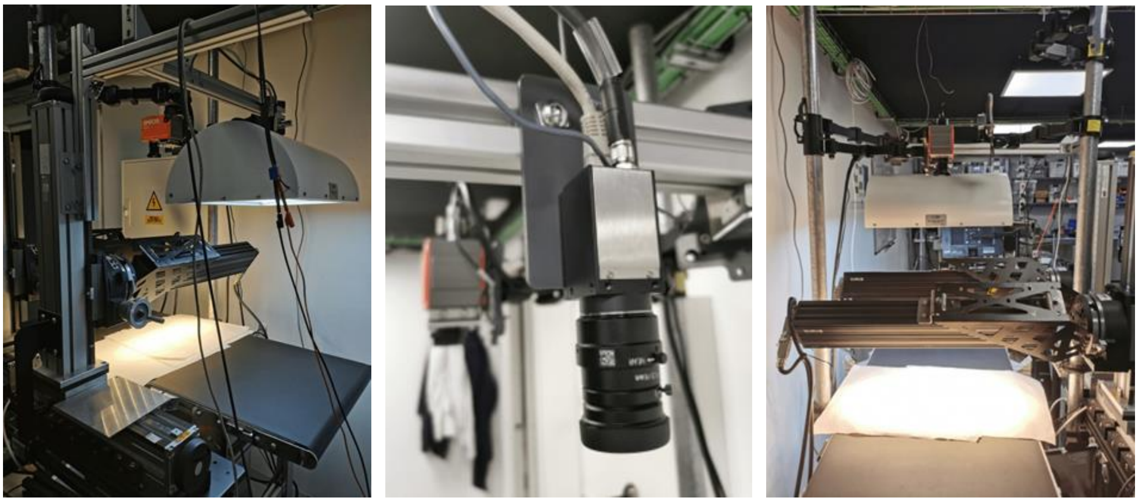

Figure 10. Pictures of the set-up to record together RGB images and HSI images.

We fed the conveyor belt with several types of wastes, and the results are shown below:

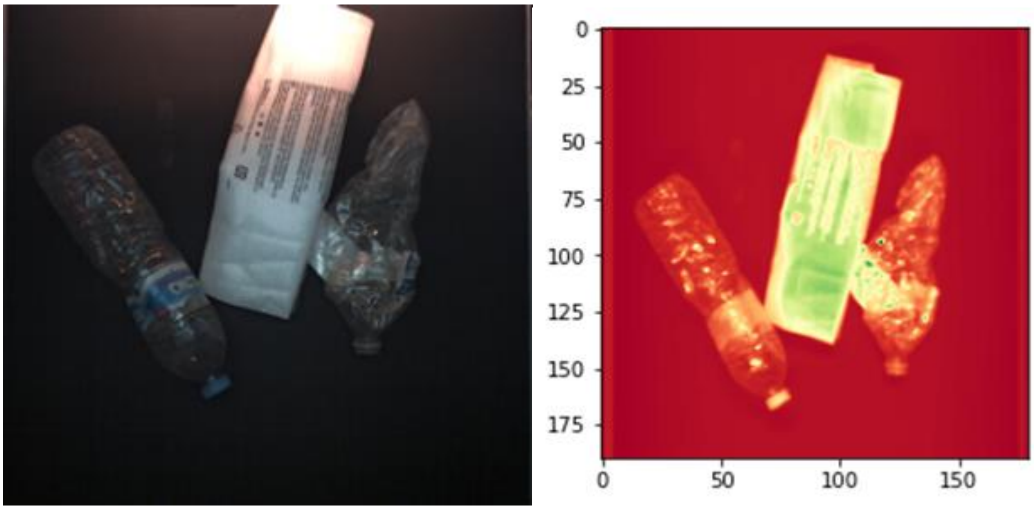

Figure 11. Pictures on the same belt from the RGB camera (left) and the HSI camera (right).

3.3.1 Camera Calibration

HSI is a line scan camera meanwhile the RGB camera produces a rectangular image per shot. In order to fuse the data obtained from both types of cameras, a calibration is needed taking into account the conveyor speed, camera field of view and image processing time. In the following schema diagram, it is depicted how the cameras will need to be placed in order to guarantee image correlation.

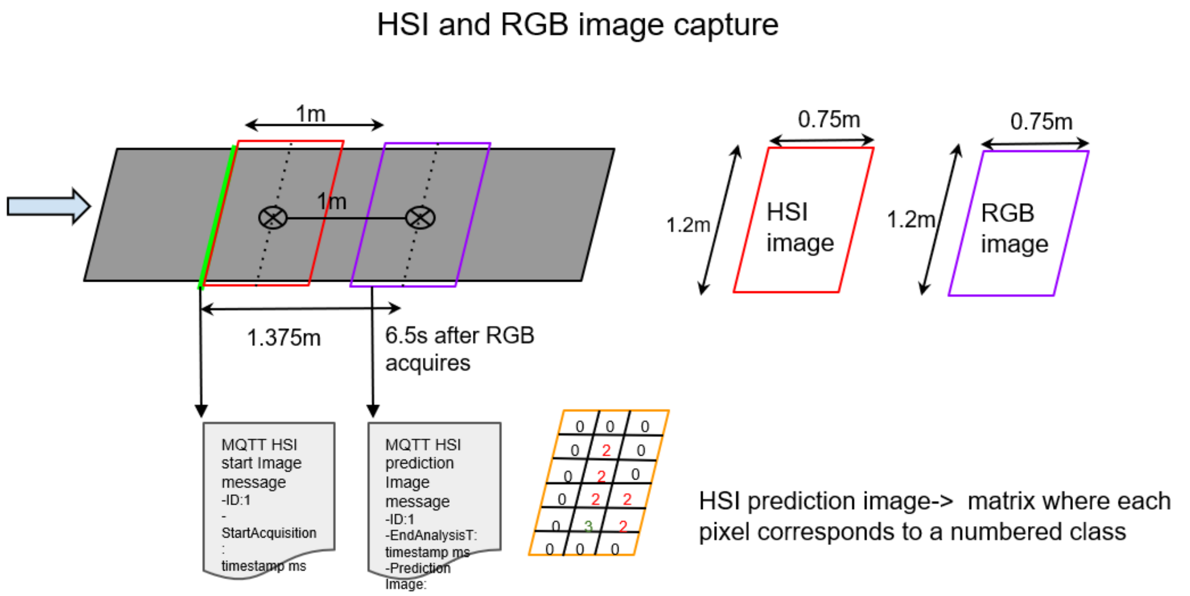

Figure 12. Fusion of HSI and RGB acquisition.

The green line shows the real field of view of the HSI camera. The HSI software accumulates a set of lines that matches the 0.75m of the RGB camera. Therefore for simplification we can call it an HSI image, as is shown in the red parallelogram of the diagram. Distances shown guarantee that there is no light disturbance and also that there is some analysis buffer time. Once HSI starts measuring every image, it sends a MQTT message to the RGB system, in the message the timestamp is sent and should be used to calculate the delay of the next RGB image acquisition.

With this system image acquisition from both systems will coincide, then the next step is to fuse the analysis outputs. From one side HSI will produce an analysis result instants before the RGB camera acquires. Due to the high amount of processing power required for HSI images, there is no available machine learning and computer vision techniques good enough to create models that take into account objects shapes. The HSI system produces pixel by pixel chemometric classification.

The HSI system will send a MQTT message with the image result discretized into a class result matrix. This means that every value of the matrix will contain the class identifier in an integer form. To facilitate the data fusion the matrix will keep the original shape of the image. This matrix will be used after the RGB system produces its result. Taking the advantage of the RGB models that can learn shapes associated with colors, the final processing step will take into account both system results. A rule induction model will take care of the color, shape and the chemometric classification to give the final classification to the object detected. A fusion software module will iterate pixel by pixel the HSI and the RGB segmentation results and with the rule induction model the final prediction of the RGB model will be adapted.

3.4 Robotic Recycling Workers (RoReWos) early implementation

RECLAIM aims to develop low-cost Robotic Recycling Workers (RoReWos) that will work as a team to retrieve and sort recyclables. As described in D2.1, the operation of the prMRF will be based on two RoReWo teams with different functional characteristics. The first group will consist of 3 RoReWos of 1.5 DoFs and the second group of 2 RoReWos one of them having 2.5 and the other 3.0 DoFs. In RECLAIM, what we call "0.5. DoF'' refers to a piston that can move rapidly back and forth using compressed air, but without real-time control of its motion. The piston is used to quickly approach, grasp and pick up the recyclable from the conveyor belt.

Of the above RoReWo architectures, the one that has the highest risk of failure is the 1.5DoF RoReWo. This is because, to achieve low cost, it is designed with the least flexible functional characteristics. Therefore it is necessary to assess early in the project the risk of using the 1.5DoF RoReWo for material recovery. Along this line, a significant part of ROBENSO's effort was directed to the development and evaluation of 1.5DoF RoReWos in the first months of RECLAIM, so that, if necessary, corrective actions could be taken in time and the progress of the project is not jeopardized.

In the following paragraphs we describe the development of the 1.5DoF ReReWo, while Section 4 also reports on the first completed operational tests of a 1.5DoF RoReWo Team.

3.4.1 The 1.5DoF RoReWo Architecture

RECLAIM considers the implementation of a new type of artificial autonomous waste sorters that exploit the low-cost architecture of cartesian robots. The, so called in RECLAIM, Robotic Recycling Workers, in short "RoReWos", are custom made robots that have been assembled from scratch by combining both hardware components (linear rail, motors, PLC, valves, pneumatic tubes, blower, button strip, encoder, PC) and software components (PLC program, target management, behavior programming) to control mechanical operations that perform tasks like object tracking, grasping and transporting.

The 1.5DoF RoReWos in particular, are prototypes that are implemented globally for the first time at a global level, in the RECLAIM project. To the best of our knowledge, to date there is no other similar system anywhere in the world. The only comparable robot used for waste sorting is the ZenRobotics FastPicker [3], which is a fully controllable 3DoF cartesian robot. Compared to the FastPicker, the 1.5DoF RoReWo aims to have 75% lower costs but only 25% lower productivity. In other words, it assumes a simplified architecture to achieve a significant reduction in hardware cost with only small reductions in robot efficiency and productivity.

The 1.5DoF RoReWo consists of a single-axis Cartesian robot with closed-loop motion control that can be easily installed above any size conveyor belt carrying recyclables. The direction of movement of the RoReWo is perpendicular to the movement of the belt (X-axis). This allows the robot carriage to move along the full width of the belt to pick recyclables. A low-cost piston is mounted on the moving robot carriage, which moves vertically relative to the conveyor belt (i.e. up/down, Z-axis) using compressed air. The piston moves toward the belt to reach and grab a recyclable item and then moves away from the belt to pick up and transport the item to the material collection bins installed on the left and right sides of the RoReWo. Attached to the piston is a suction cup that performs vacuum gripping. The suction cup holds the items to be sorted during their transfer to the collection bin and, finally, a compressed air blowing mechanism is used to rapidly release the object detaching it from the suction cup.

The synchronization of the robot's moving carriage, piston and gripper is achieved by using Newtonian mechanisms that use the speed of the belt to predict the position of the objects on the belt, position the robot carriage over the object to be sorted at the right moment, trigger the movement of the piston towards the object and timely activate the gripper to pick up the object when the piston moves upwards.

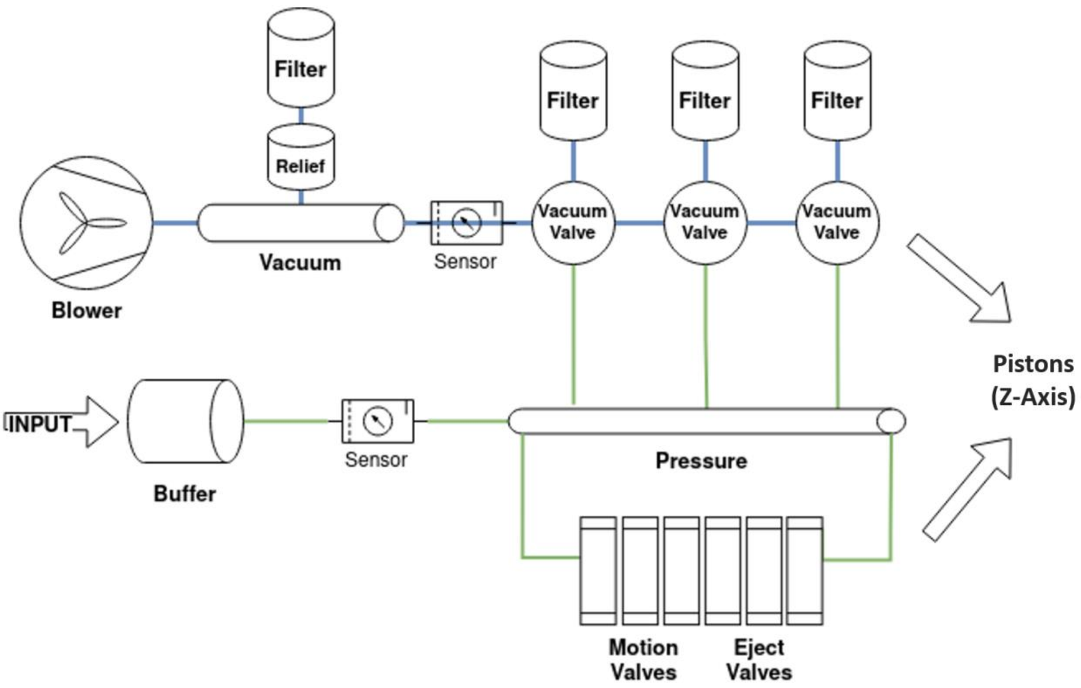

Figure 13. An overview of a three RoReWo Team architecture, which highlights the vacuum and compressed air wiring connection.

Given the limited space required by the 1.5 DoF RoReWos, many such robots can be installed above a conveyor belt to work as a team that achieves high productivity in terms of material recovery. The architecture of a RoReWo Team consisting of 3 x 1.5DoF RoReWos operating above a conveyor belt is provided in Figure 13.

3.4.2 Technical Details of 1.5 DoF RoReWo Implementation

The linear 1.5DoF RoReWo incorporates components that enable precise material recovery by moving only on two dimensions, the X-axis that is perpendicular to the movement of the belt, and the Z-axis that is perpendicular to the ground. The key components of the 1.5Dof RoReWo are shortly described below.

The movement on the X-axis is achieved with the use of linear rail that guides the movement of the robot carriage. A motorized industrial linear toothed belt (ELGA-TB-KF-80-1500) is used to move the carriage with a working stroke of 1500mm. This is achieved by using a servo motor (EMMT-AS-100) with a maximum rotational speed of 4790 rpm and a nominal torque of 6.3 Nm, mounted on the linear drive to move the linear toothed belt axis.

The movement on the Z-axis is implemented by a Pneumatic piston (Univer M1500250300) with a working stroke of 300mm. The piston makes a vertical movement to and from the conveyor belt. The piston operates with a working pressure of up to 10 bar. To provide stability on the movement of the piston over the Z-axis, a double cylinder guide is connected to the pneumatic piston and mounted on the carriage of the linear robot. Springs are installed on the cylinder guide to act as smooth passive brakes, aiding in the controlled stopping of the movement. Two compressed air tubes are used to control the movement of the pneumatic piston in the Z-axis.

A Custom 3D printed suction cup mount is attached to the end of the Z-axis piston. It holds a suction cup that is connected to a vacuum tube that provides vacuum force to securely grip the target objects. To quickly release the objects when they have been transferred over the bin, an additional compressed air tube is used to detach the object from the suction cup, ejecting the objects towards the bin.

Terminal switches are present on the X-axis for homing and safe operation. They provide reference points for the positioning and safe operation of the X-axis. A terminal switch is also present on the Z-axis. It is used to close the loop and retract the pneumatic piston after reaching the target position.

A multicore electrical cable is used to provide power supply and control signals for all the components and the terminal switches of the RoReWo. A cable carrier is utilized for cable management. It guides and organizes the electrical cables and pneumatic tubes during movement in a controlled manner, ensuring their proper positioning and protection.

3.4.3 Vacuum Gripper

To ensure secure picking of targets from the conveyor belt, each 1.5Dof RoReWo utilizes a vacuum system linked to a suction cup that is attached to the end of the piston (see also section 3.5.1.1). For generating vacuum, a double-stage industrial blower is employed. This blower has a capacity of producing 80 m^3 of air flow per minute and generates a vacuum force of -210 mbar. The blower is equipped with a relief valve, which serves to maintain a constant air flow and cool down the motor by releasing excess pressure. To control the vacuum flow, a 40mm pneumatic valve is incorporated into the system. The 40mm pneumatic valve enables the controlled rapid activation of the vacuum flow as needed during material picking. Filters are placed to all air inlets so that the valves and the blower are protected from small particles and dust. In order to produce a mature version of the 1.5DoF RoReWo several prototypes have been implemented and repeatedly tested. Two different versions of the 1.5 DoF RoReWo are shown in Figure 14.

Figure 14. Two different versions of the 1.5 DoF RoReWo.

Moreover, to minimize potential delays during material disposal, compressed air is applied right on the suction cup, toward the disposed item, to detach it from the suction cup. This is achieved by using a custom made T-shaped tube that enables fast switching between the blower vacuum (negative pressure) and the compressed air (positive pressure). The joint activation/deactivation of binary valves controlling the two air streams (vacuum versus compressed air) are significantly reducing the time needed for item disposal, which is typically about 20 ms.

3.4.4 Electrical Cabinet

Besides the fact that the 1.5DoF RoReWo is a custom-built robot developed for the first time within the RECLAIM project, every RoReWo operating in the prMRF works in harsh industrial conditions and therefore has to follow an industrial architecture that guarantees its safe and uninterrupted operation. To this end, the heart of each RoReWo-T is a carefully designed electrical cabinet that adopts critical industrial standards. The electrical cabinet enables efficient and reliable operation of the whole robotic equipment. The key elements of the electrical cabinet are summarized below.

1. An industrial enclosure houses various electrical components and wiring related to the system. It provides a centralized location for connecting and organizing the electrical components.
2. A Festo CPX-E-CEC PLC (Programmable Logic Controller) is used in the system. It serves as the main control unit, executing the control program and coordinating the operation of other components.
3. CMMT-AS motor drives are used to control the speed and movement of the motors (EMMT-AS-100) in the system. These drives provide the necessary power and control signals to the motors .
4. Digital I/O cards (MODEL) are used to interface the PLC with various digital devices in the system. They provide digital input and output channels for connecting sensors, switches, and other digital devices.
5. Solid state relay switches used to control the valves in the system. They act as intermediaries between the PLC and the valves, allowing the PLC to control the valve operation.
6. Safety fuses are used to prevent excessive current flow and protect the system from electrical faults or overloads. They help ensure the safety and integrity of the electrical circuit.
7. Ethernet-based Ethecat communication protocol is used for real-time communication between different devices in the system. It enables fast and synchronized data exchange.

8. An Ethernet hub provides connectivity and networking capabilities, allowing each individual unit or component in the system to be connected and configured. It facilitates integration and communication between different system components.
9. Additional power supplies are used to provide dedicated power to specific devices or components in the system, such as cameras and lights. They ensure reliable and stable power sources for these devices.

Figure 15. The electrical cabinet that enables the operation and control of RoReWos and their integration with the rest of the prMRF components.

3.5 Waste grippers in autonomous material sorting

The current section summarizes the gripper technologies that have been considered at RECLAIM as alternative solutions that may enhance the robustness and success rate of recyclable picking. This has been identified as a critical parameter to increase prMRF productivity.

3.5.1 Grippers

To get insight into the gripper technology applicable for the RECLAIM project diverse gripper systems and accessories were tested and developed. Different standard components were mounted and tested to detect challenges and key factors that have a role in selecting the right gripper. Additionally, some other concepts were developed and tested.

3.5.1.1 Suction Cups

The only of the shelve grippers evaluated are a variety of different suction cups, Figure 16. A selection of suction cups from Pia were mounted and tested on different waste materials both manually and with the robotic test setup available in the laboratories of KU Leuven. The early tests showed that the sealing capacity and, hence, the grasping success of suction cups is heavily dependent on the stiffness and shape of the suction cup and the waste object, particularly when an ejector is used for the generation of vacuum.

Figure 16. Suction cup examples with foam and soft lips: piGRIP suction cups [2].

When the surface of the waste object is irregular, rough or perforated, it is difficult to achieve a good seal between the suction cup and the object. If a no good seal cannot be achieved with the specific suction cup, no good grasp can be guaranteed. The lifting force of a suction cup has a positive linear correlation with the area of the suction cup and the vacuum that can be created. However, since the shape and surface of the waste objects are heavily irregular, it is more challenging for larger suction cup sizes to create a good seal. Suction cups are mostly constructed from flexible polymers. This makes them less durable than other grippers which are constructed with metal or hard polymer contact surfaces. However, suction cups have an exceptionally low initial cost, are flexible and are easy to operate. Therefore, suction cups are still a valid option.

To operate a suction cup, a vacuum must be generated. Traditionally, this vacuum is generated with either a blower or an ejector. The blower mechanically removes air from the vacuum line and suction cup to generate a vacuum. In most cases, blowers have a big inertia which causes a delay when a vacuum is requested, therefore blowers are commonly left on at all times and a valve is added to stop the vacuum creation. Because of this reason a blower is considered an energy inefficient solution. Alternatively, an ejector can be used which makes use of the venturi effect to generate the vacuum. The pressured air is activated when a vacuum is required, which means there is only energy consumption when the suction cup is being used. Although there is a short-term consumption of compressed air, the amount consumed is momentarily very large. Therefore, it is not clear which of the two vacuum generation solutions is the more energy efficient.

3.5.1.2 Parallel gripper

Consecutively, a two-jaw gripper is a popular gripper to manipulate waste objects. This type of gripper is part of the impactive gripper family and uses a form closure or friction force to clamp an object. Impactive grippers mostly have two actuator types: electricity or pressurized air. Standard impactive grippers are found with two types of jaw movement, an angular or linear movement. In industrial environments the pneumatically actuated gripper is most popular, because of faster and more robust actuation, the simple control and low initial cost. Linear grippers have a linear movement and if actuated pneumatically the gripper is either completely open or completely closed, therefore the gripper requires much free space around the target object in order not to collide with other objects on the conveyor when objects are cluttered. With angular grippers the gripper jaws make a circular movement. This is beneficial when picking objects from a conveyor belt since it requires less free space around the object. However, the angular motion of the jaws has the disadvantage that when grasping larger objects, the jaws are not parallel when an object is clamped, which causes larger objects to be pushed out of the gripper which is not desired.

To prevent this, a pneumatic actuated mechanism is designed which moves the gripper fingers with a circular trajectory while keeping the gripper fingers parallel to each other, preventing the phenomenon where the objects get pushed away. With this principle, the benefit of requiring less free space around the object, due to the circular motion, is maintained. To facilitate experiments with different gripper jaws, the gripper jaws are interchangeable allowing for quick testing and adaptation of the jaw surface to improve both friction and form closure.

Figure 17. Pneumatically actuated parallel gripper.

3.5.1.3 High Airflow Vertical COnveying (HAVCO) gripper

A prototype of a high airflow vertical conveying (HAVCO) gripper is developed. This gripper uses compressed air to generate an airflow to lift objects and move them towards a collection bin with the generated airflow. Since the gripper does not have to move to the container to drop the object in the container the time needed to perform a picking action can be significantly reduced. Additionally, the gripper only requires the object to be positioned under its opening. Therefore, precise gripper positioning and pose planning is obsolete which simplifies the integration of this gripper.

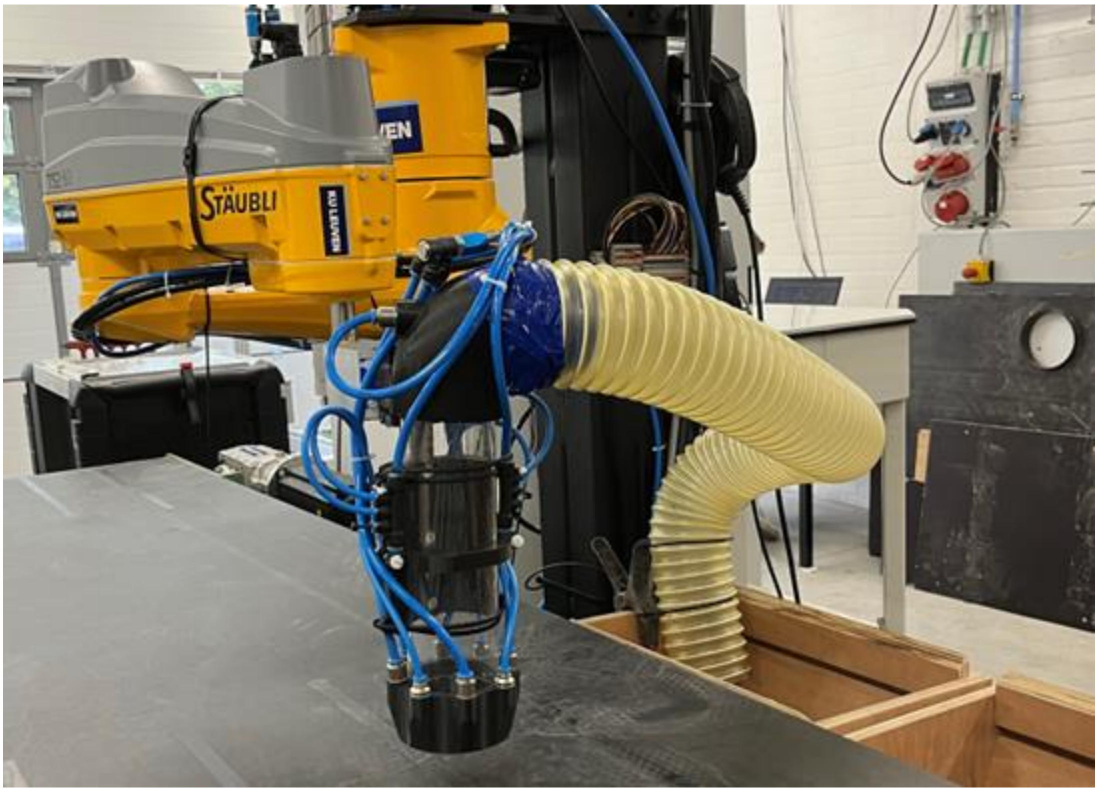

Figure 18. The first HAVCO prototype, implemented in RECLAIM.

After initial tests a new, lighter and more robust design of this gripper is developed. This gripper is designed to be manufactured with selective laser sintering (SLS) technology. To make the gripper lighter and more compact the air tubes that supply the nozzles with air are designed to be in the conveying tube of the gripper and to have equal length. However, the powder used in the SLS printer to manufacture the gripper blocked two of the air tubes. Therefore, the design will be further optimized. Also, different diameter sizes will be developed to allow for testing on different object sizes.

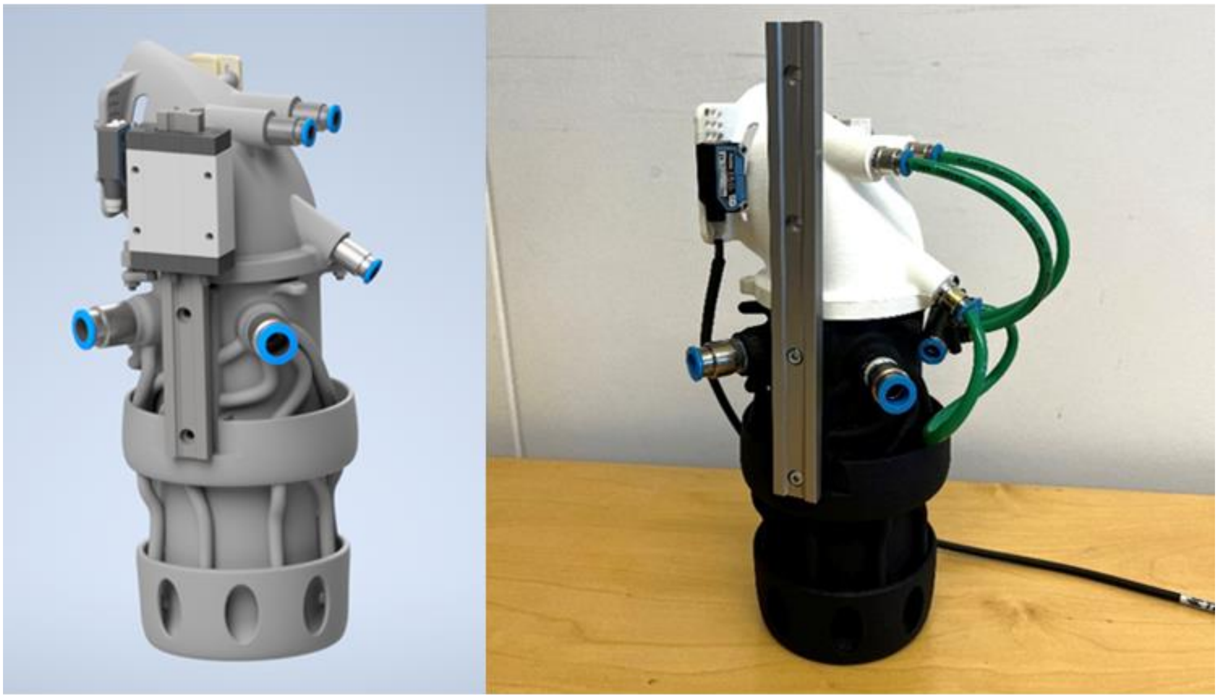

Figure 19. The second HAVCO prototype and selective laser sintered HAVCO prototype.

In the last design, the length of the gripper is reduced to remove the distance over which the objects need to be lifted. Additionally, to prevent the nozzles or air tubes from clogging during manufacturing, flexible air tubes were reintroduced to the design. However, instead of thread in couplers, inserts were used to keep the weight as low as possible.

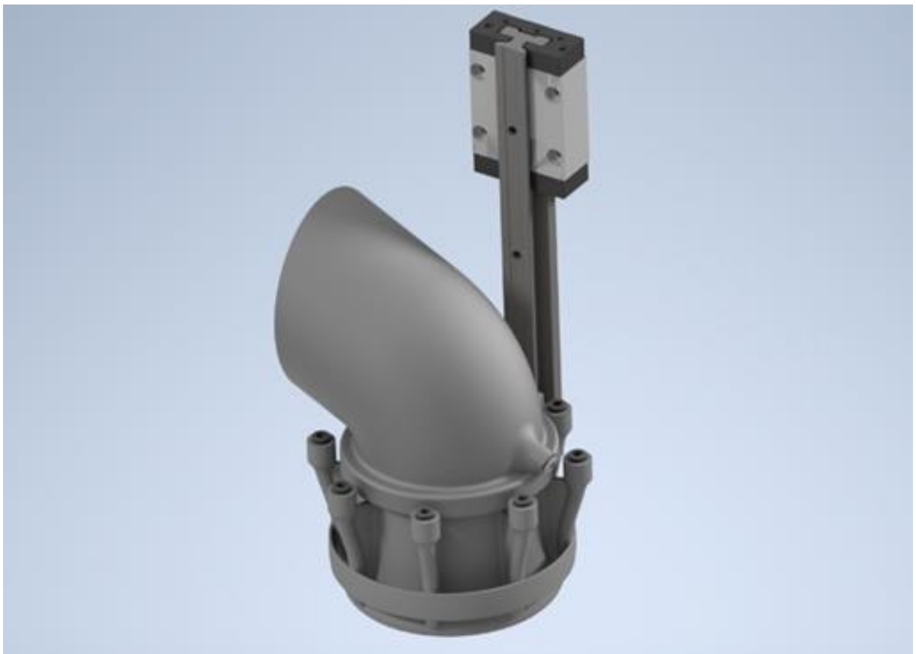

Figure 20. The latest HAVCO gripper design mounted to a linear compensator.

3.5.1.4 Hybrid gripper development

Since only a limited number of robots and therefore only a limited number of grippers can be installed in a robotic sorting installation, an effort was made to combine different gripper technologies in one gripper that can be installed on one robot. This allows for the switching between gripper principles without extra time needed for tool changing to change between gripper types. Two common gripping techniques, parallel grasping, and suction cup picking are integrated in a single gripper, Figure 21. The combination of grippers makes the construction very actuator dense. To keep the gripper light and small, tendons are used to actuate the gripper. This enables the actuators to be positioned remotely which lowers the gripper weight while allowing the actuators to be integrated with more space.

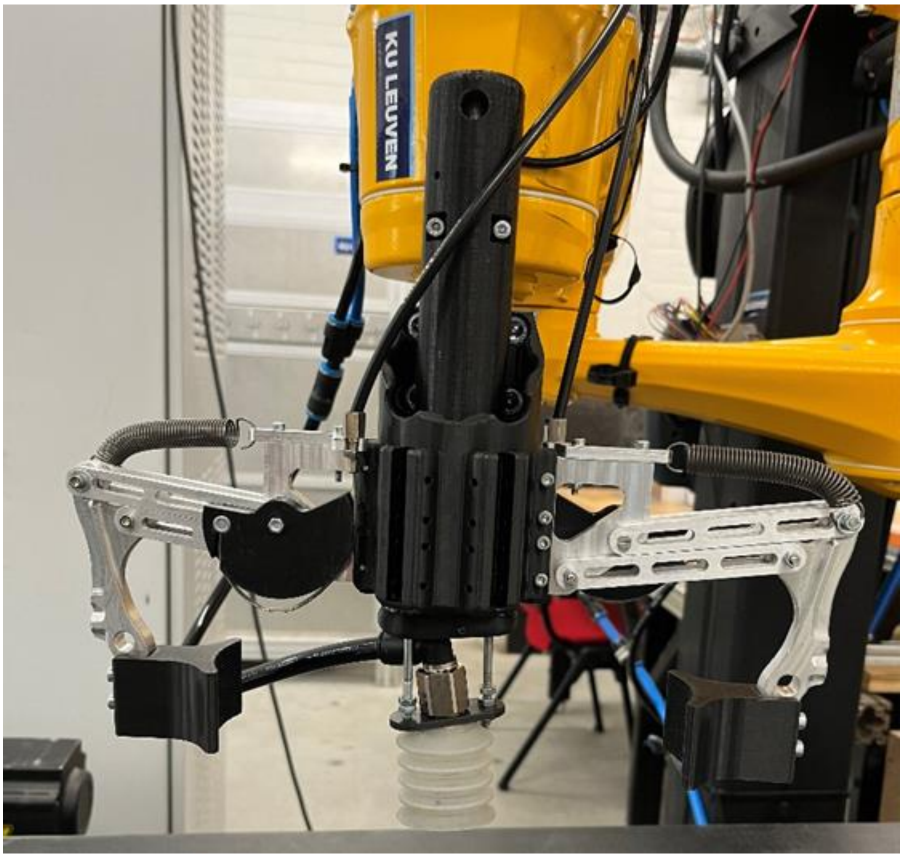

Figure 21. Prototype of hybrid gripper combining a parallel (impactive) and suction cup (astrictive) gripper system.

3.5.2 Tested accessories

Next to the attachment of the gripper to the robot the gripper mount can also yield other purposes. Possible additional purposes include safety, performance monitoring, tool changing, performance boosting.

3.5.2.1 Safety accessories

Two methods to safeguard the grippers were tested: the use of polymer bolts as a weak point and a linear compensator.

a. Plastic bolts

Polymer mounting bolts are installed to protect the gripper in case of a collision. By installing the polymer bolts as a sacrificial link in the mounting system of a gripper, the robot and the gripper are protected from excessive forces, preventing damage to the robot and gripper. To prevent the gripper from falling, which could damage or cause a loss of the gripping device, a connection is made between the robot and gripper with a safety line. In this way the plastic bolts protect the robot and gripper from excessive forces on the gripper in all directions.

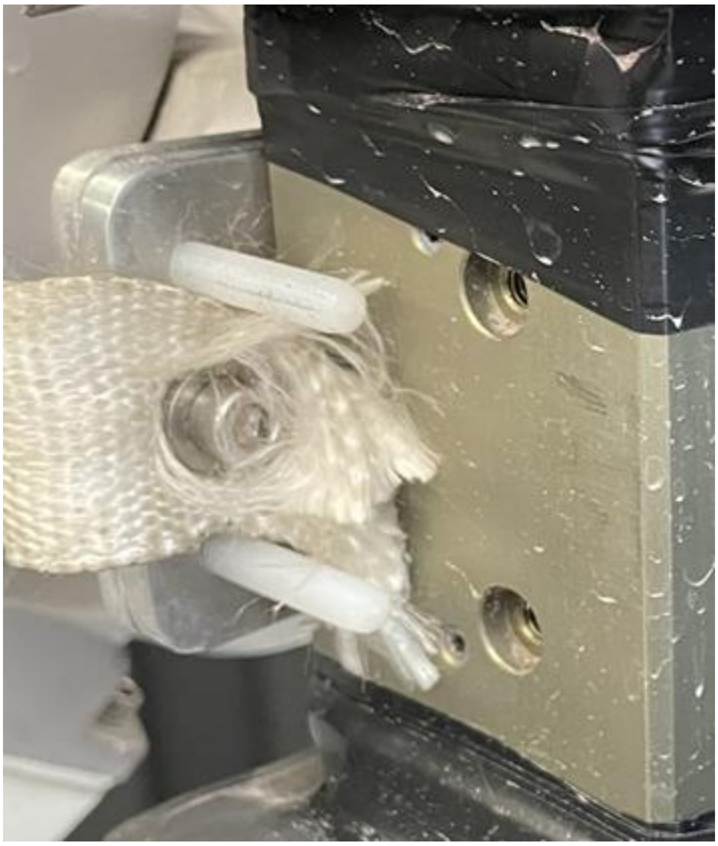

Figure 22. Gripper mounted with plastic bolts.

b. Linear compensator

The linear compensator can be installed between the gripper and the robot, so it allows for vertical movement in case of a collision during a (grasping) vertical movement. The linear compensator is spring loaded to make it return to a rest position after the collision. The linear compensator, Figure 23, only allows for compensation in the vertical direction.

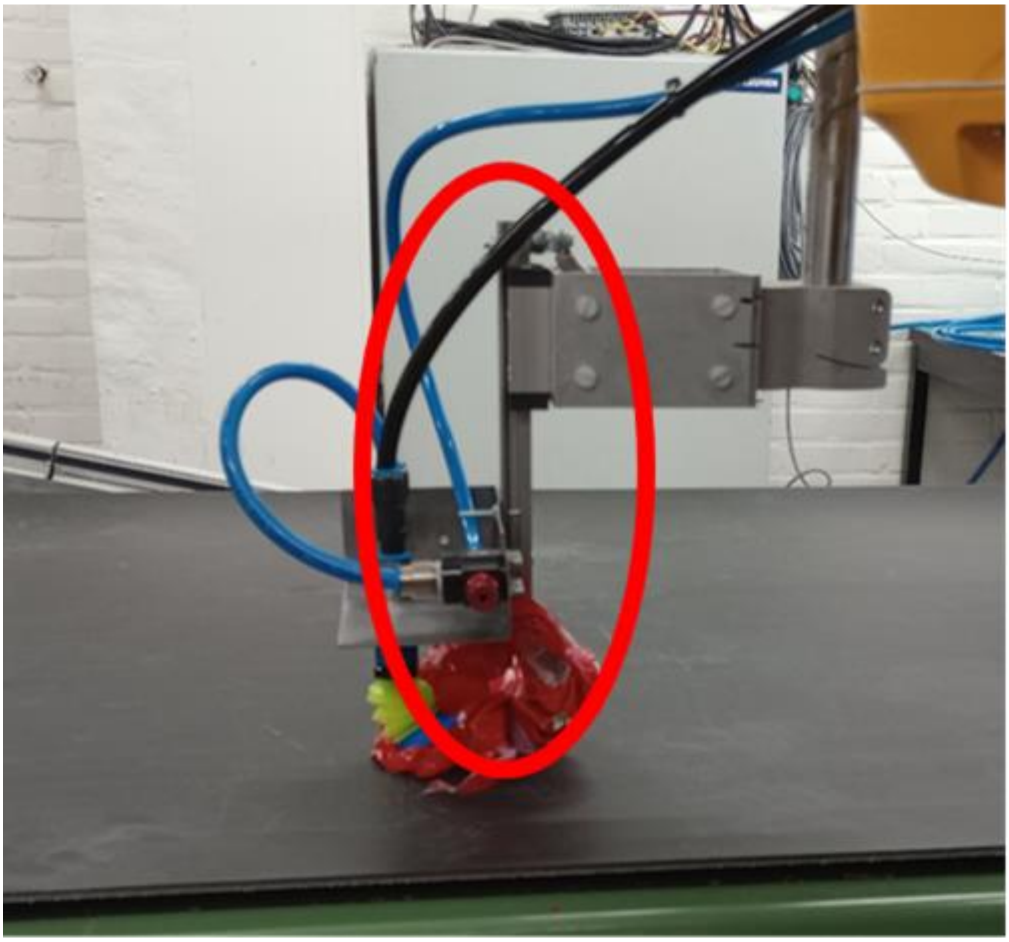

Figure 23. Suction cup mounted to robot with linear compensator in red circle.

3.5.2.2 Performance monitoring

To measure the performance of the gripper by confirming the success of a pick, a feedback system was installed and tested. This feedback system consisted of an optical sensor installed in the container in which the objects are dropped after picking. After every pick, the objects get dropped off in the container. A zigzag pattern is foreseen in the container to ensure that the objects that fall into the container get detected by the sensor. The sensor is connected to the robot. When an object gets detected, this is registered together with the log of the robot for every picked object.

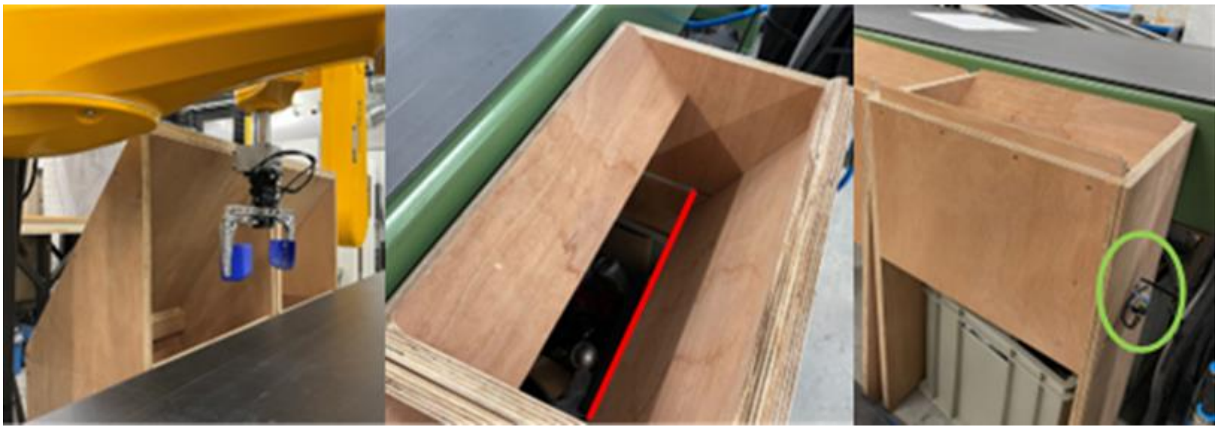

Figure 24. Waste containers with laser sensor.

3.5.2.3 Performance boosting – launching objects with pneumatic air

When picking objects from a conveyor with a suction cup the robot must move from the container to the object and back. This movement has the biggest impact on the time needed to pick an object (picking time). Limiting this movement yields major potential to reduce the picking times. Throwing or launching objects into the bin are approaches to limit the pick and place path and therefore the picking time.

To launch the object, experiments are conducted in which the pressure in the suction cup is temporarily increased to a positive pressure, by injecting pressured air, to launch the object. By angling up the suction cup before injecting the pressured air, the grasped objects are launched towards the container. To angle up the suction cup, a prototype is designed that turns the suction cup upwards to afterwards blow away the object with air pressure, Figure 25.

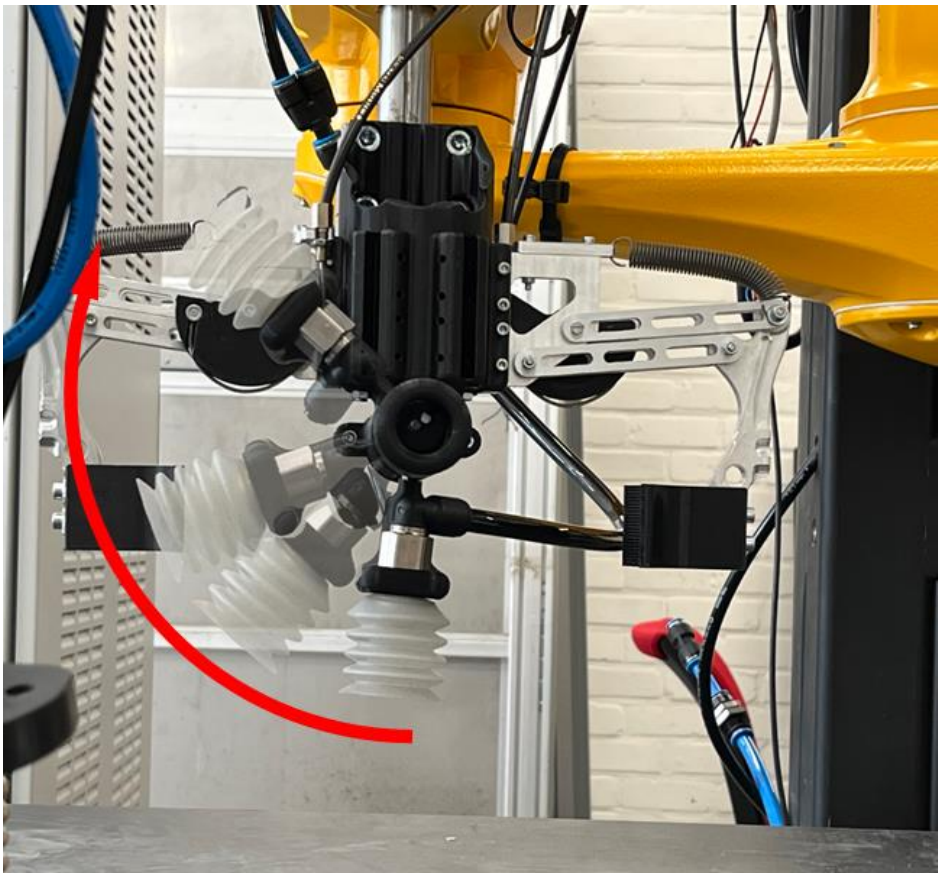

Figure 25. Alignment of suction cup before launching.

4 Preliminary results on waste sorting

In addition to the pairwise integration of the prMRF elements discussed in the previous sections, we examined the integrated operation of multiple components that achieve the processing of a stream of recyclables and the successful sorting of materials by a RoReWo Team (RoReWo-T).

Specifically, we used the mechanical equipment already available in ROBENSO's lab to examine the cooperative operation of a conveyor belt, a computer-vision based waste identification, localization and categorization module, and a team of three 1.5 DoF RoReWos. The aim was to develop the interfaces and communication protocols that allow the development of a complex prototype showing the coordinated and successful operation of the relevant components. Additionally, based on this early implementation, the dynamic variation in the operating characteristics of each component and how it affects the performance of other units was studied.

For the current set of experiments we use the dark room with the lighting surfaces on the top to reliably observe the waste stream. A PET-dedicated Mask R-CNN model is used to identify recyclables that should be collected in the PET bin. As mentioned above, the inference model operates at 5 fps, which means that each object is seen and processed multiple times until its final categorization. Given that at different times of examination an object can be assigned to diverse material categories (this is relevant to less than 10% of the total number of objects observed), to make the final categorization decision we follow a voting approach, with the category that receives the most votes being the one to which the object is finally assigned. When the identification, localization and categorization of the objects completes, the target materials to be recovered are placed in a queue from which the targets to which the RoReWos will move are finally selected.

The system incorporates an encoder to monitor the speed of the conveyor belt that moves with an average speed of 30 cm/sec. To measure the belt speed in real time, we use a rotary motion encoder that is in contact with the conveyor belt and immediately records all speed changes that affect the future expected positions of the identified targets. The encoder converts linear displacement into pulses, allowing for the calculation of the conveyor belt's speed in millimeters per second (mm/s). By correlating the conveyor belt speed with the known distance between the target's initial position and the robots, the system estimates the time it will take for the target to traverse that distance and reach the robots. Moreover, a Newton differential equation solver is used to predict when each of the targets will be at a point that can be retrieved by a certain RoReWo. This information is essential for coordinating the movement and actions of the robots, ensuring they are ready to engage with the target at the appropriate moment. This enables precise coordination and synchronization of the system's operations.

In each RoReWo, a pneumatic gripper is installed which is powered by a blower to pick and hold the recovered materials during transfer. The Control Logic for the PLC is implemented in Codesys Structured text format and the scripts controlling each robot are running in parallel. They also incorporate functionality for error handling, maintenance functions and manual control through buttons. At the current implementation, the available RoReWos are handled sequentially, letting the first RoReWo select a target, then select the second, and finally the third. This approach is expected to change in future versions, where different roles will be assigned to the members of the RoReWo-T. A snapshot of the RoReWo-T working on PET recovery is shown in Figure 26. A video from this set of experiments is also available at the following link: https://www.youtube.com/watch?v=iKJn93K33hk.

Figure 26. A snapshot of a three RoReWo-Team working on PET recovery.

As shown in the obtained results, we have been able to successfully combine the operation of three central prMRF components to implement a unified system that effectively deals with the treatment of a stream of recyclables for the recovery of a single material type.

The experimentation with the composite system allowed us to early identify critical details in the cooperative operation of the components, which seem to significantly affect the overall performance of the system. Clearly the performance of the visual material identification component is very important in providing correct and accurate targets-objects that need to be recovered. The accuracy of target location significantly affects the overall performance, as when only a part of the object is recognized, the pneumatic gripper will be applied to a sub-optimal point, increasing the chances of failure during material picking.

Due to the use of a global shutter camera, the speed of the conveyor belt does not seem to affect the performance of the visual material identification and categorization component.

Recyclables could be equally identified and categorized even at conveyor belt speeds up to 50cm/sec.

However, the speed of the conveyor belt seems to significantly affect the success rate of material picking. In particular, as RoReWos have limited degrees of freedom, they act instantaneously on the recyclables and do not have the ability to follow them as they are moved along, by the conveyor belt. This means that there is very limited time available for the suction cup to adapt to the object, and when sufficient seal is not created, the picking of the material may fail. This observation becomes progressively more pronounced as the belt speed increases.

It should be noted here that the above observation is not expected to have a significant impact on the overall performance operation of the prMRF, as in order for the RoReWos installed in the prMRF to recover the maximum number of materials, the conveyor belt should move at relatively low speeds (around 25-30cm/sec), and thus picking rate is expected to be high. In any case, this is a significant parameter in the cooperation of the prMRF components that should be closely studied in the coming months when complete versions of the prMRF will be released.

5 Future work

As presented above, in the first phase of RECLAIM, a partial integration of the prMRF elements has already been carried out, which was mainly aimed at reducing future risks regarding the cooperation of neighboring and directly interacting components. The results so far have shown that the architecture of the prMRF, as described in Deliverable 2.1, and the choices made for its components are in the right direction and that the complete prMRF construction in the following months is not expected to present inconsistencies/conflicts.

So far, the devices and experimental setups tested as part of the project have mainly been carried out under laboratory conditions rather than in the actual prMRF. As of March 2023, the container-box that will house the prMRF is fully designed and ready to incorporate the smart and autonomous recyclable materials sorting technology developed in the project. The prMRF has recently moved at FORTH premises, where the technologies developed by each technology partner of the RECLAIM project will be progressively integrated. The first 1.5DoF RoReWos have already been installed as shown in Figure 27 and experiments inside the container environment will start soon.

Figure 27. The first 1.5DoF RoReWos being installed inside the prMRF.

The development of the prMRF will follow a lean implementation that follows a test-fast/improve-fast approach, with frequent integration/improvement cycles, rapid prototyping, and close collaboration between partners teams involved in cross-functional tasks. Interestingly, the agile integration approach welcomes partially changing requirements even late in development, continuous attention to technical excellence and extensible design, regular adaptation of system components to changing circumstances and needs, daily cooperation between users and developers, frequent component delivery and incremental optimization. Based on continuous and direct integration, the implementation, testing and deployment of the prMRF components will be grounded to the particular needs of waste treatment and material recovery as specified by the use case scenarios.

It is considered that the structuring of the integration tasks in two main cycles, will provide the consortium the flexibility to address emerging project needs and finally deliver a prototype that is as close as possible to the real needs of the end-users and will attract the interest of the relevant stakeholders. In particular, the next integration cycle considers the incremental unification of all the technological advancements achieved by the RECLAIM partners, in the FORTH premises. Besides in non-fully realistic conditions, the continuous evaluation of how the integrated components affect and improve the performance of the composite prMRF will be driven by partners HERRCO and ROBENSO, both having extensive real-world experience in waste processing and material recovery.

After achieving excellent performance prMRF in FORTH premises, the prMRF will move to the actual deployment site where another major optimization cycle will start. These smaller scale optimizations will be guided by the different use-case scenarios considered in the project, namely (a) material recovery from mixed recyclables streams, (b) cleaning of citizen separated, material-specific streams, (c) immediate close to source material recovery. This will be the final version of the prMRF which will be judged on its effectiveness to efficiently manage different situations with substantially divergent characteristics.

6 Conclusions

The current deliverable summarizes the development and the early assessment of the technologies that will be integrated in the prMRF, aiming to validate the performance of the relevant components with respect to their intended function. The approach taken in the first phase of the project considered the integration of groups of components resulting in meaningful units, with clearly defined and assessable performance.

This has provided the chance to develop the first low-cost RoReWo units and demonstrate their successful performance in semi-realistic operating conditions. The latter has been particularly important because the RECLAIM RoReWos are unique and novel modules with high innovation potential that can significantly affect the methodology and cost of how recyclables are processed and sorted.

So far, the results of the testing of the effectiveness of the prMRF components are directly linked to the other project activities, in particular the development of the recycling data game (RDG). As already mentioned in Deliverable 6.1, the developments of the modules aimed at optical and hyperspectral identification of recyclable materials have enabled the collection of data already used for the development of the game. In the coming months, RDG is expected to be used to collect data from users. Our goal is to use this data to provide new training data that will lead to new, better trained models, which will then be used to acquire new data and so on.

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