Safety Protocol for Collaborative Human-Robot Recycling Tasks

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Abstract: The recycling industry in Colombia needs improvements in order to keep up with market evolution. Currently, low-income families are the ones in charge of collecting recyclable materials directly from mixed-waste bins and taking them to public collection centers, where they are manually classified. These collection centers become an interesting scenario to introduce collaborative robots in the monotonous and unhealthy task of classifying plastic bottles. However, safety and reliance are critical points that need to be ensured. This paper focuses on the design of a safety protocol required for creating a collaborative environment for the waste separation task. A system that integrates computer vision with an industrial robot is proposed to secure the human-robot interaction, based on ISO 10218-2 and ISO/TS15066 norms.
The protocol assess is conducted on a testbed created to emulate a pre-classification workstation where three types of thermoplastic recyclable materials are classified: colored-HDPE, HDPE/PS, and Green-colored-PET.

Keywords: industrial robots, collaborative robots, computer vision, safety.

1. INTRODUCTION

Everyday, industries of every kind are looking for faster, cheaper and better ways to produce in order to increase their competitive advantage. This is why industrial robots are acquiring new capabilities. Their integration with people and production systems is changing, requiring closer and more flexible human-robot interactions. These improvements bring safety challenges that need to be carefully addressed to close breaches between security and efficiency; especially in defiant layouts as the ones present in medium and small industries (SMEs), where space is a changing variable that requires optimization in order to maximize production.

Safety has been an important issue in each historical stage of robot's development. At the beginning of the robotic industry, it was necessary to cage off the robots from the world. This was a successful solution in normal operations, but it was not for the ones that needed human intervention. As time went on, the necessity to establish and create an environment where human could intervene and share the tasks of the robots, increased. Because of these needs, the concept of collaborative robots (Cobots) emerged, where robots instead of being isolated from humans will work side by side with them without safeguarding sparing space, allowing versatility in the production process.

Nowadays, the standards which govern the Cobots safety requirements and their relationship with the humans in an industrial environment are, for North America, the ANSI/RIA R15.06, while for Europe are the ISO 10218-1. According to [P. Gahan (2014)], the costs associated to workplace accidents are around 4% of annual global gross domestic productivity. Usually, companies that place higher in performance indexes (90%) rate very low in injury frequency, which translates in lower stops in production and lower costs in workplace accidents, whilst companies rating 70%, or lower, have injury frequencies about 60 times more [Hessman (2015)]. This creates the necessity of a bigger control in every aspect of production, whilst securing autonomy in every level.

Safety and reliance are critical points in the adequate performance of Cobots. The collaboration is based in confidence of being safe and of working towards the same objective, something that is still difficult to achieve because of the fear of being replaced or to be injured [Katwala (2017)]. As the need for more personal and automated tasks rises, the search of the reduction of uncertainty and more accurate perception capabilities arise as well.

A lot of these robots are programmed to stop at any change of weight or pressure in their joints, to avoid damages to themselves and to humans. As stated by [Matthias et al. (2011)], to keep on collaborative development, security must be a critical point on the evolution of Cobots. These researchers developed two approaches to risk assessment; both combining mechanical design principles, and simple control measures to supervise the robot and avoid free impact between human and robot.

Another fundamental part of collaborative work is the comfort and easiness that operators experience when working with robots. If the presence of these machines make the tasks more difficult, by making workers uncomfortable, then productivity and quality will decrease. To study this, researchers have conducted tests where the robot in action is presented to the operators whom later resolve a questionnaire to evaluate the effects of speed and distance. These studies show that larger robot body and faster robot speed movements made people uncomfortable, as well as the absence of any informative signal either visual or sonorous [P. Lazota (2017) Bartneck et al. (2009)].

This paper presents the design of an operative and inexpensive system that will enhance safety and productivity in a waste separation task. The system is composed by two algorithms. The first one recognizes human presence in the surroundings of the Cobot, delivering the exact position of the intruders. The second algorithm will determine the behaviour of the Cobot, according to safety protocols established by the standards and requirements of the industry.

From our knowledge, in the state of the art, there are no studies that propose and analyze a safety protocol for the waste separation task. Neither a collaborative human-robot environment in that area. The paper is organized as follows. Section 2 explains the recycling process in Bogotá, and presents the challenges of introducing Cobots in that task. Section 3 describes the proposed safety system. Section 4 describe the tests conducted to define the safety protocol. Finally, Section 5 presents the conclusions and the direction of future work.

2. PROBLEM STATEMENT

In Bogotá, the recycling process is mainly done manually by Recyclers (see Fig. 1). They are usually part of the vulnerable population of the city, which in many cases are in situation of poverty. Currently, the recycling process is managed by the local government through the UAESP entity (*Unidad Administrativa Especial de Servicios Públicos*), which has six recycling centers around the city.

As case of study for this paper the waste classification task at *La Alqueria* recycling center was studied, where the following materials are classified: paper; plastics (PET -Polyethylene terephthalate-, HDPE -High density polyethylene-, PS -Polystyrene-, PP -Polypropylene-), scrap (metal and cables), aluminum, newspaper, paperboard and glass.

The recycling process consists of four stages, described in Fig. 1. In the "Collection Stage", the potential recyclable materials are selected house by house, directly from mixed-waste bins by waste-pickers. In the second stage ("Transportation Stage"), the selected material is transported to the recycling center.

In the "Classification Stage", plastics are classified "intuitively" by their appearance: color, geometry, and type of content. HDPE/PS (High density polyethylene) are normally white containers like bottles of milk and whitish bottles. Colored-HDPE are usually containers of different colors, like shampoo and detergent bottles, etc. PET (Polyethylene terephthalate) is usually separated in four types by color: green, amber, transparent, and transparent bottles of cooking oil. The latter cannot be mixed with another class because its content would affect the reuse of

(a) Stage 1: Collection and Stage 2: Transportation.

(b) Stage 3: Classification.

(c) Stage 4: Storage.

Fig. 1. Stages of the Recycling Process in Bogotá

the material. Once the materials are correctly classified, they are bale out and stored ("Storage Stage").

This paper focuses on proposing a safety system for the "Classification Stage". The proposed design considers the actual layout of the waste separation workstation in *La Alqueria*, where as shown in Fig. 1(b), it is a small area, very dynamic, with people always entering, classifying, organizing, or receiving around 675 tons of plastic from different providers in a day [Circulo]. These features represent a challenge for the integration of robots in the classification stage.

To study the proposed scenario a testbed was created at CTAI ("*Centro Tecnológico De Automatización Industrial*") laboratory emulating the actual environment at UAESP's *La Alqueria* recycling center. Since the scope of this paper is limited to the safety assessment, the parametrization and characterization of the waste classification workstation and the subsequent recreation of the scenario is described in [Nicolas et al. (2018)].

Therefore, the proposed system focuses on enhancing safety and productivity in the waste separation task, by allowing the design of narrow layouts with minor costs. Increasing safety whilst reducing barriers between workers and machines.

A video describing the problem and the proposed solution is found in [Video (2018a)].

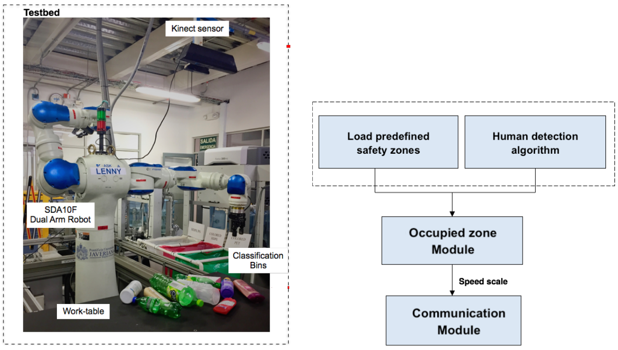
3. SAFETY SYSTEM

3.1 Framework

To recreate the recycling center's environment, the created system uses a robot, a work-table, a camera, and classification bins, as shown in Fig. 2(a). "Lenny", is the robot used in the testbed. It is a Motoman SDA10 dual arm industrial robot from Yaskawa [YASKAWA (2016b)]. For the computer vision task, a Microsoft Kinect sensor was used to locate and classify plastic bottles.

On the other hand, Fig. 2(b) shows the stages of the proposed safety algorithm. The human detection stage detects and tracks people in the images. Predefined safety zones are loaded; and the occupied zone module determines in which of the safety zones the detected person is located. Based on the location of the person, the speed scale that the robot should adopt is estimated. Finally, the communication module sends this information to the robot.

The present paper focuses on describing the procedure to design the safety protocol for the waste separation task. The explanation of the computer vision algorithms used in the protocol are out of the scope of the paper.



(a) Testbed (b) Safety algorithm

Fig. 2. Testbed, and workflow of the proposed safety algorithm.

3.2 Risk Assessment

A qualitative study was conducted in *La Alqueria* recycling center analyzing the workplace, people's interaction, and their perception with respect to robotic systems. All these with the objective of characterizing the task to create the desired collaborative environment for waste separation tasks.

In order to conduct the design as realistic as possible, it is assumed that the robot used in the testbed is located in the classification station at the recycling center.

According to the ISO 10218-2 norm, before selecting and designing appropriate safeguarding measures for the application (e.g. determining robot speed, defining the minimum separation distance, and other required parameters -article 5.11.5.4- [ISO102181 (2017)]), a risk assessment must be done. It consists in the determination of the limits of the robotic system; hazard identification; risk estimation and risk evaluation.

- Definition of the limits of the robotic system

- Related to the application

In the plastic classification task, a computer vision algorithm is in charge of detecting and classifying plastic bottles. The robot moves automatically to pick up the bottles and to place them in the proper bin. It stops when there are not bottles to pick, and/or when the operator stops it manually [Barrero and Galviz (2017)]. The only manual intervention will be when loading and unloading the elements to the robot's workspace.

The Motoman SDA10F is a robot that satisfies the performance levels and safety evaluation specified in the ISO 13849. It also fulfills the requirements of the ISO 10218-1. It was designed under specific compliance of safety norms; which allows to consider the robot inherently safe, and no further mechanical or electronic assessment is required. The security of the system will be determined by the protocols and programming associated to the task.

- Related to its location

As described in Section 2, the general layout for waste separation tasks in Colombia is characterized by narrow spaces. There are various activities being held at the same time, in undetermined areas, at different periods of time. This creates the need of a very flexible and adaptable layout that can change according to the daily waste load.

The layout designed for collaborative waste separation tasks is shown in Fig. 3. It proposes a general organization of these industries. For testing purposes, the layout is accommodated to the space in the CTAI (where the testbed is located), and complying with the ISO 10218-2.

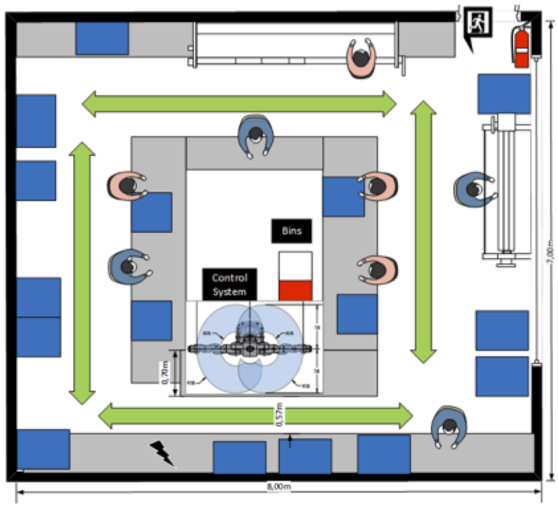


Fig. 3. Proposed layout of a waste classification workstation at CTAI. Green arrows represent the traffic routes or collaborators. Blue squares represent the bulk of material.

In Fig. 3, the arrows represent the traffic routes of collaborators; while the blue squares represent the bulks of materials in the area. The control system and the support services are signposted on the image, as well as the exit routes.

- Time limits

A complete cycle of the robot (picking and placing 1 bottle) takes in average 45 seconds. This value was found from tests conducted in [Nicolas et al. (2018)].

- Other limits

The plastic materials of the bottles, sometimes tend to be slippery and can fall out the robot's workspace, which limits the actual grasp area of the robot.

- Hazard identification

- Mechanical hazards

The following list shows different hazards associated to the studied application: movements of any part of the robot arm and end-effector; rotational motion of any robot axes; materials and products falling or ejecting; end-effector failure (separation); loose clothing, long hair; unintended movement during handling operations; unintended motion or activation of an end-effector or associated equipment; and unexpected release of potential energy from stored sources.

- Combined hazards

One possible hazard situation can be found when one person commands the robotic system to start classifying bottles, but this action is not expected by another person. Other situations are related to the misidentification of actual problem and compound problem by making incorrect or unnecessary actions; unintended release of holding devices allowing motion under residual forces.

- *Risk estimation* The potential risks associated to the studied application are defined according to the roles of the people that will interact with the robot, and the impact that can be generated by that interaction. Table 1 presents the risks that were defined for the plastic bottles classification task.

The impacts associated with human collisions are limited to the upper extremities, torso and head because of the position of the robot. These impacts are the most dangerous ones, because of the organs contained in these regions of the body. However, nor the speed or the force of the robot used on the studied task represent a severe danger to people's health.

- *Risk evaluation* Risks are evaluated to determine if they are acceptable and/or if they need to be mitigated or controlled to assure safety operations. The methodology presented in the ISO 13849 is followed. The norm proposes a traversal graph of risk with four levels to determinate the risk. The **S** level determines the severity of injury (**S1** slight, **S2** serious). The **F** level determines the frequency or exposure time to hazard (**F1** occasionally, **F2** constantly). Level **P** determines the possibility of avoiding the hazard or limiting the harm (**P1** it is possible to avoid it, **P2** there is no chance of avoiding it). Finally, **PLr** represents the required Performance Level, and refers to the amount of the risk reduction that has to be carried out by the safety functions ISO/TS13849 (2018).

The risk graph associated to the waste separation task is presented in Fig. 4. Because of the similarities among the estimated risks, the system was evaluated as a whole. Red circles represent the values chosen in each level. As a result of the risk evaluation the required Performance Level is **PLr** = c. It means the risks associated to the task is medium, i.e. a low contribution to risk reduction is required to be carry out by the safety-related parts (parts of the system in charge of providing safety functions).

This result is consistent with the application. Collaborative robots must require a lower **PLr** than industrial robots (that require **PLr** = d or higher) [Matthias et al. (2011)].

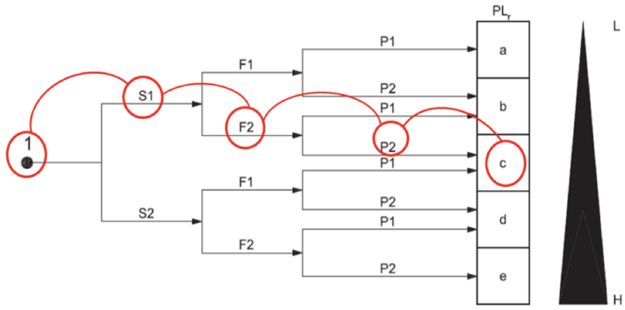


Fig. 4. Traversal graph for risk evaluation (ISO 13849). The **S** level determines the severity of injury. **F** level determines the exposure time of the hazard. **P** determines the possibility of avoiding hazard or limiting the harm. **PLr** is the required Performance Level required by the safety functions. Red circles represent the graph for the waste separation task.

3.3 Safety Protocol Considerations

To reach the **PLr** = c for the bottle classification task, a safety system based on computer vision is proposed. Safety zones are created around the robot's workspace according to a safety protocol. The protocol was designed according to the norms; and considering the perception from workers of the recycling center, about security issues when sharing their workspace with robots.

For the creation of the safety zones a minimum distance of security was needed. As neither the ISO 10218 nor the TS 15066 specify how to calculate this distance, it has been estimated based on the Speed and Separation Monitoring (SSM) equation [paper enviado Angie], shown in Eq. 1.

$$S = (v_H T_R + v_H T_S) + (v_R T_R) + B + Z_R Z_S \qquad (1)$$

where v_H is the directed speed of the operator towards the robot. v_R is the directed speed of the robot towards the operator, T_R is the time of the robot system to react to human presence. T_S the time to bring the robot to safe controlled stop. Z_R is the robot position uncertainty, and Z_S is the human position uncertainty. B is the distance traveled by the robot while braking. B and T_R are zero in this case because the robot is not traversing [68].

On the other hand, the perception of workers is studied by means of a questionnaire, that was designed according to GoodSpeed methodology [Bartneck et al. (2009)]. The questionnaire included some of the following questions:

(1) Have you ever seen a robot?
(2) Have you ever worked with a robot?
(3) Questions related to the appearance of the robot.
(4) The operator's choice related to the working distance. If he and the robot are close (around 0.5 m, 1.0 m, 1.5 m, 2.0 m), Does he prefer the robot to stop or to continue moving?
(5) Would he feel confortable working with the robot looking at him or being on his back?
(6) Would the operator feel confortable if the robot is working on his left or his right side?
(7) Do you consider the robot is useful to develop your activities?
(8) Would you consider the robot another coworker?
(9) Would you feel the robot could harm you?

Table 1. Risk estimation based on the roles of the people that will interact with the robot.

Role	Role Description	Impact
Visitor	Internal or external person with no knowledge about hazards.	Entering in dangerous contact with the robot. Any of the hazards mentioned in Section 3.2.2 could occur.
Another worker	Employees coming close to the robot occasionally, with no required interaction with it.	Entering in dangerous contact with the robot. Any of the hazards mentioned in Section 3.2.2 could occur, interrupting employee's task indefinitely, as well.
Co-existing worker	Employees working in an overlapping workspace with the robot doing independent task.	Hitting or getting hit by the robot accidentally. Any of the hazards mentioned in Section 3.2.2 could occur.
Collaborating worker	Employees interacting with the robot in regular operating mode.	Hitting or getting hit by the robot due to error in the proceeding or in the machine. Any of the hazards mentioned in Section 3.2.2 could occur.
Control and development engineer	Employees interacting with the robot, reconfiguring, repairing, exchanging and replacing devices, programing, recalibrating the robot and sensors, and executing service routines.	Safety systems may be disabled or could fail. Any of the hazards mentioned in Section 3.2.2 could occur.

(10) Would you feel more confortable if there is a light signal or a sound advertising the robot is close to you?

The questionnaire was implemented in *La Alqueria* recycling center, showing to the employees a video of the robot doing the task; and then asking their perception regarding security, comfortability, and purpose.

4. RESULTS

4.1 The Safety Protocol

The design of the safety zones starts with the calculation of the minimal distance of security using Eq. 1, resulting in: $S = 560.3mm$.

The adopted values to calculate the distance where: $v_H = 1600$, taken from the average human speed in ISO 13855. $T_S = 0.1s$, taken from expected Motoman's stopping times [YASKAWA (2016a)]. $T_R = 1.05610^{-4}s$ calculated experimentally with the vision algorithm. $Z_R = 0.1mm$, taken from robot's manual; and $Z_S = 400mm$, taken from Kinect's specification vision range [Tonelo et al. (2013)]

In relation to the workers perception for designing the protocol, the estimated S distance is coherent with the results of the questionnaires (see Fig. 5). The questionaries were presented to 7 persons, that were the ones in charge of the waste separation task in *La Alqueria* recycling center. 100% of the studied recyclers prefer that the robot stops when they get closer, at 0,5m of distance to the robot; and prefer that it keeps moving when the distance is equally or greater than 1,5m. About the task layout, 100% of the surveyed recyclers prefer to work with the robot facing them.

In relation to security, 86% considered that the robot might not hurt them and 100% of them have never worked with a robot. 57% has never seen a robot before. However, 100% of them consider a robot useful to help them with their tasks.

Regarding sympathy, results are peculiar, as 100% say they will consider the robot as a partner, 43% find it pleasant, and the rest did not believe it was friendly. The latter

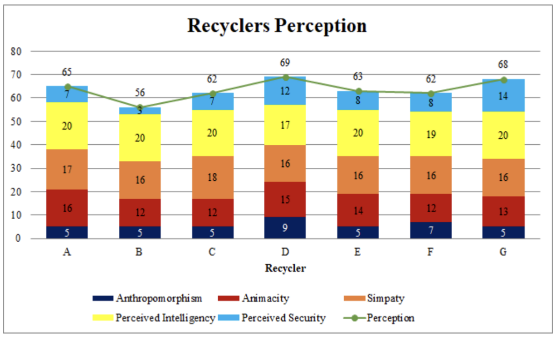


Fig. 5. Questionary results. Recyclers perception about having robots helping them classifying plastics.

is backed up by their perception of the robot's anthropomorphism, 91% said it looked artificial; and regarding animacity, workers considered that the robot was fluid and somehow autonomous, but it was not alive.

In general, recyclers average perception is about 55 points of the 110 possible (not totally negative nor totally positive). Their perception was better than expected, since given their poor knowledge about robots, and their initial attitude, some reluctance was anticipated.

As seen in Fig. 5, the highest acceptance score is with the perceived intelligence with 97%. It means recyclers are confident with the work executed by the robot. The perceived security has a 56.19% rate of acceptance which is explained by the confidence on the performance, but the intrinsic fear to the unknown.

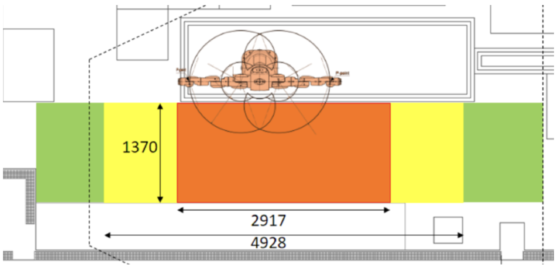
According to the results, the safety protocol was designed. The safety zones are created around the robot's workspace as shown in Fig. 6. Table 2 shows the parametrization of the safety zones; and the description of the behavior the robot must adopt, depending on which zone the human is. The hazard zone is red, the precaution zone is yellow, and the safe zone is green.

During execution of the task, the robot's speed is approximately 3.05 m/s. The average time for a human to walk from the yellow to the red zone is 0.3125 s, and the time for the robot's arm to travel the same distance is about 0.1639

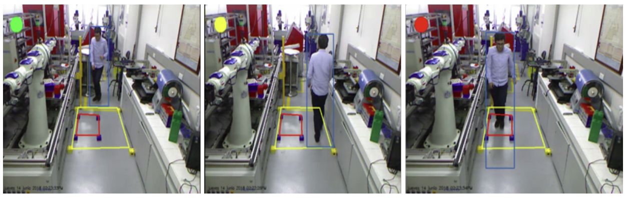
Table 2. Safety Zones Description.

Zone Color	Zone Limits	Robot Behaviour
green	> 1 m from the hazard zone.	Normal movement. The Motoman keeps with his work at 100% speed.
Yellow	1 m from the hazard zone.	Reduced movement. The Motoman keeps with his work at 50% speed.
Red	0,56 m from the hazard zone.	The robot stops immediately. Will only restart when there is no one in the red zone.

s. Thus, the time to reach the same spot is calculated in order to get the speed reduction for the yellow zone. This yield a result of 52.4% to reduce robot's speed.



(a) Safety Zones.



(b) Safety Zones Results

Fig. 6. Safety zones generated by the safety protocol

As part of the safety protocol, the following safeguards and requirements are specified for the correct implementation of the system:

- The maximum extend of the robot must always be between the boundaries of the worktable. If the extension exceeds the worktable, safeguards must be implemented. These safeguards must be equally long as the corridor and their width (or the distance for protection) must compensate the length that is no covered by the table (70 cm wide). The height does not affect the system, however according to ISO 10218-2, this should be at least 1400 mm from adjacent walking surfaces.
- Safeguards should be barriers, grids, or any fixed structure that impedes the passage.
- Collaborative workspace where direct human robot interaction takes place must be clearly defined and signposted.
- The robotic system should provide a minimum clearance of 500 mm from the operating space of the robot (including arm, the gripper, and the workpiece).
- People must not stop for long periods of time in the red or yellow zones. These are passage zones and must not be obstructed.
- Shadows in bright surfaces may interfere with the results of the recognition algorithm so any reflectance object or area (e.g. Floor) must be cover or removed from the collaborative workspace.

4.2 The Safety System

The developed system detects humans around the robot's workspace (using open source software ROS and OpenCV libraries), based on the location of the intruders in the different safety zones (that we defined by specifications and guidance of both ISO 10218-2 and ISO/TS15066), a behaviour algorithm determines different actions that the robot must adopt to secure the collaborative environment.

Before the robot starts operating, information of the safety zones is loaded. Figure 6(b) shows the different zones drawn over the image captured by the Kinect.

The computer vision algorithm detects humans around the robot's workspace (using open source software ROS and OpenCV libraries). Fig. 7 shows the workflow of the algorithm. Once humans are detected, based on their location, the behaviour algorithm determines different actions that the robot must adopt to secure the collaborative environment (e.g. stop, reduce speed, etc.). This algorithm compares the location of the points that conform the contours of the persons in the image, with the limits of the safety zones. The output of this algorithm is a signal that describes in which zone these points are located and the corresponding speed scale the robot must adopt.

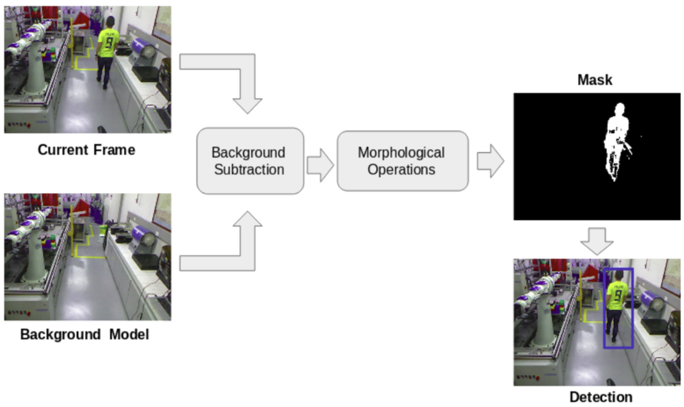


Fig. 7. Workflow of the human detection algorithm.

To modify the robot's behaviour a ROS Node was created. The algorithm publishes different speed parameters, depending on the location of the persons (0% - Red Zone, 50% - Yellow Zone, 100% - Green Zone).

- Safety Zone Test

This test has the objective to determine the effectiveness of the system alerting when a person enters the safety zones. For this test a video (370 images.) of a person walking through all the safety areas, at different speeds and directions, was recorded. As ground truth, the video was manually labeled with the information of the zones that were occupied by the person. This information was used as ground truth to compare the results obtained with the proposed algorithm, using confusion matrices.

In 165 frames from the 370 frames that contained the video, the green zone was occupied. In 104 frames the yellow zone, and in 101 frames the red zone. Table 3 shows the results. The global accuracy is 79,18%. The green zone accuracy was 87,56%, the yellow zone accuracy 80.00%, and red zone accuracy of 90.81%.

Table 3. Confusion matrices. Each row corresponds to the individual matrix.

Safety Zone	**TP**	**FN**	**FP**	**TN**
Green	86%	14%	11%	89%
Yellow	51%	49%	9%	91%
Red	97%	3%	11%	89%

It is important to notice that the system response is very good in the critical zone (red zone), which is of great importance for the safety system.

Video from the test can be seen in [Video (2018b)]

5. CONCLUSIONS AND FUTURE WORK

In this paper, a safety protocol for human-robot collaboration in waste separations tasks, was proposed. The designed system is able to establish a collaborative human-robot environment by means of a computer vision algorithm, enforcing safety in the workspace. A safety protocol was established for the classification task, as part of a solid waste recycling process. It was designed by interpreting and analyzing ISO standards. This might be helpful for other researchers looking for the parametrization of collaborative environments in specific tasks.

The system was able to recognize people around the robot's workspace, to identify their location with respect to the designed safety zones, and to take decisions about changing the robot's behaviour. All these using affordable equipment and software (Kinect Sensor, OpenCV library), that allows the flexibility and versatility required for SME.

The system is able to secure the workspace with an average accuracy of 79% using the parametrized testbed. With an accuracy of 90.8% in the most critical zone (the red one).

Current work is being oriented on integrating the proposed system with the plastic classification routine of the robot.

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REFERENCES

Barrero, N. and Galviz, D. (2017). Designing a framework to give perception capabilities to an industrial robot for waste separation tasks. In *Undegraduate project*.

Bartneck, C., Kulić, D., Croft, E., and Zoghbi, S. (2009). Measurement instruments for the anthropomorphism, animacy, likeability, perceived intelligence, and perceived safety of robots. *International Journal of Social Robotics*, 1(1), 71–81. doi:10.1007/s12369-008-0001-3. URL `https://doi.org/10.1007/s12369-008-0001-3`.

Circulo, B. (????). Bio crculo. URL `http://www.biocirculo.com/reciclaje/`. Date retrieved 09-11-2017.

Hessman, T. (2015). Safety is productivity. URL `http://www.ehstoday.com/safety-leadership-conference-2` Date retrieved 30-09-2017.

ISO102181 (2017). ISO - International Organization for Standardization. URL `https://www.iso.org/standard/41571.html`.

ISO/TS13849 (2018). ISO - International Organization for Standardization. URL `https://www.iso.org/standard/69883.html`.

Katwala, A. (2017). Institution of mechanical engineers. URL `https://www.imeche.org/news/news-article/meet-the-cobo` Date retrieved 05-11-2017.

Matthias, B., Kock, S., Jerregard, H., Kallman, M., Lundberg, I., and Mellander, R. (2011). Safety of collaborative industrial robots: Certification possibilities for a collaborative assembly robot concept. In *2011 IEEE International Symposium on Assembly and Manufacturing (ISAM)*, 1–6. doi:10.1109/ISAM.2011.5942307.

Nicolas, B., Didier, G., and Carol, M. (2018). Industrial robots for waste separation tasks: An approach to industry 4.0 in colombia. In *Proceedings of the The 9th International Conference on Production Research-Americas 2018, Bogotá 2018.*

P. Gahan, P.E.y.B.S. (2014). Workplace health and safety, business productivity and sustainability. URL `http://newsroom.melbourne.edu/sites/newsroom.melbourne` Date retrieved 30-09-2017.

P. Lazota, T. Fong, J.S. (2017). A survey of methods for safe human-robot interaction. URL `http://interactive.mit.edu/sites/default/files/documen` Date retrieved 01-04-2018.

Tonelo, C., Moreira, A.P., and Veiga, G. (2013). Evaluation of sensors and algorithms for person detection for personal robots. In *2013 IEEE 15th International Conference on e-Health Networking, Applications and Services (Healthcom 2013)*, 60–65. doi: 10.1109/HealthCom.2013.6720639.

Video (2018a). PIR Project, PUJ. Bogotá 2018. URL `https://youtu.be/F76Pe-WkP3g`. Date retrieved 03-01-2019.

Video (2018b). Safety Zones, PUJ. Bogotá 2018. URL `https://youtu.be/Z4kyongoAng`. Date retrieved 03-01-2019.

YASKAWA (2016a). Motoman Instruction Manual. `https://cdn2.hubspot.net/hubfs/366775/downloads/docume` Date retrieved 20-06-2018.

YASKAWA (2016b). Motoman SDA10F robot. `https://www.motoman.com/industrial-robots/sda10f`. Date retrieved 20-10-2016.