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Sensorless Localization of a Minimally-Actuated Robotic System for Automated Pallet De-strapping

Abstract
Purpose – In this paper, we detail the design and prototyping of a smart automation solution for de-strapping plastic bonding straps on shipping pallets, which are loaded with multiple containers secured by a top-cover as they move on a conveyor belt.
Design/methodology/approach – The adopted design methodology to have the system perform its function entails using the least number of sensors and actuators to arrive at an economic solution from a system design viewpoint. Two prototypes of the robotic structure are designed and built, one in a research laboratory and another in an industrial plant, to perform localized cutting and grabbing of the plastic straps, with the help of a custom-designed passive localizing structure. The proposed structure is engineered to locate the plastic straps using one degree-of-freedom only. An additional strap removal mechanism is designed to collect the straps and prevent them from interfering with the conveyor.
Findings – The functionality of the system is validated by performing full-process tests on the developed prototypes in a laboratory setting and under real-life operating conditions at an automotive original equipment manufacturer (OEM) assembly facility. Testing showed that the proposed localization system meets the specified requirements and can be generalized and adapted to other industrial processes with similar requirements.
Practical implications – The proposed automated system for de-strapping pallets can be deployed in assembly or manufacturing facilities that receive parts in standard shipping pallets that are used worldwide.
Originality/value – To the authors' best knowledge, this is the first mechanically-smart system that is used for the automated removal of straps from shipping pallets used in assembly facilities. The two main novelties of the proposed design are the robustness of the strap localization without the need for computer vision and a large number of degrees-of-freedom, and the critical placement and choice of the cutting and gripping tools to minimize the number of needed actuators.

Keywords Pallet Handling System, De-strapping Robot, Reliable Open-Loop Localization.

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1 Introduction

The modern world is experiencing a noticeable transition into Industry 4.0, which sees many companies adopting smart systems driven by artificial intelligence and machine learning. Seeking to optimize their processes, these industries are using robotic systems to develop measures such as quality, productivity, and flexibility (Petrescu et al., 2018). This is mainly due to robots' ability to perform highly repeatable and reproducible tasks while maintaining the same level of output over a longer period as compared to their human counterparts. Using the data collected by different sensors and cameras, robotic systems are capable of perceiving their environments and making the necessary decisions in almost any situation.

Indeed, areas related to logistics, management, and customer services have seen a rapid rise in their demand for automation (Nowakowski and Werbińska-Wojciechowska, 2014). Such industries attempt to organize a chain of simultaneous tasks and processes while adhering to strict timing schedules. They also require a large workforce to complete a wide range of tasks, most of which are repetitive and do not require special skills to complete. Hence, the logistics industry has seen a steady increase in the implementation of robotic systems that can perform mundane tasks and allow workers to focus on more organizational and cognitive functions (Echelmeyer et al., 2008). One of the logistical activities that have seen a demand for automation is the handling of palletized goods. This activity involves a series of tasks beginning with the transport of pallets to de-palletizing stations, where their contents get processed and are transferred for redistribution. The de-palletization process involves cutting and removing plastic bonding straps and top protection covers that are used to prevent stacked boxes or containers from moving or the contents from getting damaged during transport. This process requires long hours of manual labor to set up the pallets and prepare the goods for storage or transport.

Different designs of de-strapping/de-banding robots already exist in warehouses and packaging plants; the following are some examples of existing mechanisms that perform strap removal and handling (*Bwintegratedsystems.com. Robotic Destrapper Debander Material Handling*, n.d., *LBFoster.eu. Debander (Destrapper)*, n.d., Rusu and Bammer-Schur, 2013). The designs vary between armed robots, cartesian systems, and overhead mechanisms; however, the common aspects of these robotic systems are the reliance on computer vision and/or laser sensing for pallet's height detection and strap localization, and the requirement of multiple degrees-of-freedom (DOF) to approach the detected straps, cut them, then feed them to a disposing/granulating system.

Various robotic solutions that are involved in the process of pallet handling and logistics cycle are investigated. (Zhang and Skaar, 2009) presents the method of combining an un-calibrated vision and three-dimensional (3D) laser-assisted image analysis implemented to a de-palletizing robot, and (Korayem et al., 2014) proposes a spatial cable-suspended robot feedback system in which the position and orientation of an end-effector are recorded by coupling image processing (one camera) with three laser sensors. Both systems require laser or visual guidance to navigate the robot throughout the process, which adds to the complexity and development time needed to deploy these robots in an industrial environment. (Kavoussanos and Pouliezos, 1998) introduces computer vision as an inexpensive 'intelligent' requirement for the robotic system to accurately detect the pallet positions and recognize the pattern for pallet arrangement during the de-palletization process; however, the drawback of the vision system is that locating positions in a two-dimensional (2D) plane does not permit taking any deviations or tilts in the incoming packages into consideration.

(Nakamoto et al., 2016) presents a gantry robot for pallets handling that utilizes a telescopic arm for space-saving, a camera image, and a depth image for package recognition in various stacking manners and for planning the package handling order. The process relies on image processing to recognize multiple packages based on their size and color, which might be severely influenced by the changes in brightness and unstructured uncertainties in the surrounding environment. (Tanaka and Ogawa., 2019) describes a vacuum suction-type end effector with a pneumatic actuator for depalletizing robots in shipping centers. The robot utilizes a linear motion type for the main arm where the suction cups are installed for package grabbing, however, it requires 5-DOF (3-DOF for the main arm and 2-DOF for the conveyor arm), in addition to an RGB-D camera for localizing the shipping boxes. Gasparetto and Rosati (2002) illustrates a case study of a cartesian robot's accuracy, dimensions, velocity, and weight requirements to reach and handle objects using all three cartesian spatial dimensions. In sharp contrast with the aforementioned designs, the hereby proposed system is devised to localize, cut, and grab the straps by utilizing a single DOF and without the need for computer vision and image processing.

More specifically, for the handling of shipping pallets, (Lin et al., 2020) designed an automated guided logistics robot for pallet transportation to improve logistics automation. The robot moves freely in all directions without turning the chassis, and does not require additional infrastructure as it relies on a laser navigation system. In (Masood and Khan, 2014), different pattern placement strategies were investigated to improve the operational efficiency robotic palletisation of box packages, and a novel technique for the pallet loading problem (PLP) was proposed by considering constraints related to the gripper size for generating an optimal pattern on the pallet. (He et al., 2020) presents an admittance-based controller for physical human-robot interaction to enable operation in constrained task space. Machine learning models are developed to ensure collision avoidance, improve tracking, and compensate for dynamic uncertainties, and the controller guarantees that the end-effector does not violate the constrained task space.

Implementing automated pallet de-strapping robotic systems in industrial environments faces several challenges including a lack of technological infrastructure, complexity of integrating machine learning driven systems, and high investment costs (Moktadir et al., 2018). In an attempt to make these systems more accessible to industry, we hereby propose to decrease the robotic system's reliance on the ever-increasing code-intelligence by taking the 'intelligence' from the sensing, processing, and machine learning and transferring it over to the mechanical design itself. By reducing the number of sensors, actuators, and digital processes needed, we do not only reduce the cost of components, but also end up with a simpler design that requires less maintenance. To demonstrate this passive-yet-intelligent mechanical design, we present a simple, low-cost, and low-maintenance robotic system that can perform the de-strapping of industrial pallets. The proposed solution is applicable in numerous logistics and assembly facilities because the pallet strapping method is prevalent throughout different industries. Throughout this paper, this system is referred to as the Cutting Tool, and it is expected to perform the following functionalities:

- **Strap Detection**: Devise a mechanism that is capable of localizing the straps along with the covers to identify the cutting and grabbing locations.
- **Strap Cutting**: Propose a mechanism that is capable of cutting the different types of (non-metallic) straps without causing damage to the covers, containers, or pallets.
- **Strap Grabbing**: Propose a mechanism that is capable of firmly grabbing the straps without slippage by providing a high pulling force to allow for transferring the straps to the next step in the process.
- **Strap Removal**: Devise a method for transporting the cut straps to a disposal unit (e.g. shredder), so that the straps do not entangle with the process mechanisms or litter the floor and working area.
- **Strap Disposal**: Provide a solution for collecting the disposed of straps in a clean and compact fashion.

This paper offers the following contributions to the field of automated assembly systems:

- It offers a mechanically-smart robotic system without relying on ever-increasing machine learning by transferring the ‘intelligence’ from the sensing, processing, and learning algorithms over to the mechanical design itself.
- It is able to localize, cut, and grab the straps by utilizing a single DOF, which cannot be found anywhere in the surveyed related literature.
- If exhibits a robust and accurate strap localization function without the need for computer vision or other costly sensors.
- It devises prudent placement and choice of the cutting and gripping tools to minimize the number of needed actuators and motions.

The rest of the paper is structured as follows. Section 2 presents a general design methodology for the Cutting Tool where geometric and process parameters are defined. In Section 3, the generated parameters are applied to a case study involving a pallet de-strapping system in collaboration with an industrial partner. Section 4 describes the implementation of the Cutting Tool prototype along with all its subsystems. Section 5 develops the prototype to arrive at an improved and industrialized version of the robotic system. In Section 6, the testing results from both prototypes are compared and assessed. Finally, Section 7 concludes this work and provides an outlook towards future work.

2 Design Methodology

Developing a generic approach for detecting and removing plastic straps from pallets requires a robust system, which can adapt to varying configurations of packaging methods, shapes of containers, and stacking arrangements in the absence of standardized packaging methods. The motivation behind using sensorless localization is to create a fixed frame of reference for strap cutting and grabbing, relying on the cover’s geometry and using a single degree-of-freedom. The cutting and grabbing tools are to be located right above the straps, which eliminates the need for computer vision for strap detection and the demand for additional actuation of the cutting and grabbing tools to approach the straps. Thus, the critical factors that need to be addressed include the geometry of the packaged pallets, the shape of the top covers, and the strapping direction. These factors have a major impact on the ease or difficulty of strap detection and removal. Accordingly, custom solutions are required for each case, which emphasizes the need for a generic approach that takes inputs from the pallet configuration parameters and applies them to the model that we propose in this paper.

2.1 Pallet Configuration Parameters

2.1.1 Stacked Pallet Geometry

The spatial geometry of stacked pallets is defined by their length, width, and height. In general, wooden pallets come in standardized sizes that set the boundaries for stacking containers edge-to-edge and corner-to-corner. This interlocking ensures the proper weight distribution and stable palletizing of the containers. As a result, two of the spatial geometry variables can be determined from the length and width of a standard pallet. Concerning the stacking height of pallets, no standard sets the maximum and minimum height. Every industry sets its own constraints to ensure safe palletizing and transport.

2.1.2 Pallet Top Covers

It is common for stacked pallets to have some form of top covers, which prevent moisture and dirt from entering and damaging the stacked containers, and they ensure that the containers are held firmly together and do not topple or fall during transport. These covers could be plastic sheets, thick flat cardboard sheets, or thick and sturdy plastic lids. The plastic and cardboard sheets create a flat top surface on the stacked pallets, whereas the plastic lids usually have extruded bodies with grooves for straps and stacking rims. This affects the strap detection and cutting approach by limiting the areas where straps could be grabbed and cut.

2.1.3 Strapping Direction

To ensure that the containers are secure, they are strapped to the pallet to form one shipping entity. Usually, two to four straps are used, two going perpendicular along the pallet's length and two going perpendicular and flush along the width. In case a plastic lid is used on top of the stack, the plastic straps go through the dedicated grooves on the lids and wrap around the stack and the pallet. Determining the number of straps and their strapping direction is essential to their detection in the generic approach.

2.2 Detection and Cutting Approach

The generic approach should define the most efficient method to detect and cut the straps. This includes determining the face of the stacked pallet where the solution is implemented. The available faces are the top surface, the four sides, and the bottom section of the pallet. Each of these is assessed in terms of practicality and ease of access, which is strongly related to the environment in which pallets are received and processed. The bottom section is usually the least practical since it is very close to any supporting surfaces, the ground, or a conveying system, thus it is discarded. The four sides are reasonably practical to consider; however, installing the solution along the sides of the pallets may cause major disruption to the inbound logistics spatial layouts. Indeed, it is very common for warehouses to have just enough space to allow workers to move freely between pallets and their processing units.

The remaining option is the top face of the stacked pallets. Although this face imposes several constraints, it provides notable benefits as well. Approaching the pallets from the top allows for better use of vertical space, which can help in adding more functionality with a much smaller footprint. Besides, any needed movement to reach this face can rely on existing automated solutions that move in the Cartesian space.

2.3 Localization

After defining the top surface as most convenient for the strap detection and removal, and considering the dimensions of a stacked pallet, a simple and efficient method needs to be developed to make use of all the collected information on the pallet configuration. As stipulated earlier, the solution must reduce reliance on computer vision, or sensors and actuators, that tend to increase development and maintenance costs. This solution will be referred to as the “Localizer,” a simple and modular structure that sets itself on the top surface of a pallet, creating a fixed frame of reference on which the detection and removal of the straps occur.

2.3.1 Main Structure

The Localizer’s main structure involves the generation of a geometric shape that fits precisely on the top surface of a stacked pallet. It is designed to accommodate any extrusions or grooves on the top surface and ensure a level fit. It is desirable to build the structure out of extruded aluminum profiles to make its construction simple, quick, and cost-effective. The steps to develop the Localizer are as follows:

- Step 1: Measure the length and width dimensions of the pallet, which set the outside boundary of the Localizer to be flush with the edges of the stack.
- Step 2: Select a thickness of the aluminum profiles between 20 mm and 60 mm .
- Step 3: Check for extruded bodies on the top surface.
- Step 4: Check if the thickness of the aluminum profiles interferes with extruded bodies on the plastic lids if any exist. In the case of interference, change the thickness of the aluminum profiles.
- Step 5: Find stretches along the length or width of the top surface with no extruded bodies.
- Step 6: Add aluminum profiles on the internal part of the Localizer along the length or width for extra rigidity and more space for tool placement.

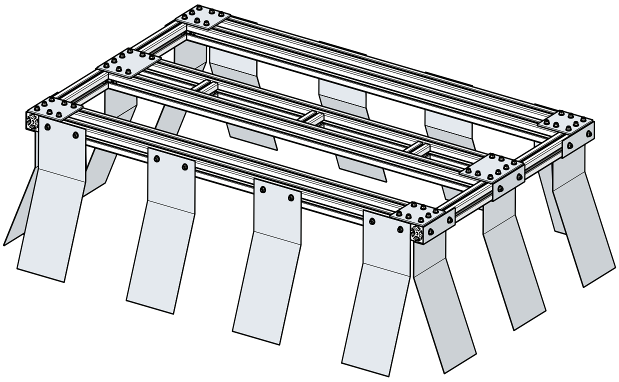

Fig. 1: Image showing the proper installation of the tapered guides on the sides of the Localizer's frame.

The resulting frame acts as the foundation on which the tools needed for grabbing and cutting the straps are installed, whereby the tools can be placed directly over the spots on the top surface where the straps are bound to be.

2.3.2 Tapered Guides

After making certain that the Localizer accurately fits on the top surface, it needs to be guided in a way that ensures its correct and precise placement on the stack. To do so, flat plates are fitted along the outer length and width of the Localizer, where the plates have a taper angle to allow them to glide across the edges of the stack, so that they automatically, yet passively, calibrate the position of the Localizer on top of the stack by simply allowing the Localizer to fall into place. The length and angle of the tapered guides determine the range within which the Localization can function properly, where larger taper angles allow for a wider accuracy range. This calibration is supported by the Localizer's own weight as it moves downwards. At its core, this localization process functions as a fitting of two mechanical parts with each other by benefiting solely from gravity and geometry. We note that the guides must be installed on the sides of the localizer and be flush with its edges, in order to ensure that as the Localizer sets itself on top of a pallet, the guides encompass its perimeter. Also, the guides need to be firmly fastened to the sides to avoid clashing with the top surfaces and fail to correct the misalignment. Fig. 1 shows the proper installation of the guides on the sides of the Localizer.

2.3.3 Localizer Installation

The design of the Localizer along with the tapered guides needs to possess spatial flexibility to adjust itself on top of the stacked pallets. The method by which it is lowered on the stack cannot be rigid, otherwise, the system would clash with and damage the containers. Accordingly, the Localizer should be suspended from its four corners using steel cables that provide it with the needed flexibility as it moves down. The suspended cables also provide the Localizer with the non-rigid compliance needed to slide in place.

3 Design Case Study

In order to assess the performance of the generic design, it is put to test on an industrial project commissioned by the robotics department at the automotive OEM partner. The project requires that plastic straps be cut, removed, and disposed of on incoming pallets in the assembly plants of the automotive OEM partner. The department decreed a simple and cost-effective solution that can perform the task in an efficient and reliable manner. This section details the design methodology involved in the development of the robotic solution, which relies on the generic approach developed in Section 2.

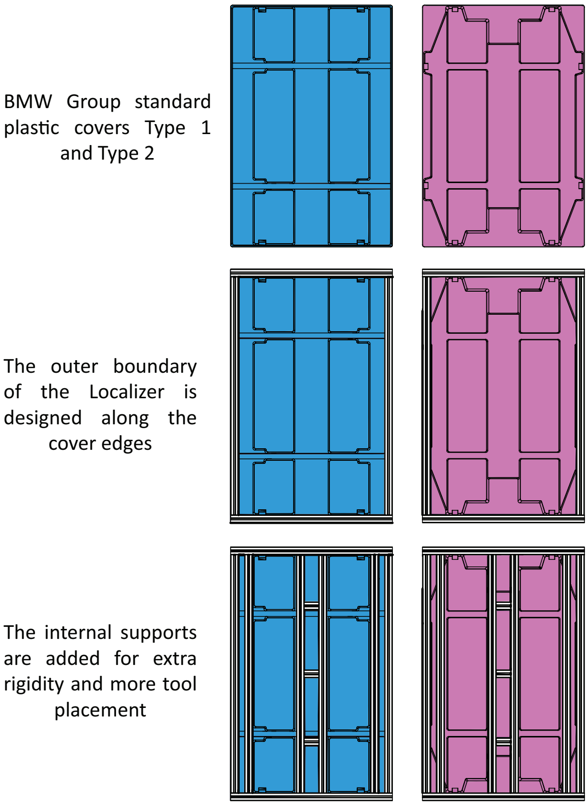

Fig. 2: The development steps of the Localizer's outer and inner components to fit both cover types.

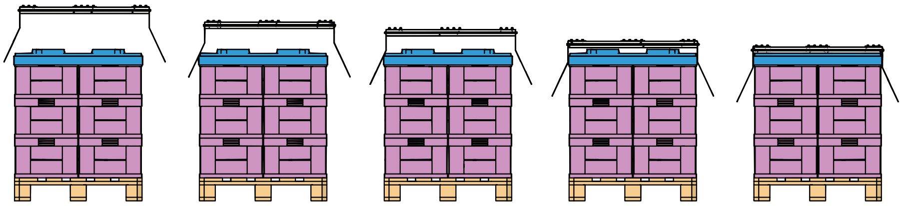

Fig. 3: A simulation sequence that illustrates the function of the tapered guides, which allow the Localizer to adjust its position on top of the cover, even in the presence of misalignment as a specified geometric tolerance.

3.1 Localizer Design

Following the generic design method proposed in Section 2, a localization structure is developed to accommodate incoming shipping pallets at the assembly plants of the automotive OEM partner. The configuration consists of standard Euro-Pallets where the part containers (also called ”KLTs”) are stacked then topped with plastic cover lids. There are two types of plastic covers, each having a different top surface geometry, which requires the Localizer design to accommodate both forms. Fig. 2 illustrates how the Localizer is designed to accommodate the two cover types. Both covers have the same outside-to-outside geometry, which allows the construction of one Localizer that engulfs both designs. At the same time, the extruded sections on the inside of the covers do not cause interference with the outer boundary, which allows finding a common space in both designs for placing the internal supports.

After establishing the Localizer design over both cover types, the tapered guides are integrated on the Localizer’s sides. The guides ensure that, as the Localizer moves downwards towards the plastic covers, it automatically adjusts its position on top. Fig. 3 illustrates how the tapered guides induce adjustment in the Localizer’s position in accordance with the assembly tolerance stack-up.

3.2 Cutting and Gripping Mechanisms

The principal approach in the straps cutting and gripping operation is to build on the covers’ geometry, thus eliminate the need for computer vision in strap detection, and ensure localized cutting and gripping with minimal tools actuation. This approach is customized based on the cover layouts by overlaying the cover designs and identifying the shared volumes where straps have a clearance relative to the covers, thus cutting and grabbing can be performed without causing damage to the cover’s surface and will be generic to all possible cover types, as shown in Fig. 4. Typically, the identified volumes are minimal, albeit they provide adequate stroke for the tools to account for possible strap deviation.

To select the cutting and grabbing end-effectors, different aspects related to the safety of operation, the number of needed actuators, geometry limitations, as well as the speed of the process are taken into consideration. The geometric con-

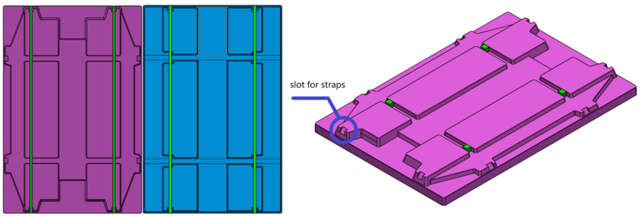

Fig. 4: Left: Top-view that shows the strap positions on the two cover types. Right: The identified shared volumes between the two cover types are shown in bright green.

straints are imposed by the width of the shared volume that dictates the tool's thickness, while the maximum strap deviation outside the shared volumes among the different cover types controls the tool's stroke. Proposed cutting and grabbing techniques span shear cutting such as scissors and blades that are actuated mechanically, pneumatically, or by reciprocating movement (Cheng et al., 2017); mechanical gripping such as clamps with locking mechanisms (Zhuang et al., 2013), and four-bar mechanism grippers (Hassan and Abomoharam, 2014, Saha et al., 2014). However, it is noted that mechanical solutions are not good candidates for cutting and grabbing since they require to be actuated vertically until they reach the gaps where cutting and grabbing should be performed, and horizontally to cover the entire volumes along the width, in addition to needing other actuators to perform the actual cutting and grabbing actions. Moreover, other techniques involving heat application (Imaizumu and Itoh, 2009) and laser-cutting approaches (Herzog et al., 2016) were also investigated. In this work, a customized heating solution that aims to embed the heated blade inside an insulating structure, and only starts heating when the blade reaches the straps, was also pursued. However, for safety considerations relative to fire hazards, a heat-based cutting solution requires specialized controllers to reduce the risk of fires, which are expensive and bulky. More importantly, this approach requires the straps to be in full tension, which is not always the case. After several iterations and testing of various design alternatives, the heat-based cutting solution was discounted.

After considering the size constraints, strap tautness, and the grabbing mechanism's pulling strength, we propose the following pneumatic solutions for strap cutting and gripping. Cutting is performed using an air nipper that consists of a size 50 nipper body and its corresponding blade, shown in Fig. 5. The blade's opening is 40 mm to allow for covering all possible strap deviations, and the thickness of the blade is 5.5 mm to fit in the designated gap. The cutting pressure of the air nipper is 4700 N, which guarantees quick and clean cutting of the plastic straps under consideration. The nipper is assembled on the Localizer directly using a long angle clamp, an elbow arm, and a nipper mount bracket.

Grabbing the straps is performed by the pneumatic sprue gripper shown in Fig. 6. The clamping force of the gripper is 142 N, which is adequate to grip all types of straps and pull them out if they get jammed between the pallet's surfaces. The gripper is attached to the Localizer using a long angle clamp and an elbow arm. The gripper's opening is 41 mm to account for all possible strap deviations, and its thickness is 12 mm to fit in the designated gap.

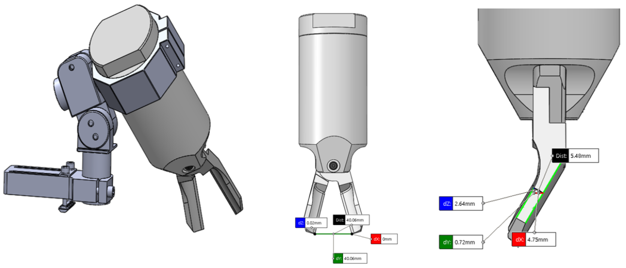

Fig. 5: Nipper assembly and dimensions, Nipper Body Part# SPT-50R, Blade Part# GSN-N30-AA (*Emicorp.com. EOAT Parts — EMI*, n.d.).

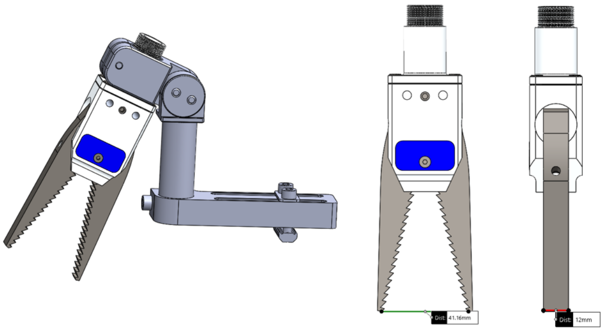

Fig. 6: Gripper assembly and dimensions, Part# GRZ-20-20-SL (*Emicorp.com. EOAT Parts — EMI*, n.d.).

The orientations of the nippers and grippers are optimized to twist the straps, but not squeeze them, as the tools approach the straps from the top. It is noteworthy to mention that the surface area between the straps and the gripper increases, which makes the strap feeding to the rollers (in the next step) more manageable. Different orientations of the nipper and gripper are considered to arrive at the optimal angle at which cutting and grabbing can be performed, without additional degrees-of-freedom. An optimal installation angle of 24°, shown in Fig. 7, achieves this purpose.

Consequently, the specified nipper can cut all types of plastic straps regardless of their shear strength, and the gripper has rubber sleeves that ensure minimal slippage and maximal pulling force. The nippers and grippers are installed to passively align above the straps as the Localizer localizes itself on both cover types, which eliminates the need for motorized actuation and additional degrees-of-freedom. Hence, combining the Localizer with the cutting and grabbing tools yields a smart ‘open-loop’ solution, shown in Fig. 8, which ensures precise cutting and grabbing of the straps.

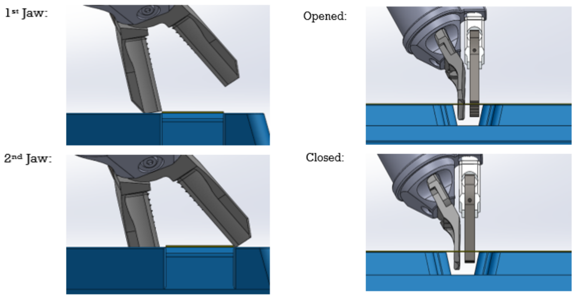

Fig. 7: The orientations of the nipper and gripper at 24° for precise cutting and gripping without extra actuation.

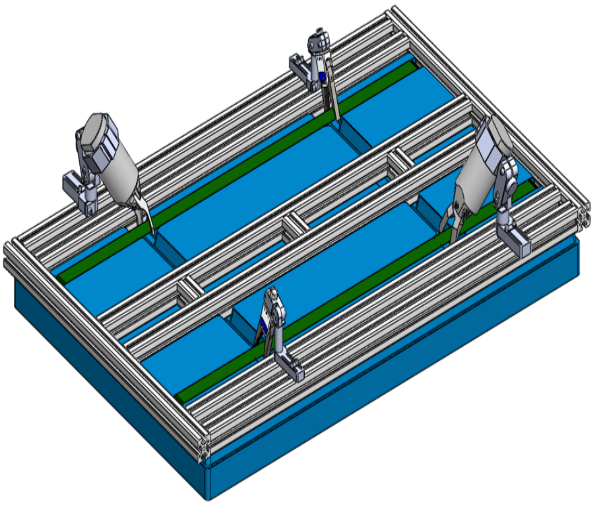

Fig. 8: The nipper and gripper assembled to the Localizer.

3.3 Disposing Mechanism

In order to find the optimal strap collection and disposal mechanisms, different de-strapping concepts are examined (Lile and Brown, 2003, Lisa, 1989, Vannice et al., 2015). The common aspect of the studied systems is the use of rollers to sweep the straps out of the system and feed them to granulators (e.g. shredders, choppers, or similar).

The adopted technique to dispose of the cut straps entails sweeping them in a horizontal motion and feeding them into rollers after clearing the way in front of the Localizer's vertical motion, as shown in Fig. 9. The designed mechanism consists of a sweeping arm that moves horizontally and a stationary disposal exit. Two idler rollers are attached to the sweeping arm and mounted to a shaft over the entire width of the frame using a ball bearing. The disposal exit is an external frame attached to the robot, which also has two rollers mounted using bearings and are driven in opposite directions: the upper roller rotates clockwise (CW), and the lower one rotates counterclockwise (CCW). The rollers have an outer layer made of rubber to provide a high gripping force that pulls the straps without slippage.

After the grippers grip the straps and the Localizer moves upward, the two straps are still held by their respective grippers, where each strap has a short end that dangles towards the cutting side and another longer end that is under the pallet. The gripper provides a clamping force that is large enough to ensure that the straps can be pulled even if they are stuck under the cargo; moreover, the rubber sleeves that coat the gripper fingers eliminate strap slippage. The sweeping arm moves and collects the straps by dragging them until they become sandwiched with the rollers on the disposal exit, as shown in Fig. 10. At this stage, the upper roller rotates to free up the short dangling part of the strap, and then the bottom roller rotates to dispose of the long extended parts of the straps. Finally, the straps are delivered to an industrial-grade shredder (not covered in this work) that granulates them.

3.4 Sensors

Eight limit switches are used to detect the target positions of the Localizer and sweeper arm as follows:

- Two limit switches are placed at the bottom of the Localizer to detect when it is in full contact with the cover.
- Two limit switches are placed at the Localizer's home position to indicate when the Localizer successfully arrives at its home position.
- Two limit switches at the disposal exit are used to detect when the rollers of the sweeper arm are engaged with the stationary rollers at the disposing frame.
- Two limit switches to indicate when the sweeper arm successfully arrives at its home position.

3.5 Actuators

A key design consideration of the devised Cutting Tool is the usage of minimal actuation, which helps in reducing initial and operating costs and achieving less maintenance and downtime. Overall, the Cutting Tool includes four electric motors and two pneumatic valves that are utilized as follows:

- A single servo motor is installed on top of the structure in order to perform the necessary ascension and descension function of the localizer. This vertical actuation, along with the tapered guiding plates, allow the localizer to accurately set itself on top of the pallet covers, thus eliminating the need for additional mechanisms to properly align the pallet inside the system.
- Two normally-open solenoid valves actuate the pneumatic nippers and grippers. Once the localizer fully and accurately rests on top of the covers, the first solenoid valve is actuated to allow the grippers to firmly grab the plastic straps. The second solenoid valve is then actuated to have the nippers cut the straps.

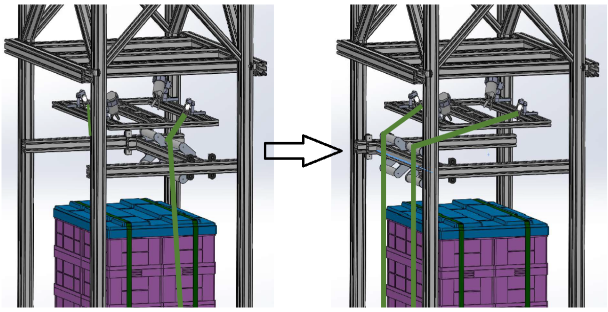

Fig. 9: The motion of the sweeping arm to collect the hanging straps (green) and feed them to the shredder (not shown).

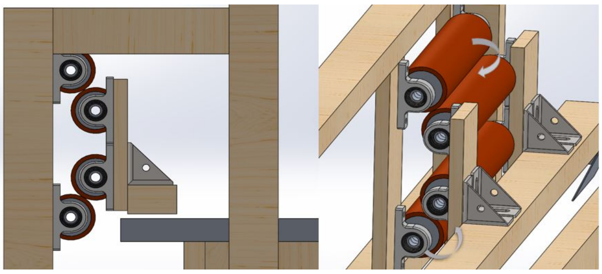

Fig. 10: The engaged rollers rolling the straps out.

- After the straps are cut and the localizer returns to its home position at the top section of the system, a servo motor actuates the strap-sweeping mechanism that moves across the structure to collect the dangling straps and sandwich them in between the rollers.
- Two stepper motors actuate the upper and lower rollers in the CW and CCW directions, respectively. This opposite rotation forces the straps through the rollers that feed them into the strap disposal system.

3.6 Automatic Pallet De-strapping Process

The de-strapping process, which is captured by the diagram in Fig. 11 and the flowchart in Fig. 12, details the working principle of the automatic pallet de-strapping system. The Cutting Tool relies on a single control signal from a light barrier to begin the de-strapping process. Once the light barrier detects a pallet inside the system's working space, it proceeds with a series of open-loop actions including localization, strap grabbing and cutting, and strap removal according to the sequence shown in Algorithm 1.

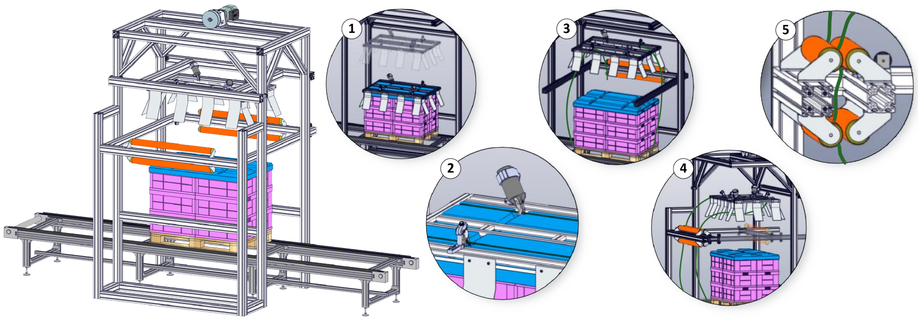

Fig. 11: An illustration of the Cutting Tool's working principle along with its individual components and sub-processes. (1) The localizer descends onto the top of the plastic covers. (2) The gripper and nipper grab and cut the straps, respectively. (3) The localizer ascends to its home position as the straps remain grabbed by the grippers. (4) The sweeping mechanism collects the straps and sandwiches them between the rollers. (5) The rollers roll the straps out of the Cutting Tool and feed them into a granulator (not shown here).

Algorithm 1: The de-strapping process algorithm.

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Step 1: Wait for the signal (e.g. light barrier) to indicate that the pallet has stopped;
Step 2: Start the process;
Step 3: Move the Localizer down;
Step 4: Wait for all limit switches to be depressed (Localizer in full contact with the
  cover);
Step 5: Stop the Localizer's motion;
Step 6: Actuate the gripper to grab the straps;
Step 7: Actuate the air nipper to cut the straps;
Step 8: Move the Localizer up to its home position;
Step 9: Wait for all the upper limit switches to be depressed (Localizer at its home
  position);
Step 10: Move the sweeper arm;
Step 11: Wait until the limit switches at the disposal exit are depressed, i.e. the
  sweeper arm reaches the disposing frame and engages the rollers;
Step 12: Stop the sweeper arm;
Step 13: Turn rollers on to start rotating;
Step 14: Actuate the gripper to release the straps;
Step 15: Stop the rollers after timeout indicating that the entire strap lengths have
  been fed into the shredder's opening;
Step 16: Move the sweeper arm to its home position,
Step 17: Wait until the limit switches at the sweeper home position are depressed,
  i.e. the sweeper arm reaches the home position;
Step 18: Stop the process and repeat from Step 1;
```

4 Customized Design Implementation

The proposed system design is applied to the two most common cover types that are used at the assembly plants of the automotive OEM partner. The top layouts of the two cover types are traced and overlapped to create a frame design that fits both covers, as shown in Fig. 13. It is noted that the frame needs to perfectly

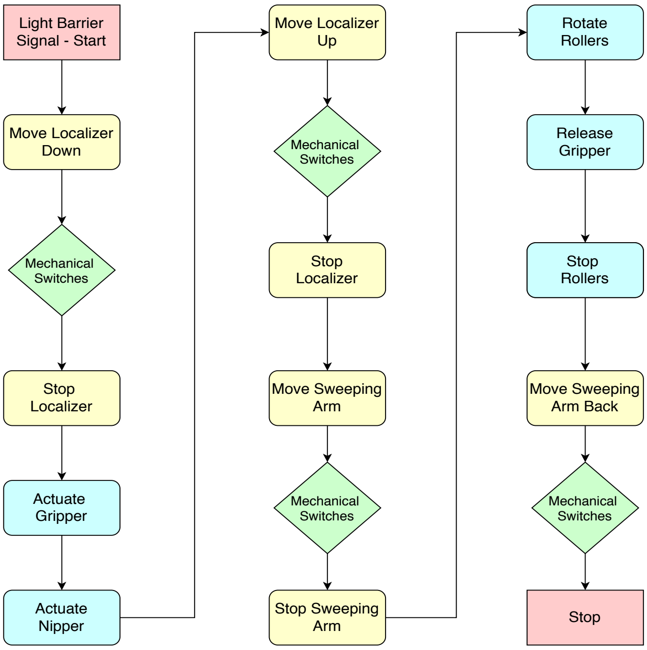


Fig. 12: The robotic de-strapping process flowchart.

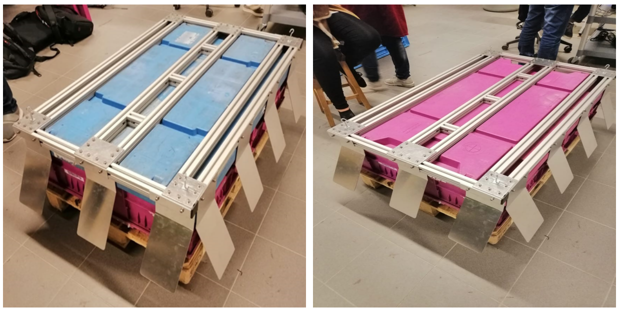


Fig. 13: The Localizer's fit on both cover types.

align with the covers to ensure a correct fit. The Localizer is constructed using 40 mm × 40 mm aluminum extrusions to ensure a rigid build, and 4 mm aluminum guides, which have a length of $36cm$ and a taper angle of 25° starting from the $13cm$ mark, to compensate for up to $10cm$ misalignment with the covers on each side given that the maximum possible misalignment of the pallets on a conveyor is $8cm$. The pneumatic nipper and gripper are mounted onto the Localizer using long angle clamps and elbow arms, as shown in Fig. 14. The pneumatic tools' air source is a 6 bar air compressor connected using spiral pipes, switches, and a pressure regulator.

The sweeping motion of the straps is realized by a mockup wooden bar with rollers attached to it, as shown in Fig. 15. The sweeping arm is connected to the

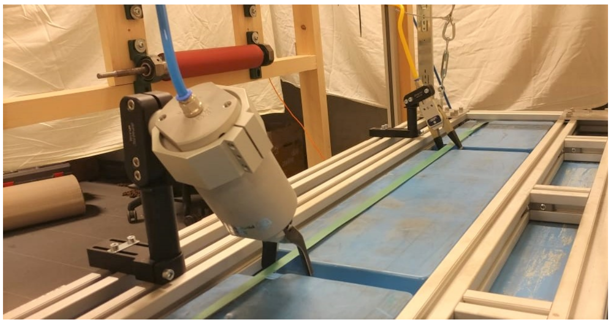


Fig. 14: The positions of the nipper and gripper after successful localization.

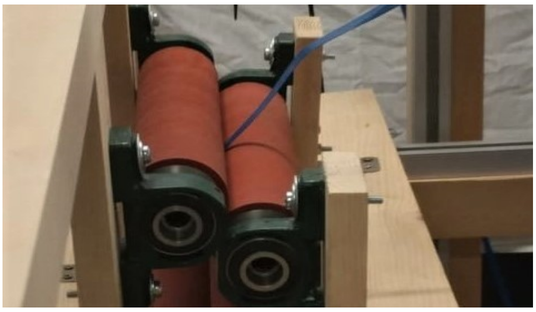


Fig. 15: The straps sandwiched between the upper rollers in preparation for being fed to the shredder.

frame using wheel attachments that roll inside aluminum guides along its length. Two other fixed rollers are mounted on the extended fixed frame on the disposal side. The four rollers are attached to the wooden bars using bearing housings. The two ends of the sweeping arm are connected to pulleys on the disposal side. Both pulleys are connected to a single shaft coupled to a small electric motor that moves the arm. The stationary rollers on the extended frame are rotated by coupling them to electric motors.

The various subsystems are assembled into a unified system to test the entire de-strapping process. The external frame is designed to fit, hold, and link all of the sub-processes together without interference during operation, and to provide a mounting structure that guides the Localizer's vertical motion. A custom cable lift mechanism is designed for this frame, and a square frame, mounted through wheel tracks to the inside of the frame's pillars, is connected to the Localizer at its four corners through steel cables. This connection allows for a steady vertical actuation of the Localizer, while giving it the freedom of motion to adjust for the possible deviations and rotations of the pallets. The disposal mechanism is attached to the square frame using telescopic tracks. A proof-of-concept prototype (Prototype-I) of the structure is built using Swedish pine wood, for a low-resolution prototype, to mount the subsystems on it as shown in Fig. 16.

Fig. 16: Mock-up Cutting Tool Assembly (Prototype-I).

5 Industrialized Prototype

The testing results of Prototype-I, which are subsequently presented in Section 6, were very encouraging and demonstrated that the localization process is highly reliable and repeatable. Accordingly, an industrialized version of the prototype was set up at an assembly facility of the automotive OEM partner, where the robot was constructed using rigid aluminum profiles and industry-grade robotic actuators. This gives the design and de-strapping process increased integrity as it eliminates issues that are attributed to the feeble wooden structure, which suffers from manufacturing errors and instability in the Localizer's actuation method. The second design iteration (industrialized version) is referred to as Prototype-II in this paper. It is noteworthy to mention that Prototype-II required minimal changes to the original design in order to ensure proper operation and to allow comparison between it and Prototype-I. This section describes how the system was designed and constructed in order to perform additional testing on the localization and de-strapping process at one of the assembly facilities of the automotive OEM partner.

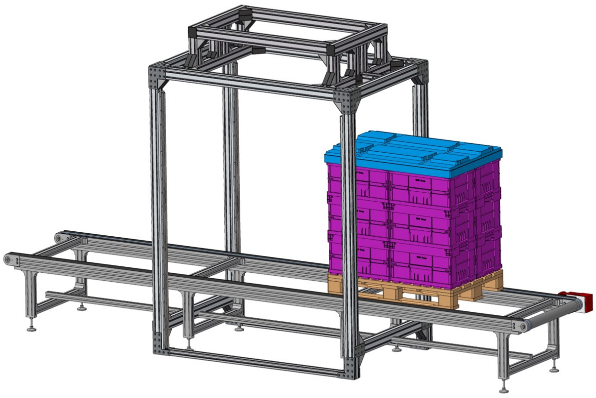


Fig. 17: The design of the main chassis of the cutting tool along with a pallet-carrying conveyor system.

5.1 Main Chassis

The proposed system was implemented on a decommissioned robotic platform that serves as the foundation of the Cutting Tool robot. To begin with, it was necessary to ensure that the system could accommodate the size of stacked pallets in its internal volume and a conveying system that passes through the robot, in order to transport the pallets in and out of the system. Also, it needed to have adequate height to allow the pallets to enter, get de-strapped, and proceed to the de-palletization process at the end of the conveyor line. The external chassis of the system was suitable for the required application with its outside-to-outside dimensions of 1.92 m × 1.2 m × 1.2 m (length × width × height). The main chassis should be large enough to accommodate the Localizer and the actuation system that allows it to move vertically inside the robot's frame. However, the original chassis did not have sufficient height to accommodate this subsystem, thus an additional section was designed and installed on top of the main chassis, as shown in Fig.17. The new section added another 0.28 m to the chassis, which reached a height of 2.28 m that is considered acceptable per the applicable safety guidelines. The chassis is centered on top of the location where the stacked pallets are intended to stop. This ensures that the gaps between the stopping point and the maximum range of the Localizer's ability to handle misalignment are minimized. Fig.17 shows a model of the main chassis of the robot, with the added section on top, along with a conveyor passing through it.

5.2 Vertical Actuation System

The additional section on top of the main chassis serves as a structure that houses the Localizer's vertical actuation mechanism. This added section is crucial for the robot's function since it determines the accuracy of the localization process, which depends on multiple factors including how level (parallel to the ground plane) the Localizer is during its downward motion, the speed at which it travels, and the initial alignment (or lack thereof) of the Localizer with the stacked pallet underneath it. The alignment issue is addressed by centering the holding structure and installing it precisely on top of the main chassis. As for the speed of descent, it is regulated by electric motors that can be controlled and fine-tuned until an optimal speed is attained. The levelness of the Localizer as it moves down is the main challenge that must be addressed.

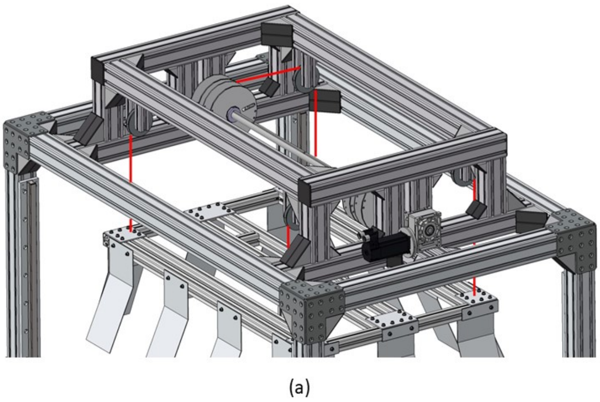
In Prototype-I of the Cutting Tool, the Localizer is connected by steel cables from its four corners, and the cables are all connected to a central point where the vertical motion actuation is performed. However, due to manufacturing tolerances and the lift mechanism design, the Localizer may be skewed as it approaches the top covers. To tackle this issue, the vertical actuation mechanism is designed to be more stable and reliable in Prototype-II. This is achieved by extending a steel shaft between the two ends of the top structure, where the shaft carries four separate spools that are used to wind and unwind the equal-length steel cables as the Localizer moves up and down. These cables are guided into pulleys attached on the top section in a way that ensures that the cables extend vertically from each corner of the Localizer, as can be seen in red in Fig. 18(a). The benefit of this configuration is that the Localizer can be actuated using only one motor, which is connected to one of the ends of the extended shaft, and this satisfies one of the main aims of the design of this robotic system where minimal actuation is to be used. Here, a key factor in making this possible is the employed method to have the cables initially wound around the spools. Fig. 18(b) illustrates how the steel cables on adjacent spools are to be guided into the pulleys in a way where one flows above the first spool and the other flows below it. This ensures that the cables have the same winding and unwinding behavior as the shaft rotates.

5.3 Strap Sweeping Mechanism

The structure that is used to be retrofitted with the Cutting Tool consists of the three principal axes of a Cartesian robot along with their respective motors and controllers. Accordingly, the strap sweeping mechanism is adapted to the axis that allows for travel across the structure's width. The sweeping motion is achieved by employing a rack-and-pinion that is driven by a single motor that is connected to the pinions through coupling shafts. Similar to Prototype-I, the rollers of Prototype-II are installed on the moving structure with another set of identical rollers fixed at the end of the rack. When the straps are cut and the Localizer returns to its home position, the first set of rollers sweep across the structure, collect the straps, and 'sandwich' them in between the second set of rollers. Note that due to geometrical constraints imposed by the original system, the sweeping mechanism is lowered and raised along the vertical axis to prevent clashing with the Localizer.

5.4 Software and Control

The electrical wiring and controllers are set up on the system following the hardware installation. The focus was more on design verification rather than software



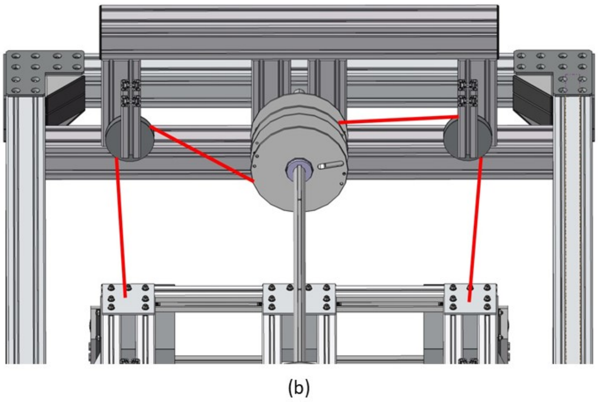


Fig. 18: The design of (a) the vertical actuation system and (b) the cable winding scheme.

and automation, and thus the control system and actuation schemes were realized in a simple and practical manner. The motors are controlled by "miControl" motor controllers, which feature a built-in motion processing unit for easy programming and provide a user interface to command the motors and read sensor measurements such as motor speeds and displacements. The motor controllers are connected to a computer using a Controller Area Network (CAN) bus interface.

5.5 Overall Assembly

Since Prototype-II is tested in a workshop, the tests cannot be performed with a conveyor passing through the robot. Instead, the pallet is set on a movable platform that is raised to a height that equals that of the conveyors used in the designated assembly facility of the automotive OEM partner. Fig. 19 shows the full assembly of the Cutting Tool robotic system that was implemented at the automotive OEM partner.

Fig. 19: The Cutting Tool assembly (Prototype-II) as implemented at one of the assembly plants of the automotive OEM partner.

6 Testing Results and Discussion

Extensive testing is performed on both prototypes of the Cutting Tool to validate their designs and evaluate their performances. Prototype-I is built and tested in a university laboratory with a total of 352 tests, split as 200 pallets with blue covers and 152 pallets with pink covers. The second industrialized prototype is built at the robotics department of the automotive OEM partner, it was subjected to 10 tests daily, split in half between pallets with blue and pink covers, over a period of one and a half months, amounting to 300 tests overall. The testing results of Prototype-I and Prototype-II are listed in Table 1.

During testing, the systems were subjected to real-life conditions that closely mimic the assembly plant conditions in terms of the pallet's location under the system and possible misalignment ranges and orientations. The localization testing was performed in multiple settings where the pallet's misalignment was up to 10 cm along the forward direction of the conveyor and up to 5° tilt angles. Also, the cutting and grabbing subsystems were exposed to different types of straps (plastic, fabric, nylon, among others), and they were artificially moved inside their designated slots on the covers by up to 40 mm deviations with various strap tension levels (full tension, loose, or even twisted).

6.1 Testing Results

The testing results of Prototype-I showed an appreciable number of failures in the localization, cutting, and grabbing sub-processes. The failures are mainly at-

Table 1: Number of failures and corresponding success rates (%) for the different sub-processes of Prototype-I (rows 3-8) and Prototype-II testing (rows 10-15).

Cover Type (Number of Pallets)	**Sub-processes**					
Prototype-I Testing	***Localize***	***Cut***	***Grab***	***Drag***	***Sweep***	***Dispose***
Both Covers (352 pallets) No. Failures	32	25	17	7	12	51
Success Rate (%)	90.90	92.89	95.17	98.01	96.59	85.51
Blue Covers (200 pallets) No. Failures	13	12	7	4	8	29
Success Rate (%)	93.50	94.00	96.50	98.00	96.00	85.50
Pink Covers (152 pallets) No. Failures	19	13	10	3	4	22
Success Rate (%)	87.50	91.44	93.42	98.03	97.37	85.53
Prototype-II Testing	***Localize***	***Cut***	***Grab***	***Drag***	***Sweep***	***Dispose***
Both Covers (300 pallets) No. Failures	6	10	5	5	7	15
Success Rate (%)	98.00	96.67	98.33	98.33	97.67	95.00
Blue Covers (150 pallets) No. Failures	3	4	3	2	3	8
Success Rate (%)	98.00	97.33	98.00	98.67	98.00	94.67
Pink Covers (150 pallets) No. Failures	3	6	2	3	4	7
Success Rate (%)	98.00	96.00	98.67	98.00	97.33	95.33

tributed to the large tilt angle in the Localizer during its descent towards the top covers. Since the system's mounting frame is constructed out of wood (non-rigid structure) and has manufacturing and assembly errors, the guiding frames do not provide stable linear motion during the process. It is important to note that although the cutting and grabbing failed a few times, most of their failures are not inherent to these two processes, but contributed to incorrect initial localization. Regarding the straps disposal mechanism, testing showed a high failure rate since the straps slid outside the grip of the rollers' outer edges. This is also due to misalignment in the installation of the rollers, which was improved upon in the second prototype.

For the industrialized prototype version that was implemented at an assembly facility of the automotive OEM partner (Prototype-II), the testing results improved significantly, as shown in Fig. 20, since the system was built on a rigid chassis with rigid movement and actuation. This eliminated sudden jerks in the descending motion of the Localizer, resulting in an increase from 90.90% to 98.00% in the localization success rate. This in turn directly affected the success rate of the cutting and grabbing mechanisms, which rely on accurate localization to perform their intended functions. Additional improvements in the straps disposal

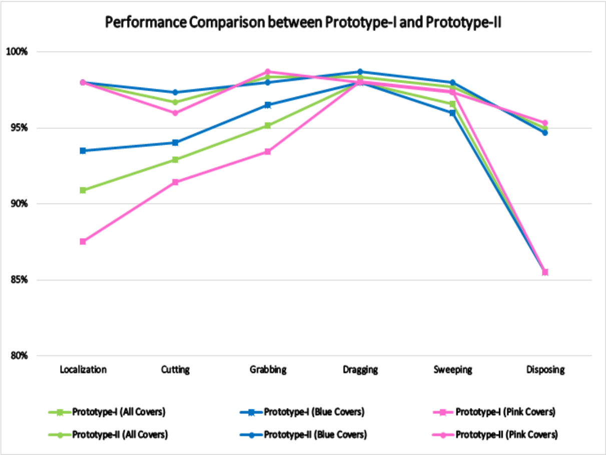


Fig. 20: Evolution of the various subsystems' performances from Prototype-I to Prototype-II.

mechanism also raised the success rate to 95.00% as compared with 85.51% in the Prototype-I. The failures in the cutting, grabbing, sweeping, and disposing systems are mainly due to the unpredictable behavior of the plastic straps since their flexible nature significantly changed their expected positions in a few of the test cases.

6.2 Discussion

The obtained results demonstrate that the proposed passive (open-loop) localization system is very effective at establishing a fixed reference on top of stacked pallets. It leads to a reliable and repeatable de-strapping process with high success rates. The recorded disparity between Prototype-I and Prototype-II emphasizes the need for the system to have appropriate stiffness, rigidity, and tolerances in order to decrease the likelihood of failures, especially in the critical localization phase, since a failure in this initial phase would prevent the remaining stages from being executed successfully. Prototype-II verified that the Localizer can indeed be accurate enough for industrial applications, as it only failed to set on covers in very few tests. We note that most of the failures were due to jams between the guides installed on the Localizer's corners and the covers' corners, when the tilt angle about the vertical axis was larger than the 10° design limit. On the other hand, all tests where the Localizer descended on pallets with acceptable tilt margins experienced no failures. For added redundancy and failsafe purposes, an error handling mechanism can be implemented, whereby successful localization feedback can be obtained directly from limit switches that are placed on the bottom surface of the localizer. In case of incomplete localization, the system can use this feedback signal to re-adjust the positioning of the localizer before proceeding with the remaining steps.

The grabbing mechanism can be optimized by sizing the gripping tool in a manner that ensures that the surface area between the gripper and the strap is maximized, thus slippage between the two surfaces is minimized. As for the nipper, optimal shear forces can be obtained by adopting higher pneumatic pressure capacities to account for the various strap materials and thicknesses.

Last but not least, it is important to note that different straps are made of different materials, and as such, the nature of their movement once cut can be highly unpredictable. This may lead to a limited number of failures in the strap collection and removal phase, a matter that will be tackled in future iterations of the proposed system design.

7 Conclusion

The design and prototyping of a robotic system for the automated de-strapping of pallets are presented in this paper. A smart, low-cost, and passive design is devised to cut, grab, and dispose of the straps from incoming pallets, with the unique feature of a reliable open-loop scheme that employs the least number of sensors and motorized actuators. The two main novelties of the proposed design are the robustness of the strap localization without the need for computer vision and a large number of degrees-of-freedom, and the critical placement and choice of the cutting and gripping tools to minimize the number of needed actuators.

Following the success of the system in performing its intended task in laboratory and industrial settings, the team will further investigate a method to offer an additional feature of removing and storing the plastic covers on top of the pallets. This will be achieved by adding more functionality onto the Localizer in order to benefit from the already well-established reference on top of the covers.

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