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Development of a Mobile Robotized System for Palletizing Applications

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Abstract—In this paper we present the architecture of a mobile robotized system for logistic applications. The task to be performed consists of extracting items from homogeneous pallets and, subsequently, assembling new pallets with heterogeneous goods. A further requirement is the capability of a safe human-robot interaction. For such purposes, we employ an autonomous mobile robot, equipped with a serial collaborative arm, a lifting mechanism, and a multi-sensor vision apparatus. The overall system is conceived to handle packages by dragging them aboard the mobile platform. Accordingly, we integrate a conveyor, whose vertical position can be adjusted by means of a scissor lifting mechanism. Thus, packages from different overlapping layers, which compose a generic pallet, can be introduced and stored on board.

Index Terms—Collaborative Robots, Mobile Robots, Industrial Logistics, Palletizing, Dragging Manipulation.

I. INTRODUCTION

This paper proposes an automated solution that concerns industrial storage and distribution. The task to be performed is divided in two subsequent steps, herein referred to as *depalletization* and *palletization*, respectively. The former consists in decomposing homogeneous pallets, whereby each one of them contains several overlapped layers of identical items arranged in form of standard packages, e.g. cardboard boxes, bottle packs, etc. The latter, conversely, refers to composing new pallets that comprise heterogeneous goods assembled from different initial pallets.

Since the advent of industry 4.0, automated robotic solutions have been receiving an ever-increasing emphasis among the most disparate industrial environments [1]. In addition, the growing demand of improving both labour conditions and industrial efficiency has laid the groundwork for the inception of collaborative robots (*cobots*), which are designed to safely cooperate with human workforce [2]- [3]. Moreover,

the requirement of optimizing the transport and distribution of products, along with the confluence of inexpensive wireless communication and improved computational power, has encouraged the employment of autonomous guided vehicles (AGVs) within modern automated warehouses [4]- [5]. However, AGVs are limited to follow a guided track in the working area. Accordingly, the need of a different path may imply an alteration of the facility infrastructure. In order to enhance flexibility and robustness, autonomous mobile robots (AMRs) have been introduced in modern industrial contexts [6]- [7]. By virtue of suitable sensors, data processing and mechanical design, they have the capability of performing self-localization as well as autonomous navigation within the environment [8]. Recently, industrial and scientific research has been deploying several efforts towards the potential interoperability between cobots and mobile platforms for logistic applications [9]- [10].

In the area of interest, Bonini et al. [11] proposed an example of mobile collaborative depalletizer system. The presented hardware consists of an elevation apparatus, which avails of pneumatic grippers to lift products from their top surface, a powered conveyor, which dispatches them to their final destination, and a sensor equipment, which allows for the interaction of the system itself with the surrounding environment. In this case, by analogy with further industrial scenarios [12]- [13], items are handled by employing vacuum gripping technology. However, such a manipulation method is restricted to those packages that are able to sustain their overall weight. Matsuo et al. [14] developed a mobile humanoid robot endowed with a self-weight compensation apparatus. In this use case, the dual-arm vacuum grabbing system prevents items from possible risks of overturning, thus requiring a suitable vacuum source. Therefore, even this solution may be deficient in flexibility. Besides, handling methods based on vacuum technology are challenging to be implemented on AMRs, especially on small-sized units.

In order to exceed the above-mentioned limitations, an

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alternative approach of manipulation is based on dragging goods aboard the mobile robotized system [15]. This choice allows the overall load that acts upon the gripper to be reduced, since the gripper must not support the payload weight, in opposition to common industrial solutions, whereby the robot lifts the entire product weight¹. In addition, the presence of a support beneath the package surface reduces the risk of falls.

The system developed herein is conceived for working in this latter scenario. More precisely, we propose a prototype, denoted as *P-COORSA*, whose hardware comprises an AMR, a cobot arm, a lifting mechanism, and a multi-sensor vision apparatus. The latter includes a fixed 3D Time-of-flight camera and an eye-in-hand 2D camera [16]. Auxiliary mechatronic components are integrated to enable supplementary functionalities, such as the safe transfer of packages on board.

The items to be manipulated in the COORSA project² are cardboard boxes with assigned dimensions. Each pair of layers in mutual contact are assumed to be separated by a sufficiently rigid interlayer. Items from different layers have to be dragged from the pallet to the system. Accordingly, the latter should have the capability of receiving boxes from different height levels. We propose a lifting mechanism whose vertical motion is enabled by a scissor linkage. An idler-roller conveyor, attached at the top of the lifting mechanism, allows the boxes to be transferred and stored on the system. The conveyor is equipped with a swivel hatch, in order to inhibit possible falls of packages while the AMR moves. A pair of rotating clips are proposed to prevent interlayers from sliding while the final boxes of a layer are processed.

The paper is structured as follows: Section II presents the task specifications, and the hardware selection. Section III describes the integration between the collaborative arm and the AMR. Section IV is devoted to the actuation apparatus, and emphasizes the working capability of the overall system.

II. SYSTEM OVERVIEW AND HARDWARE SELECTION

In compliance with *COORSA* design specifications, packages are represented by cardboard boxes, whose dimensions are 150 mm × 250 mm × 300 mm, with their mass ranging from 2 kg up to 10 kg. Boxes are stacked upon standard EPAL 800 mm × 1200 mm, in such a manner that they form at most 4 overlapped layers separated by rigid interlayers. The overall depalletizing task may be subdivided into the following sequential steps:

- self-localization within the workspace;
- autonomous navigation towards the pallet whence collecting the item;
- detection of the spatial location of the package;
- object extraction from the pallet and placement on board;

This paper deals with the last step only. Other steps are described in other contributions [16].

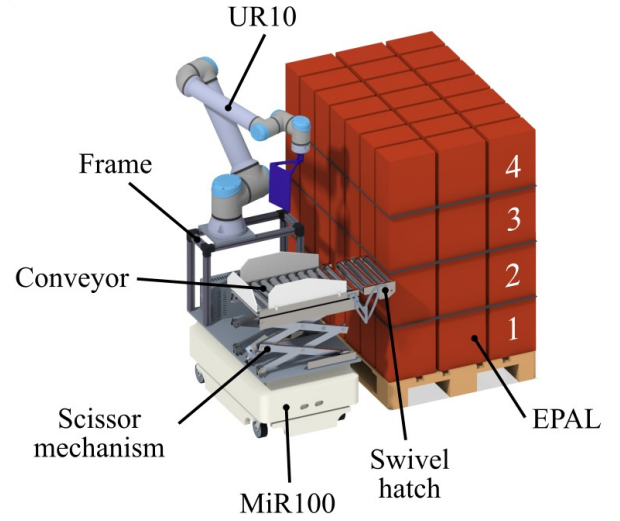


Fig. 1. Conceptual Scheme.

We propose to use a serial collaborative manipulator UR10, provided by *Universal Robots*³, installed on a *MiR100* AMR supplied by *Mobile Industrial Robots*⁴. In addition, the adopted method of manipulation requires a system that may receive and store one or more boxes aboard the AMR. We select a conveyor attached on a support that can move along the vertical direction. The resulting lifting mechanism (LM) is able to approach an arbitrary layer of boxes (Fig. 1). The terminal part of the conveyor, referred to as *swivel hatch* (SH), which is adjacent to the pallet during the manipulating stage, is able to be set in two different configurations. Indeed, whenever a box has to be moved either from the pallet to the platform or vice-versa, the SH is lowered and set adjacent to the pallet at the same height of the layer to be manipulated. Otherwise it is lifted, hence preventing the boxes from possible falls.

A. Selection of the Conveyor-Lifting Device

In this Subsection, we discuss some possible solutions with regard to the electromechanical drive selection for the conveyor lifting mechanism.

1) *Recirculating Ball Bearing Guide (V1)*: A recirculating ball bearing guide, driven by a brushless motor has the advantage of being a commercial component. Moreover, the motor position is fixed with respect to (w.r.t.) the AMR frame. Thus, its center of mass may be located in the lower area of the LM, in order to enhance the overall system stability. Nevertheless, the LM frame needs to be sufficiently tall to allow for the reachability of the upper layer and may interfere with the robot workspace. Lastly, the adoption of a double frame in parallel connection may be required to increase the LM bending stiffness (Fig. 2).

2) *Belt Driven Mechanism (V2)*: Alternatively, the guide actuation may rely on a belt mechanism. Also in this scenario the motor position is fixed w.r.t. the AMR frame. The belt

¹www.easyrobotics.biz/products/robot-arms/easypalletizer/
www.palletizur.com/#two

²<http://www.coorsa.it/>

³www.universal-robots.com/it/prodotti/robot-ur10/

⁴www.mobile-industrial-robots.com/it/products/mir100/

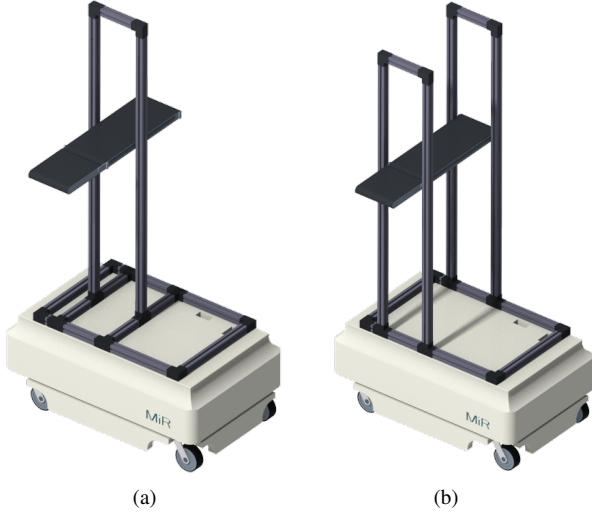


Fig. 2. Frame Configurations: (a) Single Frame (b) Double Frame

transmission commonly has a limited weight. Conversely, the presence of a double frame may likewise be needed, thus reducing the robot workspace.

3) *Telescopic Guide (V3)*: A linear telescopic guide may require the installation of multiple synchronous actuators. This solution results in the LM frame not having constant dimensions. Hence, when the LM frame is not in the maximum extension configuration, the interference with the cobot workspace is reduced. Even in this case, the overall stiffness may require to be enhanced by employing a double frame.

4) *Scissor Lifting Mechanism (V4)*: A scissor lifting mechanism (SLM) represents a widespread solution among different application domains, e.g. public transport [17], rehabilitation [18], etc. Similarly to case V3, the resulting LM frame brings the advantage of having variable dimensions. The main drawback is the requirement of a bespoke design.

The assessment of the best solution is carried out on the basis of the following criteria (Tab. I):

- T_1 : simplicity of design;
- T_2 : interference with the cobot workspace;
- T_3 : height of the motor center of mass;
- T_4 : issues induced by a double frame.

Each solution is ranked as acceptable (+), unacceptable (-), or requiring further study (!) for each criterion. The outcomes of the analysis are reported in Tab. I. Since both the Telescopic Guide and the SLM show a similar result, a further study needs to be performed. More precisely, we define more targets and assign a corresponding weight W (Tab. II):

- O_1 : simplicity of design $W = 0.20$;
- O_2 : simplicity in integration with the conveyor $W = 0.25$;
- O_3 : number of required motors $W = 0.25$;
- O_4 : issues induced by a double frame. $W = 0.30$;

Each target is assigned a score from 1 to 4. According to the chosen criteria, the best solution is represented by the SLM (Tab. II).

TABLE I
SELECTION DIAGRAM FOR THE LM

	T_1	T_2	T_3	T_4
V1	+	-	+	-
V2	+	-	+	-
V3	+	+	+	!
V4	!	+	+	+

TABLE II
CHOICE DIAGRAM OF THE LM

	O_1	O_2	O_3	O_4	TOT
V3	4	2	2	2	2.40
V4	2	3	4	3	3.05
W	0.20	0.25	0.25	0.30	

B. Selection of the Moving Conveyor

Once the LM is established, we need to select the conveyor to be attached upon the upper platform of the LM itself. Specifically, we discuss two solutions, i.e. an idler-roller conveyor (IRC) and a motorized belt. The former is a cheaper solution, but it needs an external system, e.g. the cobot, to carry out the task. In addition, a suitable apparatus may be required to constraints the boxes aboard, since they might strike within the conveyor while the AMR moves.

Otherwise, in the event of using a motorized belt, the higher friction forces between the belt and the boxes may prevent them from moving, and the operation of handling the items above the platform could be performed by the belt. However, this solution is more expensive and the motor center of mass would be close to the upper platform of the LSM, thus penalizing the system stability. We select the IRC. Indeed, beyond the cost-effectiveness, the higher is the number of the operations performed by the robot, the less complex is the functionality required to auxiliary components.

C. Selection of the Swivel Hatch

The integration of a swivel hatch (SH) is needed to both reduce the footprint of the system while the AMR moves and constrain the boxes within the IRC. For the sake of simplicity, lightness and cost-effectiveness, we only discuss passive solutions. All mechanisms proposed in this analysis are four-bar linkages (FBL). The initial FBL (L1) is composed of three revolute joints and an intermediate prismatic joint, which is made by a gas spring (Fig. 3(a)). This solution is compact and light-weight. Nevertheless, the mechanism may interfere with the cobot workspace. An alternative mechanism employs a FBL that comprises four revolute joints, in two distinct configurations, namely L2 (Fig. 3(b)) and L3 (Fig. 3(c)). The distinguishing feature of the solution in (Fig. 3(c)) is that the coupler and the crank are placed in a cross-configuration. In this case, the frame may be placed below the conveyor without interfering with the cobot workspace. In addition, the mechanical stiffness is higher w.r.t. the previous cases. The evaluation of the best solution is performed on the basis of the following benchmarks, which are related to a corresponding weight (Tab. III):

TABLE III
CHOICE DIAGRAM FOR THE FBL

	O ₁	O ₂	O ₃	TOT
L1	3	3	2	2.65
L2	3	3	2	2.65
L3	2	4	3	3.05
W	0.30	0.35	0.35	

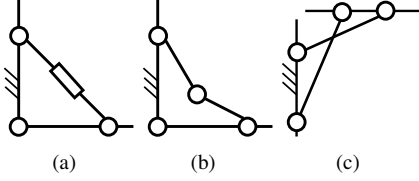


Fig. 3. Three Different FBL Configurations: (a) 3 Revolute Joints and 1 Prismatic Joint (b) 4 Revolute Joints; (c) Crank and Rocker Member in Cross-Configuration.

- O₁: simplicity of design $W = 0.30$;
- O₂: interference with the cobot workspace $W = 0.35$;
- O₃: mechanical stiffness $W = 0.35$;

The results of this analysis are displayed in Tab.III. The best solution is L3 .

III. SELECTION OF THE COBOT BASE

Several architectures are analyzed to integrate the cobot and the lifting device, since this aspect may influence the operational capability of the overall system.

A. Cobot on a fixed support

A fixed frame, installed alongside the LM, is proposed to sustain the cobot (Fig. 4). The support may be composed of commercial links and the space below may be exploited to integrate additional components, such as the cobot controller. During task execution, the LM raises progressively, whereas the overturning stability is not furtherly penalized by a possible ascent of the cobot base.

B. Cobot upon the LM

The cobot may be attached on the upper platform of the LM (Fig. 5). In this case, throughout the manipulation of all items, the mutual position between each layer of boxes, the conveyor and the cobot base would be invariant w.r.t. the platform height. Therefore, such a solution may simplify the task execution by reducing it to a bidimensional problem. However, this approach may also imply several shortcomings. The LM actuation apparatus would have to introduce an extra amount of energy to lift the robot; the limited accessible space on board may preclude the integration of additional components; meanwhile the LM rises, the system stability progressively decreases.

C. Cobot on a telescopic guide

The vertical motion of the cobot base may be controlled by an automated telescopic guide (Fig. 6), thus being decoupled

TABLE IV
CHOICE DIAGRAM FOR THE COBOT BASE

	O ₁	O ₂	O ₃	O ₄	TOT
C1	4	2	4	4	3.50
C2	2	2	2	1	1.85
C3	2	4	4	3	3.15
W	0.40	0.25	0.20	0.15	

from the LM actuation. We consider a commercial component, denoted as Lift Kit supplied by SKF⁵. Accordingly, the cobot has an additional degree of freedom, which extends its workspace. Since the Lift Kit stroke can range from 500 mm up to 900 mm, three boxes in a single row may be directly processed, whereas in both C1, C2 (Tab. IV) the AMR would be able to only handle the closest two boxes. Nevertheless, this potential benefit may result in the overall center of mass being located excessively upwards, hence worsening the system stability. In addition, installing two independent actuators penalizes cost-effectiveness.

The most suitable solution is evaluated in compliance with the following weighted criteria:

- O₁: overturning stability $W = 0.40$;
- O₂: cobot workspace $W = 0.25$;
- O₃: space availability on board $W = 0.20$;
- O₄: simplicity and cost-effectiveness $W = 0.15$.

The optimal solution is C1 (Tab. IV).

D. Selection of the Optimal Layout

Due to the rectangular footprint of the AMR, the cobot and the LM may be installed aboard the AMR in two different layouts, referred to as longitudinal (LL) (Fig. 4) and transverse (TL) (Fig. 7), respectively. Though the former ensures an enhanced stability under working conditions, the possible interference between the IRC and the cobot limits the base joint rotation (Fig. 8(a)), thus inhibiting the boxes to be handled along the entire IRC length. In addition, the possible demand of introducing the boxes onto the IRC with both feasible orientations (Fig. 9(b)) as well as the need of not exceeding the internal limits of the cobot workspace (Fig. 8(b)) may require the IRC to be expanded beyond the AMR footprint (Fig. 9(a)).

The TL allows to overcome such limitations as a result of a larger mutual distance between the cobot and the LM. However, the AMR navigation may be more challenging, since Mir100 is not endowed with an omni-directional steering system and, therefore, cannot directly advance towards the pallet.

In the case at hand, the presence of a non-actuated conveyor on the LM promotes to implement the TL, otherwise the boxes may not be processed adequately. Such a disposition would also provide a wider available space on board.

IV. ACTUATION AND WORKING CAPABILITY

Once the hardware is selected, we focus the analysis on the actuation system. The linear actuator T2AP, provided by

⁵www.skfmotiontechnologies.com/en/nl/products/telescopic-pillars/liftkit

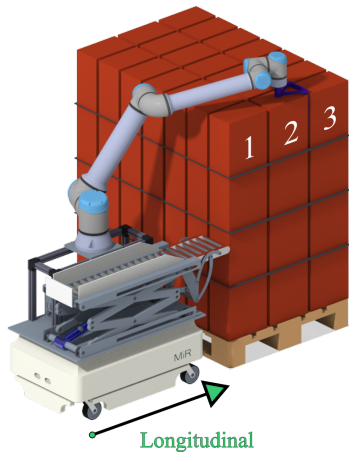


Fig. 4. Configuration 1: Cobot on a Fixed Base.

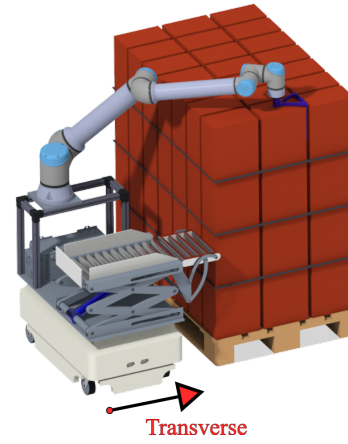


Fig. 7. Configuration1: Transverse Layout.

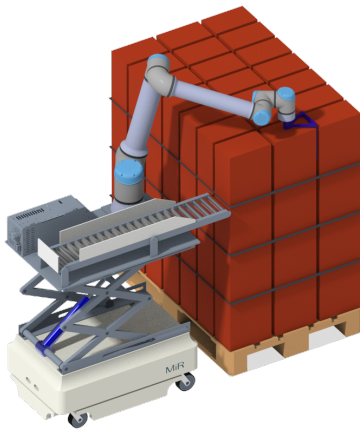


Fig. 5. Configuration 2: Cobot upon the LM.

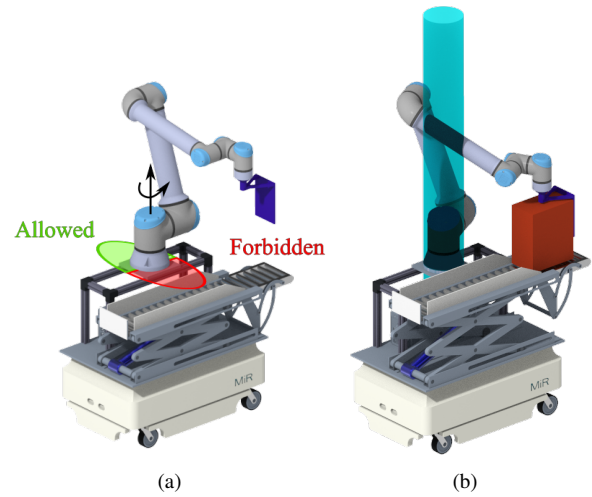


Fig. 8. Cobot Working Limits: (a) Base Joint Rotation (b) Internal Workspace.

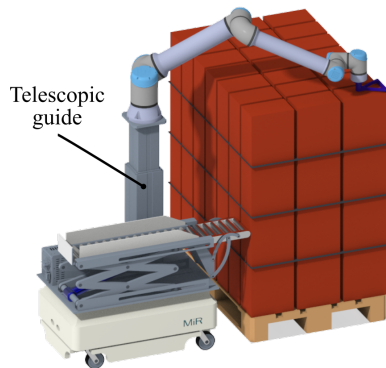


Fig. 6. Configuration 3: Cobot on a Telescopic Guide.

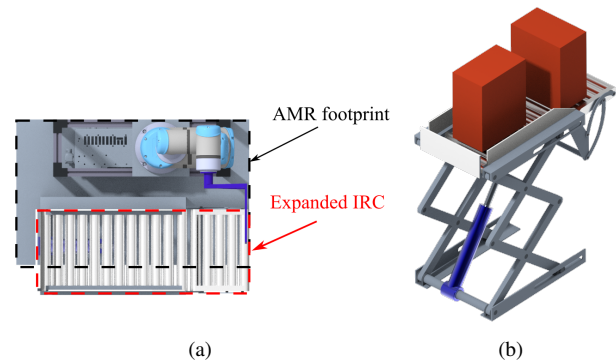


Fig. 9. Expanded IRC Width: (a) AMR Footprint Excess (b) Feasible Boxes Orientations.

TiMotion⁶, powers the SLM, which can withstand external loads, applied on the IRC, up to 30 kg. On the other hand, for the SH motion, we propose a subactuated solution that exploits the linear horizontal displacement of the SLM upper prismatic joint (Fig. 10). By employing a suitable rod-crank

mechanism (RCM), a linear motion can be converted into an angular rotation of the FBL crank member. During the SLM ascent, the displacement s (Fig. 10) increases and a torsion spring drives the SD into the open position, otherwise the SD converges into the close configuration with the spring being counteracted by the SLM itself.

The developed system is able to introduce the items onto the IRC in both possible orientations. Since the IRC length is 500 mm, up to 3 boxes can be contained on board, as long as their larger sides are normal w.r.t. the longitudinal direction of the IRC. Otherwise, the alternative feasible orientation limits the IRC capacity to 2 boxes.

It is worth observing that while the AMR remains still, the workspace of the current UR10 cobot allows only the 2 boxes closest to AMR to be reached and dragged on board (Fig. 7). Accordingly, the handling of the 3rd box in a package row requires the re-positioning of the AMR on the other side of the pallet. This shortcoming can be overcome by using a cobot with a longer reach, preferably mounted on a larger AMR. Another limitation comes from the fact that the shortest height of the conveyor (due to the heights of the Mir100 AMR, 352 mm, and the completely-folded SLM, 160 mm) makes it impossible to process the lowest two layers, if the pallet is laid on the ground. The current system, based on a Mir100 AMR and a UR10 cobot, is able to process only two layers of boxes, placed on a pallet installed on a dais raised 400 mm from the ground. A problem might occur to the interlayer during the manipulation of the last boxes contained in a generic layer. Indeed, friction phenomena might result in an undesired sliding of the interlayer. Therefore, we propose a pair of rotating clips, able to apply a normal force upon the interlayer surface, thus preventing it from moving (Fig. 11). A simulation of the system working principle is available in [19].

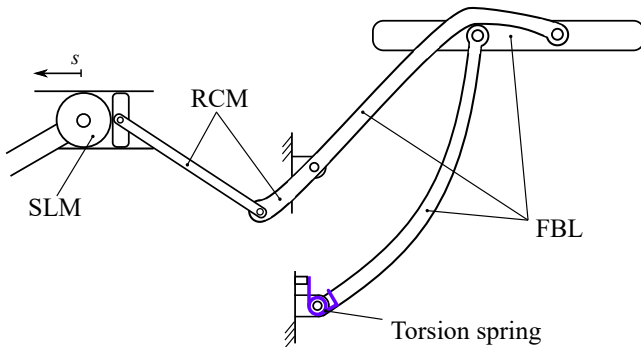


Fig. 10. Functional Principle of the FBL

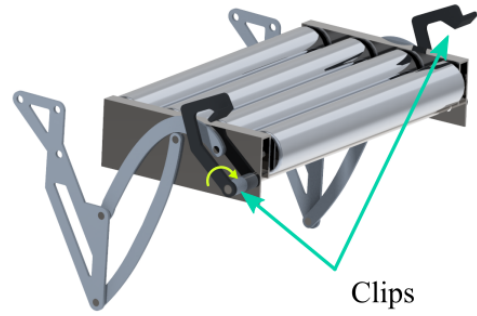


Fig. 11. Rotating Clips

V. CONCLUSIONS

In this paper, we presented the design of an innovative mobile robotized system for automated depalletizing applications. The system is designed to autonomously decompose homogeneous pallets and assemble new pallets with heterogeneous items. The proposed solution comprises an autonomus mobile robot, a serial cobot, a lifting device with a conveyor, and a multi-sensor vision apparatus (with the latter being described in [16]). In order to reduce the external load on the robot end-effector, packages are dragged by the cobot either from the pallet to the conveyor or vice-versa. Depending on the reciprocal orientation between the conveyor and the boxes therein contained, up to three or two boxes can be included on board. A prototype is currently under construction and experimentation will immediately follow in order to assess its effectiveness.

In conclusion, we remark that, though some drawbacks emphasized in the paper can be overcome by using suitable hardware (e.g. a cobot with a longer reach can be used in order to process more packages with a single positioning of the mobile robot), the approach on which P-COORSA is based, presents two unavoidable limitations. The system is limited to process pallets that contains a rigid interlayer between different layers of packages, and the vertical dimensions of both the mobile platform and the scissor lifting mechanism requires the pallet to be installed on a raised dais.

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⁶<https://www.timotion.com/it/product/detail/linear-actuators/ta2p-series>

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