Scuola di Ingegneria

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Design, Planning, and Control of Collaborative Dual-Arm Mobile Manipulator for Depalletizing Tasks

Tesi di Laurea Magistrale in Ingegneria Robotica e dell'Automazione

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Abstract

The industrial logistic market increasingly needs autonomous systems capable of performing complex tasks in an environment that is still not fully digitalized: palletizing and de-palletizing, pick and place, and transport are just some of them. The problem of de-palletization is addressed in this thesis work, whose goal is designing and controlling a Collaborative Dual-Arm Mobile Manipulator capable of replicating picking primitives inspired by human movements. Starting from the individual robots, a task-based manipulability analysis of the system shows us an efficient relative configuration of the robots. Subsequently, I create the model and implement a planning and control algorithm to synchronize the different loco-manipulation tasks. Thanks to several tests in different possible scenarios, the effectiveness of the proposed system is confirmed.

1 Introduction and problem definition

Technological research and the enormous diffusion of e-commerce have promoted the massive integration of robots into warehouse industries. The intralogistics sector is one of the most studied sectors, where robots are programmed to autonomously perform repetitive and human tasks while trying to keep high the efficiency of the entire logistics system at the same time.

Focussing on *material handling* robots, the main tasks executed concern transporting and pick-and-place movements. Order picking is one of the highest priority areas for improvement to maximize warehouse productivity and nowadays this process is still mostly performed by human workers.

Figure 1.1: UR5e (left), Stretch Boston Dynamics (center), Agility Robotics (right)

The problem we try to resolve in this paper is unloading an industrial pallet (de-palletizing), in which goods of different sizes and weights are stacked and organized. There are several challenges these types of systems can encounter: the high variability of goods in terms of shapes and dimensions, the restricted number of available faces for gripper contact, the deformability of the objects, and the porosity of the object surfaces.

There are many different types of existing robots used for this purpose, each with its characteristics. The most widespread are single manipulators with a vacuum gripper as an end-effector, but these are less suitable for goods with an irregular surface. Mobile manipulators can be used to expand the capability of a robotic arm to a wider workspace. Recently also humanoid or legged robots are programmed to execute particular picking movements (Fig. 1.1).

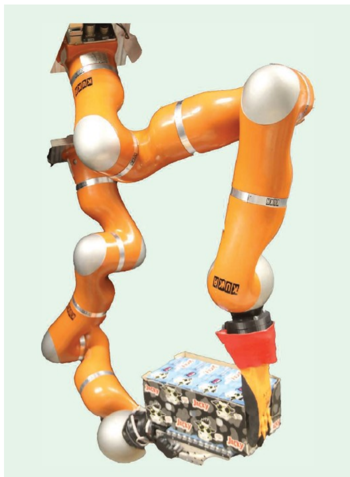

Figure 1.2: WRAPP-up Robot

Previously, the University of Pisa, in collaboration with the Centro Piaggio (involved in the European project ILIAD, *Intra-Logistics with Integrated Automatic Deployment*) examined the same case presenting the **WRAPP-up** [1] robot, a Dual-Arm Manipulator composed of two *KUKA* serial robots (7 DoF) and two dedicated end effectors: a *Pisa/IIT SoftHand* and a *Velvet Tray*. The picking strategies in this work derive from an analysis of human operators at work, recording during the execution of manipulation tasks in a food warehouse. These human-inspired manipulations are related to those picking movements that cannot be executed with only one hand.

In this thesis work, I create an efficient system for the de-palletizing task, designing a new robot that keeps the same performance in terms of picking strategies as the WRAPP-up project, but also integrates a mobile base. The new **Collaborative Dual-Arm Mobile Manipulator** is composed by:

- a *Robotnick Summit XL Steel*, a mobile robot with four omnidirectional wheels, 250kg of maximum payload and high connectivity;
- a *Franka Emika Panda*, a collaborative robot inspired by the human arm with 7 DoF and high accuracy;
- a *Universal Robot UR10e*, a 6 DoF robotic arm with a larger workspace, up to 1.3m, and a 12.5kg of maximum payload;
- a *Pisa/IIT SoftHand* and a *Velvet Tray* for object manipulations.

After the implementation of the control and planning algorithm, some simulations and experimental tests are executed to validate the system.

2 Picking Strategies

In industries, there is a wide variety of objects organized and packed on pallets. Most of them can be grouped into two main categories: cuboids and cylinders. The picking strategies chosen for these types of goods are the result of a deep analysis based on human movements: operators were observed at work and selected those movements involving the use of both hands. It was noticed that one hand often executes support tasks while the other one does most of the handling. In this sense, the support tasks are assigned to the UR10e with the roller, given his large workspace and the maximum payload of 12.5kg; on the other hand, the Franka Panda with the SoftHand will perform most of the manipulations given the high flexibility of the redundant arm and the adaptability of the hand to objects of various types. Additionally, the chosen picking primitives are designed to be executed in tight environments where not all object faces are available or other objects are present near them.

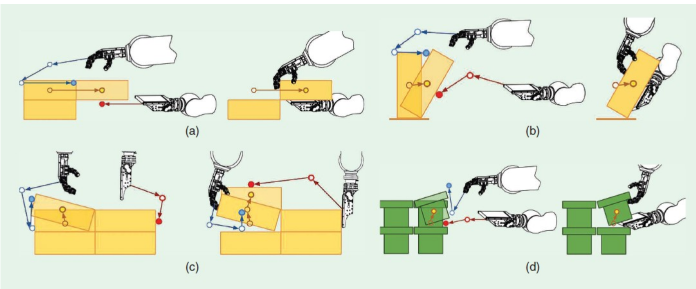

Figure 2.1: The four picking strategies.

The four picking primitives chosen are (Fig. 2.1):

- **Sliding**
  For thin objects without any particular base constraints, the hand pushes the object on the roller toward the edge of the pallet, causing the box to slide. In this case, the roller is activated to assist the hand in gripping.

- **Horizontal axis rotation**
  In the case of thin boxes, or where the support surface cannot slide, the hand rotates the object on its horizontal axis by placing it on the roller, in this case inactive.
- **Vertical axis rotation**
  For thick objects in depth, with no constraints on the base surface, the object is rotated around the vertical axis using the two end effectors to have access to the back of the object. This strategy may involve one or more objects at the same time, depending on the arrangement of the objects in the packaging and the accessible sides. Once the necessary space has been created, the sliding primitive is executed.
- **Cylindrical objects lifting**
  Specifically for cylindrical objects with a thick top edge, in this primitive the hand has the initial task of lifting the object to allow the roller to slide under it. Then the roller is activated and pulls the cylinder on itself.

3 Robot Design

After choosing the robots and the tasks to be performed, we now ask what is the best configuration to mount the manipulators on the mobile base. For this reason, a manipulability analysis based on the evaluation of static and task-oriented performance indices is performed. The parameters we are looking for are twelve: six for each arm (three for translations and three for rotations in Euler ZYX parameterization). These parameters uniquely describe the transformation between the first link of these and the upper center of the mobile robot plate. The literature [2][3][4][5] proposes a large number of relationships and strategies to address the problem of kinematic and static manipulability, and the indices and methods used are:

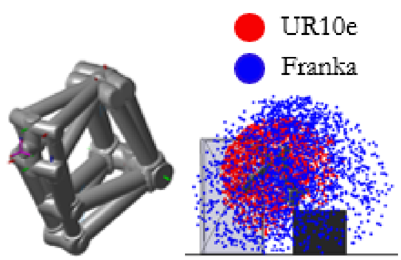

Figure 3.1: Some results of PTCWV and SAR analysis

- Static Performance Indices (Single Arm)

  - **PTCWV** (Product of Total and Common Workspace Volume)
    A quantitative index of the workspace size of each arm and the intersection between them or with the task space showed us how the UR10e workspace always includes the smaller Franka workspace. It is therefore preferable to place the Franka as close as possible to the task space.
  - **SAR** (Swivel Angle Range)
    Exploring solutions in the null of inverse kinematics, the manipulability of the arm is evaluated while holding the end effector at the same pose. The redundancy of the Franka's joints makes the SAR high for almost all the analyses

performed, for the UR10e, however, a mounting position more outward from the base of the Summit is preferable to utilize the four elbow-down configurations, with the same roller position.

- **MC** (Motion Capability), **FC** (Force Capability) and **GII** (Global Isotropy Index)
  The classical kinematic and force manipulability indices based on the Jacobian relationship indicate the preferred directions of motion given a specific manipulator configuration. These indices analyses show us the presence of a zone of low manipulability for both manipulators along the axis direction of their first joint. This zone is preferred to be as far as possible from the manipulation zone.

• Task-oriented Performance Indices (Dual Arm)

- **DAMM** (Dual-Arm Manipulability Measure) and **TOMM** (Task-Oriented Manipulability Measure)
  These indices are based on the intersection volume between the arm manipulability ellipsoid and desired ellipsoid. More information about the picking primitives is included at this stage.

Possible Configurations

	Franka						UR10e					
	x $[m]$	y $[m]$	z $[m]$	R_x $[rad]$	R_y $[rad]$	R_z $[rad]$	x $[m]$	y $[m]$	z $[m]$	R_x $[rad]$	R_y $[rad]$	R_z $[rad]$
1	0.25	−0.15	0.02	0	0	0	0.25	0.22	0.02	0	0	0
2	0.25	−0.22	0.20	0	$\pi/2$	0	0.35	0.32	0.05	0	0	0
3	0.25	−0.22	0.15	0	$\pi/4$	0	0.35	0.32	0.05	0	0	0
4	0.25	−0.22	0.10	$-\pi/8$	$\pi/4$	0	0.30	0.25	0.10	0	$\pi/2$	0
5	0.25	−0.15	0.15	0	$\pi/4$	0	0.15	0.20	0.30	0	$\pi/2$	0
6'	0.25	−0.22	0.15	0	$\pi/4$	0	0.32	0.35	0.05	0	0	0
7'	0.25	−0.22	0.20	0	$\pi/2$	0	0.35	0.32	0.05	0	0	0

	TASK AB						TASK C					
		Franka		UR10e				Franka		UR10e		
# Config	$DAMM$	$\langle TOMM \rangle$	$TOMM_{max}$	$\langle TOMM \rangle$	$TOMM_{max}$	SAR_{UR10e}	$DAMM$	$\langle TOMM \rangle$	$TOMM_{max}$	$\langle TOMM \rangle$	$TOMM_{max}$	SAR_{UR10e}
1	0.493	0.294	0.359	0.282	0.304	5	0.552	0.125	0.139	0.239	0.251	8
2	0.285	0.217	0.224	0.279	0.300	7	0.255	0.114	0.128	0.227	0.236	8
3	0.321	0.241	0.303	0.276	0.300	7	0.287	0.125	0.133	0.227	0.236	8
4	0.143	0.255	0.295	0.135	0.157	5	0.224	0.143	0.155	0.182	0.204	8
5	0.163	0.236	0.271	0.207	0.282	5	0.061	0.125	0.144	0.055	0.057	4
6	0.328	0.243	0.303	0.281	0.310	7	0.287	0.126	0.133	0.233	0.242	8
7	0.285	0.218	0.224	0.278	0.300	7	0.255	0.114	0.128	0.227	0.236	8

Figure 3.2: Seven possible configurations and relative results indices.

This analysis is conducted by examining both the quality of the workspace with a fixed configuration and evaluating the performance of a set of configurations with a fixed pose of the end-effector. Seven good candidates are presented in figure 3.2 with different orientations and positions of the manipulator bases. The chosen configuration is the number 3 (Table 3.1), which is the best compromise between the size and the orientation of Franka's workspace and the maximum number of elbow-down UR10e configurations available.

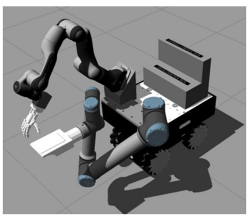

Figure 3.3: Robot 3D Model.

	x $[m]$	y $[m]$	z $[m]$	R_x $[rad]$	R_y $[rad]$	R_z $[rad]$
Franka	0.25	−0.22	0.15	0	$\pi/4$	0
UR10e	0.35	0.32	0.05	0	0	0

Table 3.1: The chosen configuration.

At this point, it was possible to create the complete model on ROS/Gazebo environment with all the parts involved: the two manipulators, the mobile robot, the arms base, the two end-effectors, and the controller manipulator boxes. The latter have been added because, in reality, they must physically belong to the complete system. Their position is at the rear of the Summit plate trying to balance the weight of the manipulators for better tip-over stability.

4 Planning and Control Algorithm

Defined the tasks and robot design, one of the most delicate aspects of this project is the planning and control algorithm. This is developed on *MATLAB/Simulink* respecting all the synchronization requirements with *ROS/Gazebo*, and creating the equivalent manipulator kinematic models. The main algorithm scheme can be divided into three large subsystems: inputs, outputs, and the planning flow.

Input

System inputs include the state of the robot's components: the manipulator joint state provided by the ROS controllers, the end effectors state, and the mobile robot pose. In a real system, this latter information is provided by a navigation system assumed to be known and accurate in this work, using the exact data directly from the simulator.

Also in this section appears the information obtained from the outside world by a hypothetical vision system, which is assumed to be perfect at the simulation level, providing us with the position and orientation of the objects, the pallet, and the conveyor belt.

Output

The outputs of the system, on the other hand, consist of commands to be sent to ROS controllers to manage the robot, and a generator of external forces to be applied to objects. The manipulator control is handled by a state machine, which is used to synchronize the main flow and the transmission of the commands to ROS. There is also a checking block: if the current joint position is equal to the desired one within a certain tolerance, the flow can continue to the next state. Specifically, the waypoints sent to ROS are generated in configuration-time space, actually managing the timing of trajectory execution.

For the mobile robot, control speed commands are constantly sent and are based on *x-y* planar and *yaw* control. Also in this case, the actual position and orientation are compared to the desired one to control the flow of the mission, and a saturation on the speed commands is added to avoid unreal dynamic system behavior and possible jerks.

This section also contains the blocks for generating an external force if the roller is activated and there is contact with an object. This force is applied directly to the box and follows the longitudinal direction of the roller, whatever its orientation. To this purpose, a collision detection function between the roller and the box is also required. This algorithm uses the position of the end effector and the position of the box to geometrically discriminate the presence of a collision. In parallel, using the same idea, signals are generated to indicate when a box is detected as *taken* or as *discharged*, helping the execution of the main flow.

Finally, there are specific blocks for hand control: only a single variable indicating the strength of the hand grip is set.

Planning Approach

The modular nature of a mobile dual-arm manipulator requires a trajectory planning algorithm that takes into account both the *locomotion* and *manipulation* aspects of the robot, attempting to integrate them as best as possible. The literature on this subject is wide [6] and for this particular solution, a separate type of control of the two parts is chosen. The general flow is characterized by two main phases: the **picking phase** and the **release phase**. During the first, the system approaches the pallet and places itself relative to the box to be picked: in this first movement, the manipulators are fixed in a basic configuration. Next comes the picking phase in which the robot picks, with loco-manipulation movements, the object and holds it between the two end effectors. Finally, depending on the position of the conveyor belt, the robot reaches the release position and unloads the object.

The general state machine is set up to manage the execution of the entire mission and generates the waypoints for the mobile robot and the manipulators, receiving information to proceed with the execution via the input and output blocks just described above. In detail, the loco-motion planner follows the transformations shown in figure 4.1.

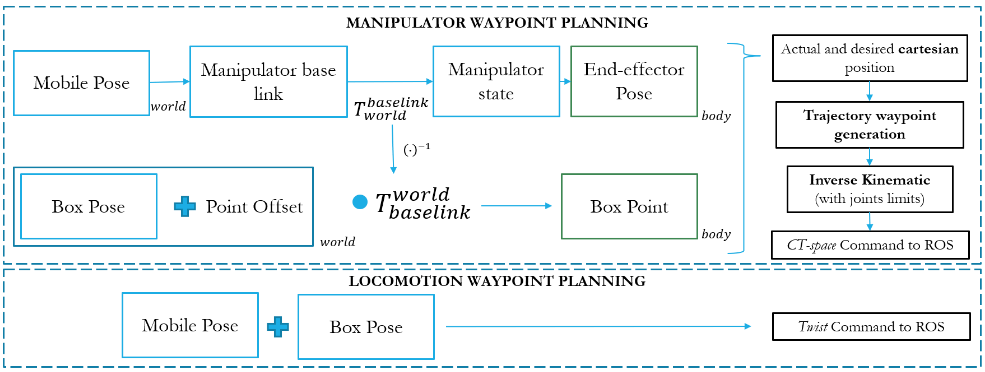

Figure 4.1: Loco-manipulator waypoint planner scheme.

- The **locomotion trajectory planning** is based on positions relative to the object to be manipulated or the conveyor belt. From these, the algorithm generates speed commands via a planar and yaw control. These relative positions have been chosen to achieve manipulator configurations characterized by good manipulability. They also help to prevent the manipulators from being too close to the pallet and incurring undesired collisions during their movements executions.

- The **manipulation trajectory planning**, on the other hand, is based on the kinematic inversion of known cartesian points relative to the position of the box. In detail, the entire execution of picking strategies is divided into several known positions that the end effector of each arm must reach sequentially. These waypoints are generated online based on the current pose of the box and are interpolated by the algorithm. Then the CT-space commands are computed using a kinematic inversion algorithm, with only joint limits as constraints. Again, the successive manipulation points, specifically for each picking strategy, are chosen to allow the robots to operate with good manipulability and safety, far from collisions between robot parts and surrounding objects.

5 Tests

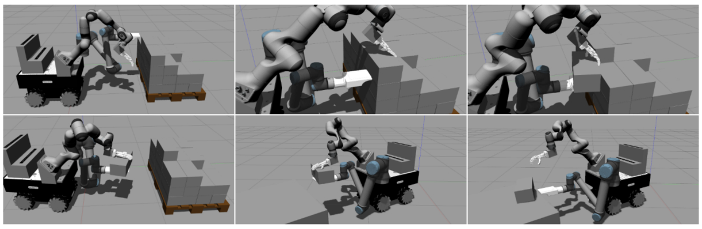

Figure 5.1: Sliding Primitives.

Once the control and planning algorithm is ready and all the involved parts communicate correctly to each other, four simulations are performed for the different types of picking strategies.

The first simulation implements the sliding primitive (Fig. 5.1): this is the simplest of all and is the one executed in the smallest number of states. The second picking strategy (first row in Fig. 5.2) is more articulated and the hand must execute many movements to guide the box on the roller and allow it not to fall.

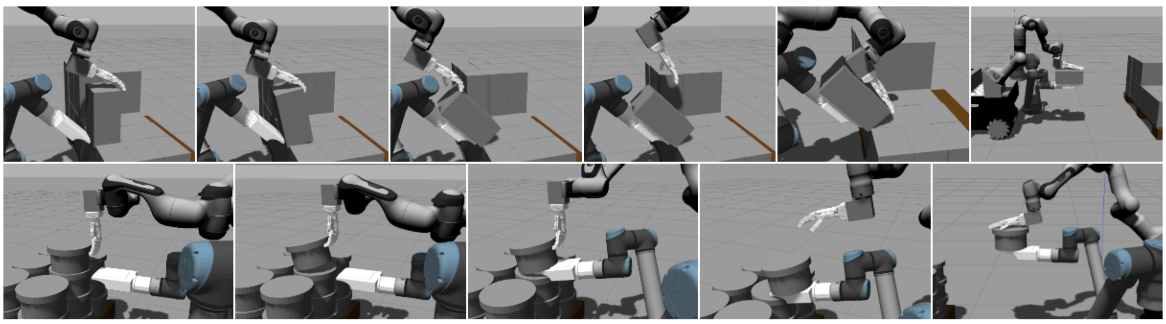

Figure 5.2: Second and third picking strategies.

The third simulation (second row in Fig. 5.2) instead is specific to cylindrical objects. In this case, we use both the roller functionality and the redundancy of

Franka, which will assume particular configurations. The last case is the most articulated of all and involves the manipulation of two boxes to pick them. In fact, in the first phase, the robot uses the pose of both boxes to place itself in the center and create the necessary space to perform the sliding primitive to the first box. Similarly, it will apply the same concept to pick the other one.

In all simulations, as the robot moves from the pallet to the conveyor, it can be seen how the end effectors hold the object to avoid losing it during movement. This bi-manipulation phase is naturally customized to the size of the object itself. Subsequently, the release phase is the same in all cases, consisting of a handful of standard movements always adapted to the object.

In addition, the various scenarios were designed to demonstrate the adaptability of the robot to the positions of the pallet and conveyor belt, placed differently from case to case.

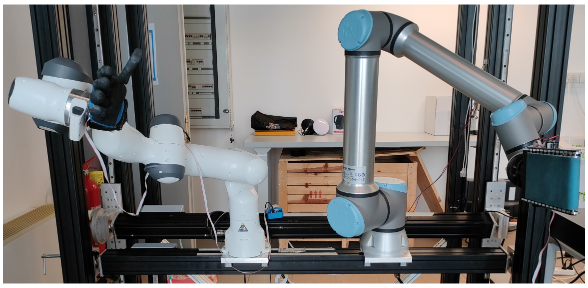

Figure 5.3: Experimental setup.

After the simulations, some experimental tests are performed with the real robot in the CrossLab laboratory. In this case, the tests are focused on the manipulation tasks so the manipulators are mounted on a fixed structure and the mobile robot is not considered. The configuration chosen is the first of the seven possible ones shown in figure 3.2, in which the arms are aligned to each other, separated at a distance of 50cm and a height equal to the mobile robot's superior plate. With this setup (Fig. 5.3), the UR10e configurations with the elbow down are not available, so the planning phase is more accurate to avoid unexpected collisions between arms.

The figures 5.4 - 5.6 show the adaptability of the planning algorithm to execute the same picking strategies also with a different robot configuration and with real commercial items. In this experiment, the position of the goods is known preliminary, provided by a hypothetical vision system.

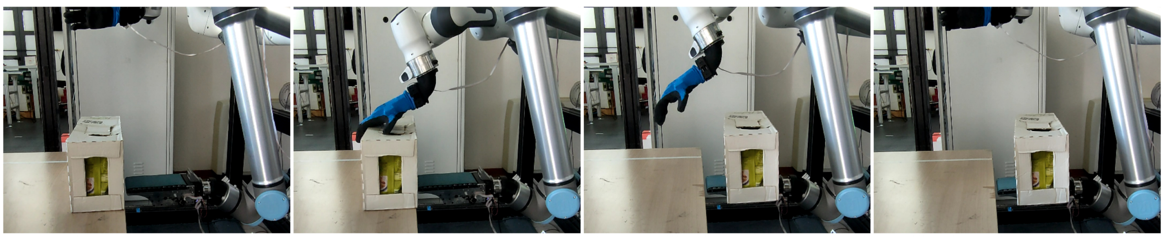

Figure 5.4: First picking strategy.

The full videos of simulations and experiments can be downloaded at this link [7], while the entire code is available at my GitHub repository [8].

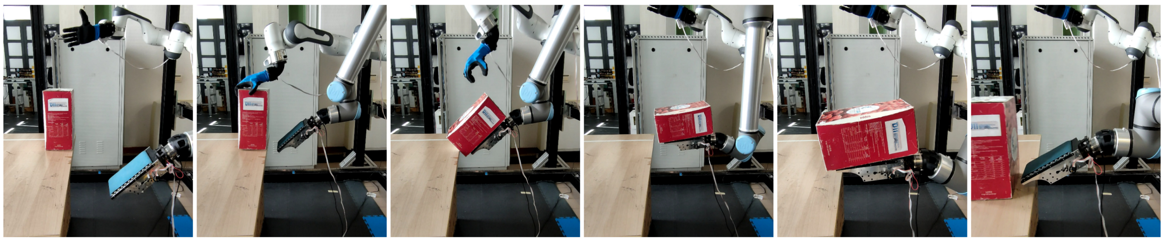

Figure 5.5: Second picking strategies.

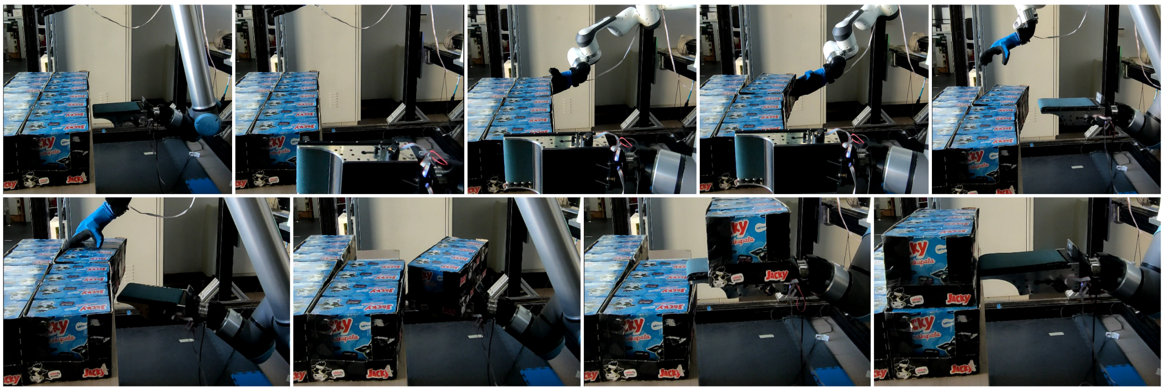

Figure 5.6: Fourth picking strategy.

6 Conslusions

In conclusion, this thesis work presents a possible solution for an automatic system for de-palletizing commercial pallets. The proposed robot is a Collaborative Dual Arm Mobile Manipulator capable of replicating picking strategies for objects similar to the most common goods on the market. The design starts from the choice of robot configuration, through the creation of the control algorithm, to simulations and experiments, demonstrating the validity and flexibility of the system. Although the proposed algorithm can be considered simple, the simulations and results obtained nominate this work as a good candidate for a more complete and complex mobile manipulator design.

At the end of this project, several interesting ideas for extending and improving the proposed project can be considered.

- Firstly, the implemented **loco-manipulation planner** separates the locomotion part from the manipulation one. The former is based on reaching predetermined desired positions based on the position of objects and applies proportional yaw and planar control. The second generates waypoint trajectories in CT-space by kinematic inversion known positions relative to the object. This is the simplest way, but the literature offers numerous alternatives: in [9], for example, the random-based planner is applied to the complete system with all its degrees of freedom, but depending on the distance to the object, it switches from a locomotion-only zone to a mixed zone, to a manipulation-only zone finally; in [10], the planning algorithm is based on the popular RRT* with cost indices related to manipulability and energy consumption; in [11], the algorithm is adaptive with cost indices also relating to possible collisions with dynamic objects. Implementing one of these planners can certainly improve the performance of the entire system at the expense of the computational load.

- In this type of system, the **Tip-Over Stability** must be taken into account: it is possible that a manipulation away from the robot's center of mass could create instability and cause the robot to tip over. There are several techniques to investigate the stability of the system in this sense, calculating indices such as ZMP [12] [13], FA [14], TOM [15], MHS [16] that report the equivalent angular momentum along the tipping axes of the system. They can be both quantitative and qualitative and can easily be added as a cost index in the trajectory planner.
- In this project, the poses of the manipulated objects and the robot position are supposed to be known, i.e. a perfect **vision system** and a **navigation system** are assumed to be available. A possible development could be including these systems in the simulation phase, trying to replicate their dynamics and thus 'dirty' the information that has so far been assumed to be known exactly.
- The collision detection algorithm and end-effectors force feedback implemented in the simulations are not used in the real system. The setup used in experimental tests, like the WRAPP-up robot, has a force/torque sensor mounted before each end-effector to sense possible collisions with the outside world. A possible upgrade could be considering these sensors and making the robot more sensitive to collisions.
- Finally, inserting a decision phase at the start of the mission that makes the robot able to choose which picking strategy to use, according to certain parameters, could significantly increase the system's autonomy.

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