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DELIVERABLE 1.5
Adaptation and finalised DARKO mobile platform

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1 Introduction

The DARKO project has developed two distinct approaches to enhance robotic throwing capabilities: an elastic manipulator with built-in Bi-Stiffness Actuation (BSA) developed by TUM, and an elastic wrist with complementary hand-held tools developed by UNIPI. These two approaches aim to address the limitations of conventional robot arms, particularly in terms of throwing performance and object manipulation in confined spaces.

The deliverable **D1.5** describes the integration of the developed systems in two mobile platforms introduced in the Deliverable **D1.1**. First, this report provides a description of the two mobile platforms and the developed elastic systems. Then, the integration process of the elastic arm and the elastic wrist onto their respective platforms is documented, including hardware mounting solutions, control system architecture, and the implementation of ROS-based interfaces. Finally, the report outlines the future development envisioned for the next period of the project, which will mainly focus on the improvement of the throwing capabilities of the elastic arm and the pneumatic hand-held tool.

2 Description and objectives of the mobile platforms

This project includes the development of two mobile platforms, depicted in Fig. 1, capable of moving in an industrial environment and perform the manipulation and throwing of objects. As the requirements for locomotion, localization and motion planning are identical for the two platforms, they have identical mobile bases (*Robotnik Kairos+*). In order to facilitate the development of features and integration between the involved partners, both bases are equipped with identical sensors in order to ensure large field of view and scene understanding (*Ouster OS0* lidar and *Basler Ace* cameras) and object detection (*Azure Kinect* cameras with pan/tilt units and Intel *Realsense* D435 camera). As some features require extensive computational power, the two platforms are equipped with *Nvdia Jetson AGX Orin* units.

(a) Darko mobile platform from ORU, also described in the deliverable **D1.1**.

(b) Darko mobile platform from TUM.

Figure 1: Mobile platforms developed in the scope of DARKO. Their main differences rely on the strategy used to perform robotic throwing: the ORU platform uses developed robotic hands and end-effectors combined with specific control strategy, and the TUM platformed developed a specific robotic manipulator (the elastic arm, see its description in Section 3.2).

The main differences between the two platforms are related to the robot that they embed: while the TUM platform (Fig. 1b) aims to be equipped with the developed elastic arm, the ORU robot (Fig. 1a) is the main platform used for the development of the features related to navigation, localization and human-robot interactions. As a result, this platform is equipped with a *Franka Emika* robot for the development of control strategies related to manipulation and throwing. The robot intent and communication with human users is investigated with a *NAO* robot placed on the ORU platform.

3 Developed systems for enhancing throwing performances

Improving robot throwing is one of the objective of DARKO, and one of the solutions investigated consists in developing and improving hardware. This section first recalls the development of an end-effector and tool that can be used for enhancing the throwing capabilities of commercially available robot manipulator. Then, a second approach based on the development of a robot arm with embedded elasticity is presented. Each of these solutions will be integrated on the respective DARKO mobile platform.

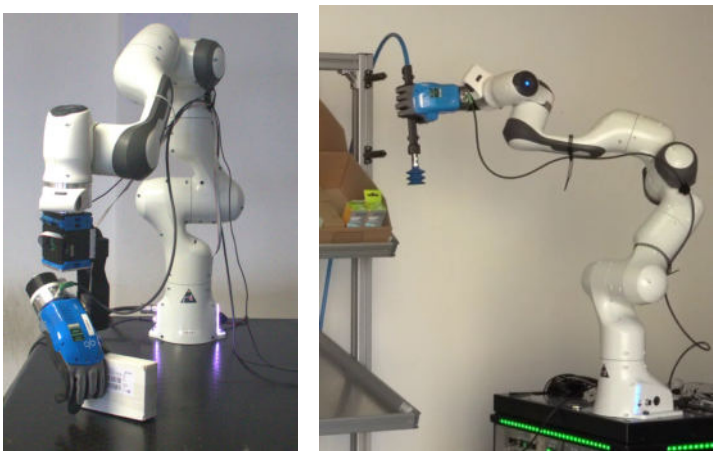
3.1 Elastic wrist and hand-held tool

As the mobile manipulator evolved in an industrial environment, it has to be able to interact and manipulate objects of various shapes and sizes. Robotic hands are already known for the numerous types of objects they can handle. However, some object placements such as small boxes placed in baskets can lead to scenarios where a robotic hand does not have the space to operate properly. Consequently, UNIPI decided to address this problem by developing two independent solutions, detailed in the deliverable **D1.4**, that can be used by an industrial robot such as the *Franka Emika Panda*.

First, an elastic wrist containing and internal spring-based mechanism has been developed in order to offer a compact design while conserving elastic properties. This design allows to improve the insertion of the hand inside a cluttered area (e.g. a box) for increased reachability of the end-effector. It also provides a wide range of motion (-90°to +125°) to the *Softhand 2*, which allows for better manipulability and the possibility to perform a wider range of grasping motions.

Then, if the accessibility of the object to grasp, a second device in the form of a pneumatic hand-held tool has been developed. This tool, comprising a suction-cup connected to a pneumatic pump, is appropriate for handling objects placed in narrow areas, where the *Softhand 2* can not access. The device is capable of inverting the airflow provided to the tool, which allows the system to both manipulate or throw object to a desired location.

The Deliverable **D1.4** details the preliminary experiments and results carried on the simulated model of the 3-DoF manipulator and the physical prototype. These results were obtained using an optimal velocity-based control strategy for overarm throwing. Current works focus on the improvement of the throwing performances of the elastic arm: while the BSA can be used for torque control, the dynamic parameters of the robot have recently been identified and open the study of throwing performances under torque control. First insights, not published yet and using conservative requirements, show that the robot can throw to a given location with satisfying repeatability. Future work on the elastic arm aim to evaluate the maximal throwing capacity of the system, and the improvement of the robot's design.



(a) Developed elastic wrist assembled on a *Franka Emika Panda* robot.

(b) Pneumatic tool hold and elastic wrist connected to a *Franka Emika Panda* robot.

Figure 2: Elastic wrist and pneumatic hand-held tool developed by UNIPI. These devices, connected to the *Softhand 2* anthropomorphic gripper, can grasp and throw various types of objects.

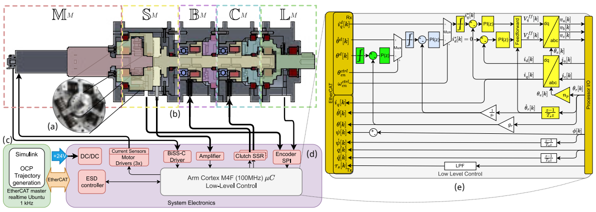
3.2 Elastic manipulator

The other strategy for the improvement of robotic throwing has been to adapt the robot arm itself. The joints of the commercially available robot arms are often assembled with harmonic drives. While they can provide high positioning accuracy and deliver high torques, they are often limited in terms of maximal velocity, peak power and energy efficiency. Thus, TUM's strategy has been to develop an actuator that can exploit intrinsic elasticity for storing energy and provide highly efficient energy release for throwing tasks.

This concept, named Bi-Stiffness Actuation (BSA) and detailed in Deliverable **D1.3**, aims to augment the classical motoreductor scheme with a brake, a deformable spring and a clutch. The combination of these elements, illustrated in Fig. 3, allows for different working modes. These working modes can be used to control the actuator as regular rigid actuator, store energy by deforming the internal spring, and release it at a desired time. Unlike the Series-Elastic Actuators that also use internal elasticity, the BSA does not induce oscillating behavior and ensure a fast and efficient energy release.

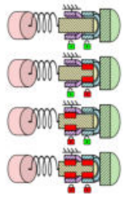
The first version of the BSA prototype, illustrated in Fig. 3a is made of a succession of the different functions of the actuator (motor, spring, brake, spring, link) and has been used to evaluate the potential of the BSA concept. It embeds customized low-level controller compatible for position, velocity and current control. After validation of the concept, a more compact of this actuator has been designed and integrated into a 2-DoF system. This system, combined with an optimal velocity-based control have shown satisfactory results in term of end-effector maximal velocity and energy-release sequence for throwing tasks. More details regarding the prototype, the control strategy and experiments can be found in Deliverable **D.13**.

These satisfactory results enables the development of a 3-DoF elastic arm shown in Fig. 4. As a first design it has been decided that the two first joints of the arm (which offers a rotation around a vertical axis and an horizontal axis, respectively) are considered as rigid joints, and only the final joint is made as BSA. In this decided, it has been considered that it



(a) Structure and low-level controller structure of the first version of the BSA.

Mode	c_1	c_2
DEC (Decoupled)	0	0
SEA	0	1
STG (Storage)	1	0
BRK (Braked Storage)	1	1



(b) Actuation modes of the BSA. If $c_i = 1$ the clutch is engaged, else if $c_i = 0$ it is disengaged.

Figure 3: Description of the initial BSA actuator, which consists in a succession of constitutive units: Motor, Spring, Brake, Clutch and Link, and the corresponding low-level control scheme. The different states of the actuator are gathered on the table place on the right side of the figure.

is important to maintain the center of mass of the distal link close to the rotation axis of the second motor. As a result, the link uses the BSA as a counter-balancing system and the desired motion/torque is conveyed to the end-effector using a transmission belt. As the main objective of this prototype is the study and the improvement of the throwing capabilities of the BSA, the compactness of the design has not been a key concern during the development.

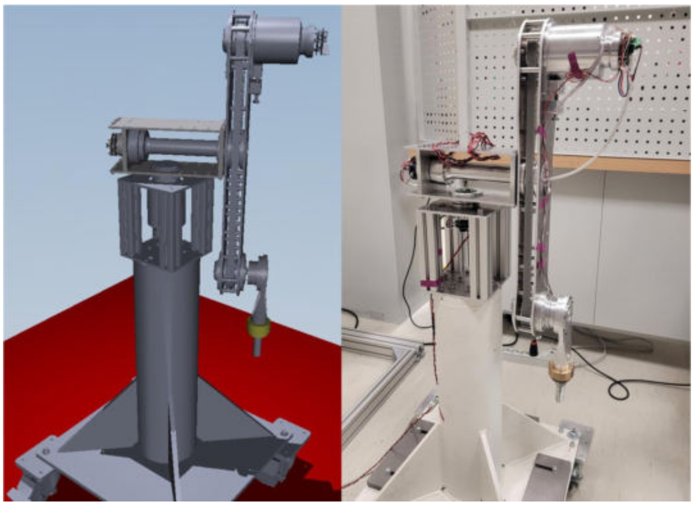


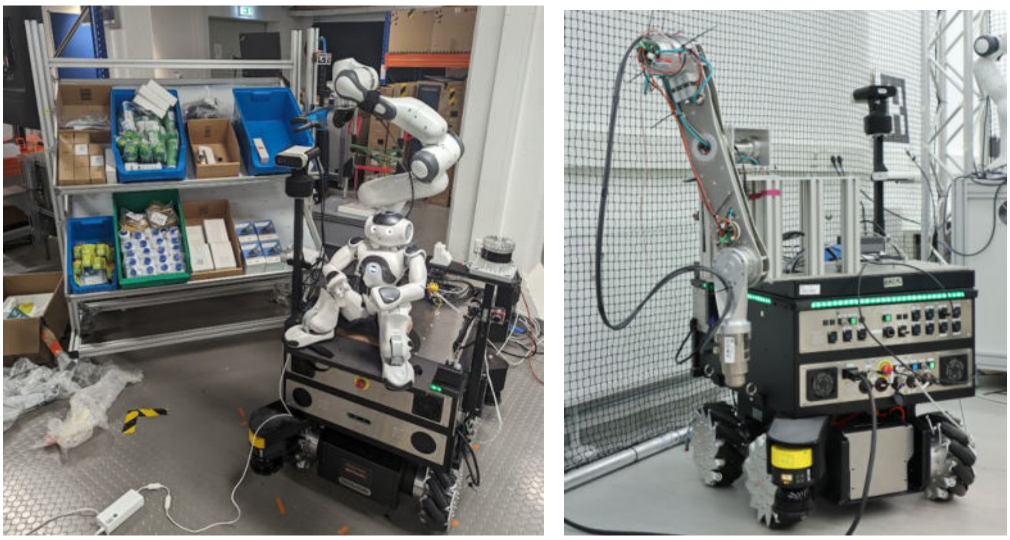
Figure 4: CAD representation and actual prototype of the 3-DoFs elastic arm assembled on a fixed testing structure. The 3D model on a simulation environment has been used for testing throwing control strategies, which have then been implemented on the physical prototype.

4 Integration of the developed throwing systems on the mobile platforms

While robotic throwing is an important aspect of DARKO, this feature should be integrated among the features developed by the consortium in the mobile manipulators. Thus, this section details the integration on the mobile platforms in the scope of the MS3 milestone. The reader should note that this section focuses on the features that are integrated on the platform that contains the elastic arm: as a result, features such as the human-robot interaction enabled by the use of the *NAO* humanoid robot is not presented here. A global overview of the features demonstrated during the MS3 milestone are gathered in the Deliverable **D8.4**. In what follows, the integration of the developed hardware on the two mobile platforms is presented. Then, the global firmware structure is introduced. Finally, this section gives a brief description of the features implemented in both mobile manipulators.

4.1 Hardware integration on the mobile platforms

The elastic wrist and hand-held tool developed by UNIPI is first integrated on the ORU platform, as illustrated in Fig. 5. As the whole development of the wrist has been carried out considering the *Franka Emika Panda* robot as a desired use case, the hardware integration has been done without significant issue. The hand-held device has been conceived so that it can be fixed on a desired location (e.g. on a shelf) and can be easily accessed by the robot using dedicated visual markers.



(a) ORU platform equipped with the elastic wrist during MS3.

(b) TUM platform equipped with the developed elastic arm and a magnetic gripper.

Figure 5: Current status of the ORU and TUM mobile manipulators.

The elastic arm has been integrated in the TUM mobile platform. The hardware integration did not show particular issue, as a specific platform adapter (as mechanical interface) has been designed to place the robot on a desired location on the top plate of the mobile base. As the throwing motion of the robot can require a large range of motion, it has been decided to place the elastic arm in a corner of the mobile base and to restrict its motion to a vertical 2D plane to avoid potential collisions with embedded cameras and sensor. As a consequence, the throwing direction is imposed by the orientation of the mobile base. It should also be mentioned that the *Robotnik* robot base can also accommodate for a potential scenario where both the elastic arm and a *Franka Emika Panda* robot are simultaneously assembles on one platform.

As the elastic wrist and *Softhand 2* devices are integrated in the ORU platform, it has been necessary to use a different end-effector for the elastic arm. Thus, it has been decided to temporarily use a *Schunk EMH-RP 036-B* magnetic gripper for the first implementations related to MS3. The use of this gripper required the implementation of a specific mechanical and electronic connection interfaces with the elastic arm, The programmable Embedded electronics consist of a local micro-controller with EtherCAT communication and 2x 24V outputs for controlling the magnetic gripper. The optimization of the cable routing to avoid potential damages during the throwing has also been addressed. Due to the specific properties of the magnetic gripper, the experiments performed with the elastic arm are currently limited to lightweight metallic objects.

Additionally, electronics has been enhanced to support Full-Duplex(Half-Duplex) RS-485 protocol which is a common communication standard for various industrial grippers. In particular, it has been done as a part of integration efforts to accommodate *Softhand 2* gripper, that has been provided from our partners from UNIPI. Integration of required interfaces at the end-component level has been done primarily to avoid using any intermediate electronics board (such as EtherCat to RS-485 repeater, etc. - as was the approach for initial integration efforts), which can introduce additional delays, unnecessary cabling and require non-standard way of integration within the control software stack.

4.2 Firmware and control

Each mobile manipulator is controlled using ROS, which helps providing and understandable structure and interfaces for the different partners to collaborate. The elastic wrist and the *Softhand 2* are connected to a PC using dedicated RS485 and USB interfaces and communicate with the rest of the system using ROS nodes. The elastic arm also interacts with the rest of the system via ROS, however it has been necessary to build a custom firmware detailed in Fig. 6. In practice, the robot is connected to a PC via Ethercat, and the PC serves as ROS node host to provide ROS interface between the robot and the rest of the system, which corresponds to the grey block in Fig. 6. The main unit for robot control consists of the Simulink real-time interface extended with UDP input ports to facilitate the communication with external controllers on one side and the EtherCat library on the other (to communicate with the robot). The Simulink interface embeds the model of the elastic arm required for the control. Exposed UDP ports allow control from outside Simulink, in this case by a Low-level C++ Control Library, similar to *libfranka* (familiar interface should ease the integration of the features of the other partners). ROS is also utilizing mentioned Low-Level C++ Control Library to enable user to interact with the robot this way as well. In our case there is an online trajectory generator that is sending commands via ROS. The received trajectories can be verified in simulation using the Simulink model. Once validated, the trajectory is transferred to every joint using Ethercat.

The control of the elastic wrist and the pneumatic tool, described in Deliverable **D4.5**, is implemented on ROS using dedicated ROS services. To fully perform the task, the robot has to perform a sequence of movements:

- Reach and grasp the pneumatic tool,
- Reach and grasp the desired object,
- Move the object to a desired pose and throw.

The motion planning is performed using a ROS service that calculates a trajectory considering the natural behavior of a human arm. This approach facilitates the positioning

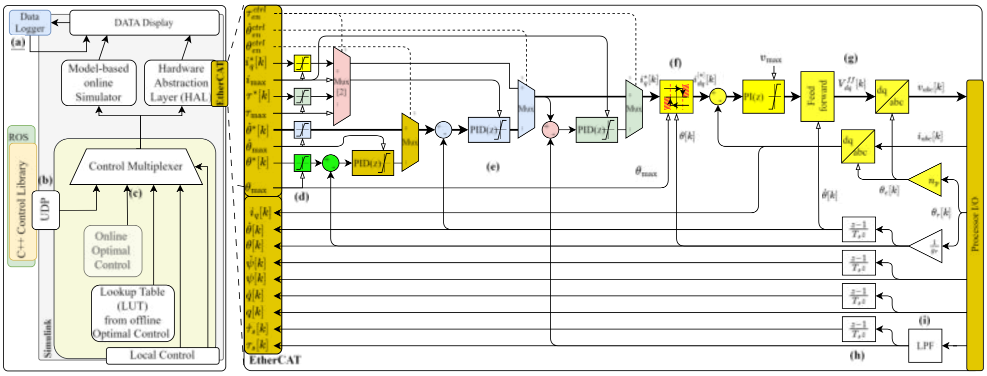


Figure 6: Detailed architecture of the main and embedded controller firmware. New features such as (a) Data logger, (b) External mode control using ROS, and (c) a central control multiplexer are highlighted on the left. Multilevel Cascaded Controller with (d) safety functions to prevent any wind-up and ensure angular position and velocity boundaries, (e) PID controllers, (f) current/torque out of bounds protection and (g) PI-based Field Oriented current control, (h) differentiators for θ, ψ, q and τ, and (i) a τ low-pass filter.

of an anthropomorphic hand (such as *Softhand 2*) and can increase the success rate of the grasping. The trajectory is then followed by the robot by using a Cartesian impedance control strategy. Finally, the throwing sequence is performed by an embedded Arduino device which can communicate to ROS using a dedicated ROS service.

The current implementation for the elastic arm uses a control scheme developed by EPFL and relies on Rucking trajectories. After estimating the kinematic and dynamic parameters from simulations using a simulator developed by TUM and PyBullet, the throwing trajectory has been developed considered all the joints as rigid actuators. The development of control interfaces similar to the ones required for the *Franka Emika Panda* facilitated the transfer of the control to the elastic arm. Indeed, this robot has extensively be used by the consortium throughout the project. As the dynamic identification was not ready for the MS3, a velocity-based controller has been used. Furthermore, various safety aspects have been implemented, such as the handling of control communication loss, joint speed, and position limits, and a sudden abortion of the trajectory execution. For the latter, when the velocity control is aborted, the fall back to joint impedance control around the last controlled position, which provides a controlled stop.

These systems have been capable of showing successful throwing sequences in the scope of the MS3: the TUM platform, as shown on Fig. 7, was able throw a small object in a desired location (represented as a blue box) from an initial pose obtained after moving the mobile base along a predefined trajectory. On the other hand, the ORU platform has been used as the main platform to showcase the various features developed during the project. During this demonstration, the platform showed its ability to move toward a shelf, pick-up a desired object using the hand-held pneumatic tool and throw it to a desired target located on a conveyor belt. Further details regarding the different demonstrations showcased by the ORU platform can be accessed in the Deliverable **D8.4**.

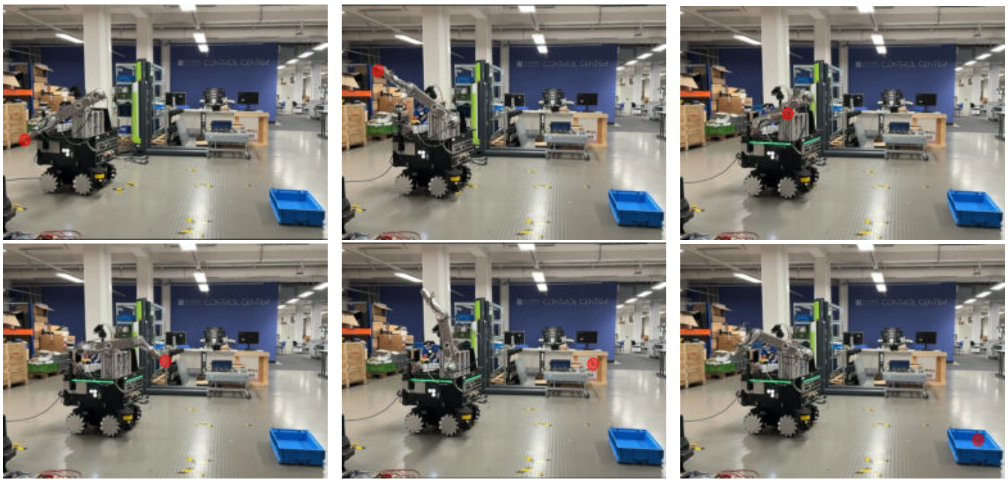


Figure 7: Example of throw performed by the TUM mobile manipulator equipped with the elastic arm. The location of the object at each time instant is highlighted by a red circle.

5 Future integration and development

The integration efforts carried for the MS3 allowed to obtain two functional platforms for manipulation and throwing. After discussion with all the partners, no specific request regarding the elastic arm have been received. Thus, it has been considered that three DoF are sufficient for the current throwing application and TUM will then focus on the improvement of the throwing performances. While the initial plan for future development considered the integration of the *Softhand 2* to the elastic arm, it appeared that the acceptable payload on the end-effector of the elastic arm is not sufficient to perform a throw with the elastic wrist. In addition, the behavior of the elastic wrist under the high dynamics imposed during the throwing motion has not yet been evaluated. Since taking the risk of damaging the developed device at this stage of the project can lead to significant delays, it has been decided to use the elastic wrist only on the ORU platform.

As a result, it is necessary to find a new gripper for the elastic arm. To find a suitable candidate, an extensive review and testing has been performed on commercially available grippers. As depicted in Fig.8, multiple criteria have been considered for various systems, such as the release time and the release force. Based on the gathered experience during this project, it has been noticed that the response time and the release force time are the more prominent factors for ensuring a fast and efficient throwing. As a result, the *Robotiq 2F-85* has been selected as current gripper alternative.

Even if the *Robotiq 2F-85* gripper has the fastest release among the commercially available devices, it is yet still limited compared to the desired throwing sequence: as the optimal controller defines an exact release time, it is important that the gripper performs an 'instantaneous' release. For that purpose, TUM is currently developing a custom gripper based on the BSA concept: in this design, the grasping of an object is performed by storing potential energy in a spring mechanism.

Gripper Name	Variable		Apply Force	Apply Force Time	Response Time (Increase)	Release Force	Release Force Time	Response Time (Decrease)
	Speed	Force	N	s	N/s	N	s	N/s
Festo HGPL	Min	-	48.16	8.72	5.52	48.20	0.62	77.77
	Max	-	59.94	0.19	326.25	55.86	0.23	247.08
Franka Hand	Min	Min	29.05	0.14	208.49	25.67	0.16	169.73
		Max	63.24	0.83	76.23	45.64	0.30	156.04
	Max	Min	113.61	0.08	1582.17	22.40	0.07	325.83
		Max	113.30	0.04	2832.38	54.98	0.09	668.96
Schmalz Cobot Pump	-	-	28.45	0.23	123.19	26.31	0.10	297.85
Schunk EMH	-	Min	28.84	0.05	666.02	25.46	0.05	606.38
	-	Max	68.74	0.10	725.18	61.01	0.05	1526.08
Robotiq 2F-85	Min	Min	26.47	0.27	99.93	22.51	0.44	51.35
		Max	84.97	0.62	138.23	78.82	0.45	178.80
	Max	Min	229.88	0.06	3831.33	208.16	0.07	2973.71
		Max	233.99	0.07	3411.83	214.29	0.07	3061.29

Figure 8: Comparison of the grasping performances of commercially available grippers.

6 Conclusions

This report presented the efforts carried for the development and integration of the elastic manipulator and the elastic wrist on the mobile manipulators. These devices have been developed as two potential alternatives to improve throwing using robots: the first one by changing the design of the arm itself, the second by providing tools that can be installed on currently available manipulators.

The two systems could be assembled on their respective bases without significant issues. Both use ROS for communication with the other parts of the platform, facilitating the integration with the features developed by the other partners within the consortium. The integration of the elastic arm required the development of a specific firmware, capable of verifying the feasibility of potential trajectories sent by an external motion planner using an embedded simulation environment. As the consortium extensively uses the *Franka Emika Panda* robot as a prototyping and testing interface, the controllers associated to the elastic arm followed an architecture similar to the one of the ones provided by the commercial robot. As a result, the implementation of control architectures developed by other partners could be transmitted to the elastic arm without major issues.

While the TUM mobile platform currently partially processes the features developed during the project, they can be sufficient as the main objective of this platform is to showcase the throwing capabilities of the robot mounted on the platform: the future demonstrations using this platform aim to perform throwing after a predefined displacement of the base.

The current version of the elastic arm have been considered sufficient by the consortium, and it has been decided that the elastic wrist developed by UNIPI will remain on the ORU platform. Therefore, further developments will focus on the improvement of the throwing performances for both systems, by leveraging both the hardware and control strategies.

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