Design of a Reconfigurable Mobile Collaborative Manipulator for Industrial Applications

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Design of a reconfigurable mobile collaborative manipulator for industrial applications

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This paper addresses the design of a reconfigurable mobile manipulator consisting of a mobile base and a collaborative serial robot. The robotic system is meant to work in an industrial environment and perform different logistic tasks. Unlike commercial solutions, the mobile base and the anthropomorphic arm are free to decouple and work separately as two different entities, thus optimizing working times and maximize the hardware utilization ratio. The proposed mobile manipulator is equipped with: an automatic braking system to ensure safety and stability during manipulation, a lifting system that allows the robotic arm to work at different heights, and a spatial referencing process to compensate positioning error of the mobile base. An illustrative working cycle is implemented in an industrially-relevant environment to test all features and show potentialities, in terms of flexibility and reconfigurability, of the presented solution.

1 INTRODUCTION

Logistics is a key factor in the management of a company, since it influences various aspects of an industrial process, such as productivity or product quality. In recent times, with an ever-increasing demand for goods, logistics is gaining the more and more central role and, combined with the advent of Industry 4.0, is driving the development of increasingly automated solutions to ensure high efficiency and performances. In several applications the implementation of anthropomorphic robots has become a standard approach [1]. These, are generally used to manipulate a wide variety of products, and to perform several operations, from pick and place to depalletizing tasks. Despite advantages, such as high repeatability and productivity, a serial robotic arm is often a heavy machinery that has to be surrounded by cages in order to avoid any possible damage to human operators [2]. Moreover, being installed in a fixed position, it is unsuitable for the reconfiguration of the working environment, a requirement that is in increasing demand in modern production lines. Collaborative robotics offers solutions to overcome these limitations. Collaborative robots, or cobots, are robotic arms smaller and lighter than traditional industrial manipulators [3]. Their low inertia, com-

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bined with joint sensors, allows cobots to quickly stop if an external collision is detected, therefore, they can be considered a human-safe solution. In addition, thanks to their light weight, cobots can be transported by a mobile base. This feature gives the solution a high degree of flexibility, as one robotic arm can operate in different modes and areas around the working environment. Regarding mobile robots, *Automated Guided Vehicles* (AGVs) represent a widespread and consolidated solution. However, their navigation system is bonded to fixed infrastructures, such as rails or magnetic strips, which cause a lack of flexibility [4]. On the contrary, *Autonomous Mobile Robots* (AMRs) are mobile robots able to detect and avoid fixed and dynamic obstacles, thanks to an equipment of laser scanners and proximity sensors. Moreover, by relying on a set of pre-loaded maps, AMRs are capable of autonomous driving and localization [5].

A collaborative mobile manipulator consists of the integration of an AMR and a collaborative robot. In this field of application, many efforts have been made by several research institutes. The MOCA prototype is a mobile manipulator presented in [6] and [7]. It is designed to perform different logistic tasks from box pick-and-place to pallet displacement. A solution for a similar application is shown in [8], where a collaborative robot is installed on a commercial motorized forklift, thus allowing to both transport a pallet and process products on it. Another solution is shown in [9], where a cobot is installed in a horizontal configuration on a vertical column and the whole structure is moved by an autonomous mobile base. This system, equipped with a vacuum gripper, is meant to manipulate generic items arranged in a warehouse. A similar robotic system designed for warehouse tasks is presented in [10], but unlike the previous solution, the robotic arm is installed with a vertical orientation. A different mobile manipulator is presented in [11], which comprises a cobot equipped with vision sensors and a gripping system, installed on an autonomous mobile base. It is designed for handling generic items, such as screws and nuts. Another example comes from *TIMAIRIS* [12] and its evolution *MAXIMA* [13, 14], a mobile manipulator equipped with vision sensors, intended to feed raw material (cardboard blanks and paper reels) to a packaging automatic machine. Other relevant examples can be found in [15] and [16], where the P-COORSA prototype detects and manipulates boxes by dragging them on a suitable device installed alongside the cobot arm, with both of them being mounted on an AMR. LittleHelper and omniRob [17], instead, are two twin mobile manipulators able to perform different tasks in an industrial scenario, with particular focus on part-feeding and assembling. The applications of this technology can be as varied as the solution presented in [18], in which a mobile manipulator handles boxes and navigates in outdoors and semi-structured environment. The development and spread of mobile collaborative robotics are borne out by the fact that several companies have started producing mobile manipulators as an industrial product. Examples are the KUKA KMR iiwa [19], the OmronMoMa [20], the Fetch mobile manipulator [21] and the whole range of products offered by Robotnik [22].

Despite the advantages such as flexibility and safety, some drawbacks are evident. The purchase of a mobile manipulator typically requires a significant initial investment, justified by the high cost of the hardware. This might translate into a long return on investment, which could deter small and medium-sized companies from using this technology. An alternative approach to overcome these limitations could be to optimise hardware utilisation time by separating the mobile base from the collaborative robot. In this way, the AMR is in charge of the cobot transport but, during the cobot operation, it is free to decouple and perform other logistic tasks. An example of this application can be found in [23] where a 6-DOF (Degrees Of Freedom) robot is installed on a cart. An AMR can be anchored to the wheeled structure thanks to the extraction of two lateral pins. By means of that, the autonomous mobile robot can move the anthropomorphic arm where it is required, and subsequently, the mobile base is free to decouple and proceed to perform other tasks. However, when the cart is left stand-alone there are no systems that can guarantee stability during the manipulation as wheels are free to move. In addition, the trolley can only be deposited at physical markers that help the accuracy and repeatability of the mobile base and this could bring a lack of flexibility.

In this paper we present a reconfigurable collaborative mobile manipulator meant to perform various logistic operations in different positions of the working environment (Fig.1). The collaborative robot is installed on a cart whose wheels are equipped with an automatic braking system, meant to guarantee stability and safety when the robot is in operation. In addition, a lifting mechanism allows the cobot to manipulate items at different heights. To enhance flexibility, the cart can be displaced by both an AMR and a human operator. The cart can be located at fixed locations identified by physical markers or at custom destinations in free space. The AMR can be coupled not only with the cobot cart, but also with other elements of the plants, such as movable racks, thus maximizing reconfigurability.

The content of the paper is structured as follows. Sec.2 gives an overview of the system and addresses the selection of different hardware, such as the top module of


(a) (b) (c)

Fig. 1. Reconfigurable collaborative mobile manipulator: (a) collaborative robot installed on a mobile cart; (b) mobile rack; (c) AMR. The AMR can autonomously couple with both the cart and the rack, displacing them around the shopfloor.

the mobile base (allowing the cart transport), the braking system, and the lifting mechanism. Sec.3 describes the mechanical, electrical, and control architecture design. An experimental demonstration is reported in Sec.4 and finally, conclusions are drawn in Sec.5.

2 HARDWARE SELECTION

According to our project specifications, we propose to use a serial cobot Fanuc-CRX-10ia provided by *Fanuc*[1] (Fig.1(a)), with a maximum payload of 10kg and a reachability of 1249mm, and an AMR MiR250 provided by *Mobile Industrial Robots*[2] (Fig.1(c)) with an admissible onboard load of 250kg.

2.1 Transport strategy selection

As mentioned in the previous section, the collaborative robot is mounted on a cart moved by the AMR. The design of the system starts from the selection of the cart-displacement strategy, as it influences several aspects of the whole project. Three different options are analised and, by means of a selection table, the best solution is carried out (Fig.2):

Lifting (T1): the AMR goes under the cart and lifts it through a suitable device. In this configuration, the cart wheel-braking system is simplified, because brakes could be always engaged except when the operator moves the cart. In this situation, they can be manually deactivated. On the other hand, the transport performed by the AMR is less stable than the other solutions, as its footprint, highlighted in orange in Fig.2(a), is smaller. In addition, if the coupling would be based on friction (which is the simplest option), a precise relative positioning would not be guaranteed.

Dragging (T2): the mobile base anchors and drags the cart (Fig.2(b)). The cart has a larger footprint than the mobile base, so the transport can benefit from a higher stability. Moreover, a precise relative positioning can be ensured by a suitable centering device. Despite these advantages, the braking system is more complex because an automatic engaging and disengaging solution must be designed.

Hooking (T3): the cart is hooked and transported in a towing-trailer mode (Fig.2(c)). As for the dragging solution, this strategy can ensure more stability and positioning precision. However, the towing-trailer mode makes the system less manoeuvrable.

The assessment of the best solution is carried out on the basis of the following weighted criteria:

O_1: braking system simplicity $W = 0.10$,
O_2: stability during the transport $W = 0.30$,
O_3: system maneuverability $W = 0.30$,
O_4: coupling precision $W = 0.30$.

Each strategy is assigned a score from 1 to 4 for each

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[1] https://www.fanuc.eu/it/en/robots/robot-filter-page/collaborative-robots/crx-10ia

[2] https://www.mobile-industrial-robots.com/solutions/robots/mir250/

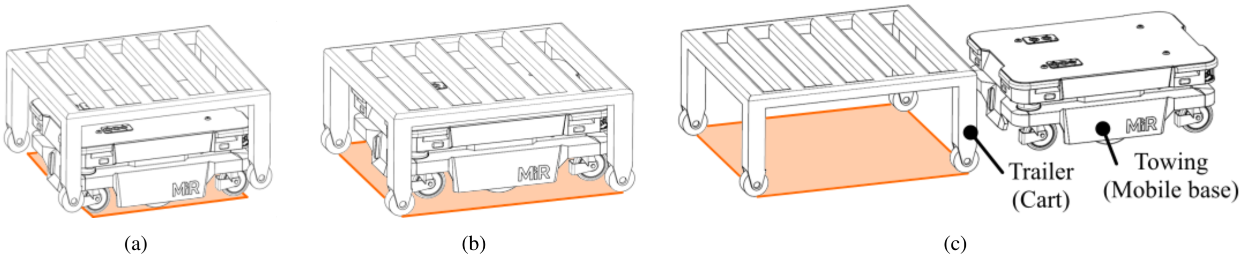

Fig. 2. Different transport strategy: (a) the mobile base lifts the cart; (b) the AMR drags the cart; (c) the mobile base hooks the cart and transports it in a towing-trailer mode.

Table 1. Selection table for the transport strategy.

	O_1	O_2	O_3	O_4	Tot
T1	4	2	4	2	2.80
T2	2	4	3	4	3.50
T3	3	4	1	3	2.70
W	0.10	0.30	0.30	0.30	

criterion and results are shown in Tab.1. The dragging strategy is elected the best solution mainly thanks to its high stability and maneuverability. This choice complicates the design of the braking system, whose study will be addressed in the following section.

The next step is to study and select the device by which the AMR is coupled to the cart. We considered two possible approaches: the first consists of designing a custom device, while the second is to purchase a commercial solution. Even if the former is cheaper and could offer more design freedom than the latter, a commercial solution represents a ready-to-use system; moreover, we can take advantage of the guarantees given by the provider in terms of safety and robustness. The MiR250ShelfCarrier is a ”top module” provided by *Mobile Industrial Robots*[3] that satisfies our requirements. It has to be installed on the MiR250 top plate and, thanks to the extraction of two vertical pins, binds the cart to the underneath mobile base. In addition, it offers the possibility to anchor the trolley, not only with the aid of a physical marker, but also in a free-space mode, increasing the flexibility of the system. Finally, this solution benefits from simplicity of installation and use, since it is a product supplied by the same manufacturer of the mobile base.

2.2 Braking system

During the manipulation stage, the cobot exerts forces and moments on the cart on which it is mounted. These actions might cause the sliding of the entire structure since the wheels are free to move. In this section the design of a suitable braking system is addressed. It is meant to ensure safety and stability during the cobot operating phase. Several models of caster wheels, used generally on carts, are equipped with a braking pedal that can be manually actuated but, as the mobile manipulator is required to be fully autonomous, it is necessary to implement an automatic device. Currently, on the market no solution satisfies this requirement. It is possible to start from a free wheel and develop the whole braking system, or to study an actuation mechanism for the braking pedal of a commercial caster wheel. Developing a custom device implies no certificates of safety and effectiveness of the brake, so, we choose to study and design an actuation mechanism for a commercial solution. We propose to use an 80mm diameter caster wheel provided by *Blickle*[4] and coated with thermoplastic polyurethane (TPE). A sheet-metal plate allows its fixation, while a foot pedal mechanism secures it. The custom braking system consists of a four-bar-linkage (FBL) directly attached to the braking pedal of the caster wheel (Fig.3). A discrepancy emerged in the brake engaging force values compared to those stated by the provider, which made it necessary to use a double actuation. In order to obtain the same motion law for both motors, a mechanism with a unit transmission ratio is required. We opted for a parallelogram linkage (PL) directly linked to the previous FBL, in which rod and crank members have the same lengths. Two servo motors with a maximum torque of 2.5Nm and an operating voltage of 7V are implemented to actuate the entire mechanism. They are mounted on a 3mm sheet-metal support in the wheel symmetry plane in order to avoid unbalanced stress on the pedal. A threaded rod links the two mechanism sides while pins are real-

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[3] https://www.mobile-industrial-robots.com/it/solutions/top-modules/mir-shelf-carrier-250/

[4] https://www.blickle.com/

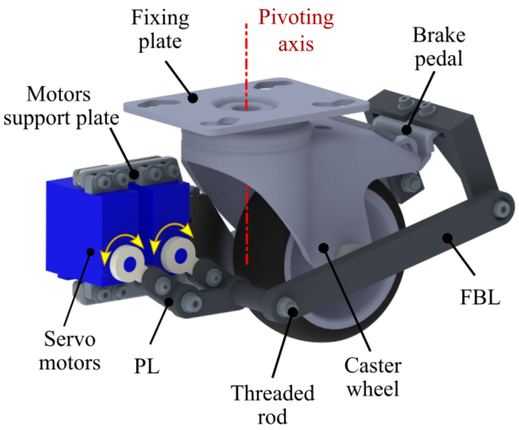

Fig. 3. Braking mechanism.

ized with screws and bronze bushes. Other components, such as linkage members, are 3D-printed components. As the caster wheel is free to rotate around its pivoting axis some issues may arise in the integrity of cables that deliver power and control signals to servomotors. To avoid cracks or cables fraying, an electrical rotating contact or ”slip ring” is implemented. This device, if installed on the pivoting axis, allows sending electrical signals regardless of the orientation of the underlying rotating part.

2.3 Lifting system

To further increase the flexibility of the mobile manipulator, a variable cobot installation height is required from the project specifications. Lifting the base extends the cobot workspace and allows the robotic system to work in different configurations and to feed the most disparate machines. In this field of application, there are some industrial solutions on the market. For example, the lifting system provided by Ewellix [24] is a telescopic linear actuator directly attached to the cobot base. However, whenever the robotic arm is lifted and picks an object, the object placement on the working plane requires the telescopic column to be lowered. In the case of handling several objects, the overall operation may take a long time. To overcome such limitation we decided to lift, not only the cobot base, but also the cart working plane. Firstly, different lifting mechanism options are analyzed:

Belt-driven actuator (L1): A belt-driven actuator is employed to lift the working plane and the cobot base. This solution is a ready-to-use commercial product and, thanks to its thinness, allows an easy access to internal parts of the cart, such as robot controller and batteries. On the other hand, it requires a fixed frame above the cart working plane and, in the lowered configuration, such a frame can interfere with the cobot workspace, thus limiting its reachability. In addition, it has a low mechanical bending resistance that may endanger the structure integrity during the manipulation.

Scissor lifting mechanism (L2): a custom-designed scissor lifting mechanism offers some advantages, such as high mechanical stiffness and the possibility of high stroke with low minimum vertical dimensions. In addition, there are no fixed parts of the frame interfering with the cobot workspace. Despite these pros, this solution limits the access to cart internal parts and, moreover, its design is a time demanding activity.

Linear telescopic actuator (L3): since it is mounted below the cart working plane, a telescopic actuator does not interfere with the cobot workspace. Moreover, the telescopic technology ensures a low vertical dimensions combined with a high mechanical stiffness that can be certified by the manufacturer. Finally, this solution does not reduce accessibility to cart internal components.

Linear actuator (L4): a linear actuator presents similar advantages as *L3* in terms of, mechanical stiffness, cobot interference, and accessibility, but for the same vertical stroke, it has a larger minimum dimension than the telescopic solution.

Table 2. Selection table for the lifting mechanism.

	O_1	O_2	O_3	O_4	O_5	Tot
L1	2	2	3	3	1	2.10
L2	4	3	2	1	3	2.80
L3	3	4	3	4	3	3.40
L4	3	3	3	3	3	3.00
W	0.25	0.25	0.15	0.15	0.20	

The selection of the best choice is based on the following weighted criteria, and every lifting mechanism is ranked with a score from 1 to 4:

O_1: vertical dimensions $W = 0.25$,
O_2: mechanical stiffness $W = 0.25$,
O_3: accessibility to internal parts $W = 0.15$,
O_4: ease of design $W = 0.15$.
O_5: interference with the cobot workspace $W = 0.2$.

Results, shown in Tab.2, report that the telescopic linear

Fig. 4. Cobot mounted on a telescopic column.

actuator is the most suitable solution, mainly due to its reduced dimensions, combined with a high mechanical stiffness. We propose to use the TL3 telescopic column provided by *TiMotion*[5] with a vertical stroke of 400mm. It is capable of lifting up to 200kg, while withstanding a static (respectively dynamic) bending moment of 2000N/m (resp. 1000N/m). Finally, the motion is generated by a 24V DC motor.

Once selected the type and model of the lifting mechanism, the study and selection of its mounting configuration is addressed. The first option deals with installing two telescopic columns at the working plane edges and on its symmetry plane. Forces exerted by the robot arm would be uniformly balanced by the two actuators. On the other hand, issues may arise in synchronising the two motors. Alternatively, one single column is mounted on the center of gravity of the cobot and on the cart workplane. In this way, the entire mechanical stress is withstood by one single actuator, but the motion control is simplified. The cobot, at the maximum reach with the maximum payload applied, generates a 500N/m bending moment and this value is considered acceptable, by taking into account the structural limits mentioned before. For this reason, we choose to install one single linear telescopic column (Fig.4).

2.4 Spatial referencing

The positioning of autonomous mobile bases at one generic destination is affected by an unavoidable error. Considering a mobile manipulator, this discrepancy from the theoretical position may compromise the effectiveness of the cobot actions, as the error has an impact on its base position. From datasheet, the MiR250 has an accuracy for a generic position in free space of ± 60mm, along directions x and y (Fig.5), and ± 5°for the rotation around the vertical z axis. Instead, if a physical marker aids the positioning, the mobile base has a repeatability of ± 3mm, along x and y axis, and ± 1°of rotation around z axis. Even if the latter values could be considered acceptable for low-precision applications, they imply the presence of several fixed markers placed along the working environment. This could bring to high costs and, moreover, makes the application less flexible. To take advantage of the flexibility given by a free-space positioning, an error compensation process is required. Computer vision science offers different solutions to accomplish this demand. Two different computer vision tools are considered:

> *IrVision*: is a computer-vision software property of Fanuc. Code functions are built-in in the Fanuc CRX controller and their integration into the software architecture is simple and time-saving. The process needs an initial manual training followed by the identification of the target object based on edges and contours detection technique [25]. However, preliminary tests highlighted a high sensibility to the light intensity of the working scene. Changes, such as the evolution of light during the day, may bring to a severe drop in the effectiveness of the solution.
>
> *OpenCV*: is a computer-vision library developed both in Python and C++ language [26]. It offers the possibility to detect the pose of different markers, such as QR-Code or ArUco, that can be attached on the object to pick or on a working station. By recognizing the position of the marker, it is possible to spatially refer the cobot to the surrounding working environment, thus guaranteeing a correct manipulation. The identification of a known marker is a robust solution, but at the same time, it requires a greater effort in terms of integration in the software architecture.

From the perspective of an industrial application, the more robust solution is preferred. As a result, we propose to implement an OpenCV algorithm based on ArUco markers, in particular, the detection of a ChArUco diamond board, which consists of a 4 ArUco pattern [27]. In addition to the board Cartesian pose, it is possible to also extract semantic information by personalizing the 4 ArUco sequence. For example, different sequences might identify different working stations or objects. The implemented gray-scale 2D camera is provided by *KOWA*[6] and, since it is mounted on the robot wrist, an eye-on-hand

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[5] https://www.timotion.com/en/products/lifting-columns/tl3-series

[6] https://www.kowa-optical.co.jp/e/

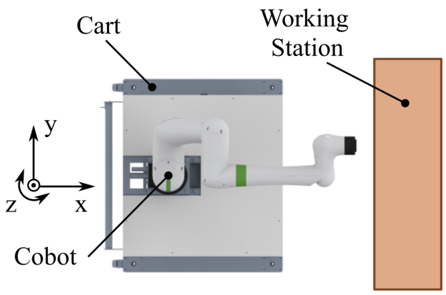

Fig. 5. Example of a working scene.

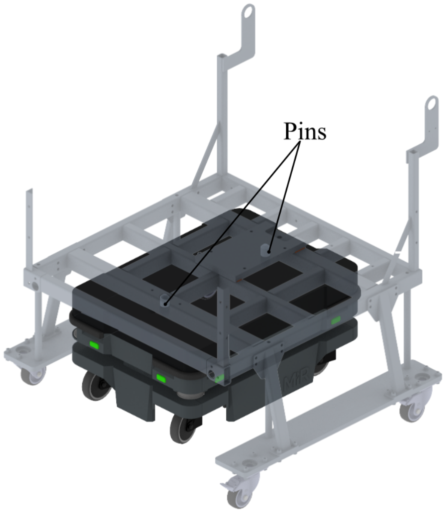

Fig. 6. Cart anchoring phase.

calibration process is required. We use a hybrid method divided in two phases. Firstly, the camera is moved by the robot in several positions, and by taking photos of a calibration chessboard, intrinsic parameters are estimated [28]. After that, following the method illustrated in [29], it is possible to reuse the same images and calculate the relative pose between the camera frame and the cobot base. By means of that, pose determined by the computer-vision algorithm can be expressed in the robot arm frame.

3 MOBILE MANIPULATOR DESIGN

Once the hardware has been selected, it is possible to tackle the design of the mobile manipulator in all its aspects (Fig.7). The collaborative robot Fanuc CRX is installed on a wheeled cart. Wheels are installed on two 15mm-thick steel plates connected to the lower plane by 4 asymmetric cylindrical legs and 4 struts (Fig.7(a)). The former are used by the MiR250 as reference for the coupling procedure. By detecting their position, the mobile base is able to refer and anchor to the cart. On the other hand, the latter have the function of guaranteeing the structure integrity. According to MiR top-module specifications, the laser scanners of the mobile base allow the presence of only 4 asymmetric cylindrical legs, other components would be considered as an external obstacle that triggers the AMR emergency stop. To avoid that, the laser zone has been modified by adding blind areas in order to hide the strut footprint. Every other component belonging to the cart lower part, such as wheels, are placed below the limit of the laser zone. The lower plane is a welded frame made of 50x30x3mm steel profiles and it is used as a fixation structure for all internal components, such as the CRX controller, batteries, and the lifting column. Two holes on the symmetry plane house the two vertical pins extracted from the mobile base during the cart anchoring phase (Fig.6). A handle is attached to allow the cart transport also by a human operator. Regarding the upper frame, it is composed of 30x30x2mm welded steel profiles on which a 800x800x5mm plate acts as the working plane. The telescopic column is installed beneath the center of gravity of the upper part, which includes the upper frame, the working plane and the collaborative arm. Finally, the entire structure is covered with 0.8mm metal sheets. The casing is also telescopic to avoid any cutting part during the ascent and descent phase of the lifting system. The cobot installation height starts from 850mm and can be increased of 400mm, thus extending the vertical reach of the Fanuc CRX, that goes from 500mm up to 2500mm. Finally, the mobile wagon weights 210kg (including the cobot) and has a 900x900mm footprint.

The whole system is supplied power by a 24V battery pack provided by *SCE*[7] and, with a capacity of 88Ah, it ensures 4 hours of continuous work. Batteries are also equipped with a battery management system (BMS) and an inverter. The former is used to manage data and parameters, such as errors handling, the state of charge or the instant current. It also guarantees protection of the battery cells in case of emergency. The latter, converts the power signal from 24V DC, coming from batteries, to 220VAC required by the CRX controller. Other components, such as the telescopic column and the brakes control box require a 24VDC power supply, so a suitable AC-DC converter is implemented. Disconnectors are installed in the electrical box to simplify cabling operations and to isolate parts in case of electrical failures. There is also a magnetothermic relay to protect components from shortcircuits

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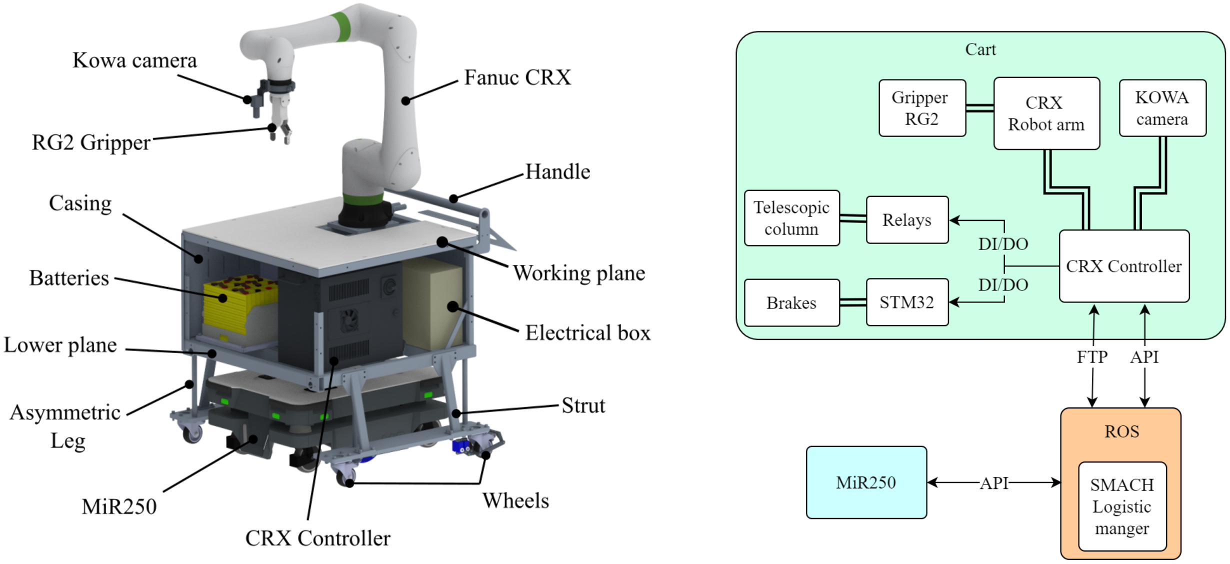
[7] https://www.sce.it/en/



(a)

(b)

Fig. 7. Proposed mobile manipulator: (a) mechanical design, (b) system control architecture.

or overcurrent situations. Finally, an insulation monitoring device (IMD) controls the correct electrical insulation of the entire circuit, in order to avoid injuries in case of external contacts. Regarding the architecture control, the whole system is monitored by Smach Logistic Manager, a ROS (Robot Operating System) package that allows defining a process subdivided into sequential or parallel states (Fig.7(b)). Each state is related to one single action or task. Through API (Application Programming Interface) it is possible to launch and monitor MiR missions. They are composed of basic logic operations and moving actions around pre-recorded positions of the working environment. Aboard the mobile wagon the CRX controller acts as a local hardware manager. Also the CRX arm is controlled by using the API protocol. It is possible to remotely launch robot programs, read and write data or position registers, and control other features such as emergency or digital inputs and outputs. The KOWA camera is directly cabled to the CRX controller and images are extracted through FTP (File Transfer Protocol) communication protocol. A micro-controller provided by *STMicrolectronics*[8] controls the motors brakes by generating a modular PWM (Pulse Width Modulation) signal, and different duty cycles correspond to different angular goal positions. Digital 24V signals, from CRX controller, act as engaging or disengaging commands. Regarding the telescopic column, its 24VDC motor is controlled by two electrical relays and two digital outputs swap the power supply polarity. The actuator lifts and lowers respectively if +24V or -24V is applied, on the other hand, the actuator is stationary when no voltage is applied.

4 EXPERIMENTS

An experimental working cycle is carried out to test the effectiveness and flexibility of the proposed mobile manipulator. In this demonstration, our robotic system is required to move around different positions of the working environment and perform various logistic tasks. In particular, a picking operation of a tray at the warehouse and a subsequent placing at a different working station (Fig.8). The demonstration is outlined as follows and the video is available also at an increased speed (Tab.3):

1. the mobile wagon is placed in the starting position by the human operator;
2. the logistic manager is started and, the MiR250 anchors the wheeled cart (Fig.8(a)). As mentioned in Sec.3, the correct relative positioning between the

Table 3. Demonstration video.

Links to demonstration video		
Mobile Manipulator	Video (1x)	Video (2.5x)
Mobile Rack	Video (1x)	

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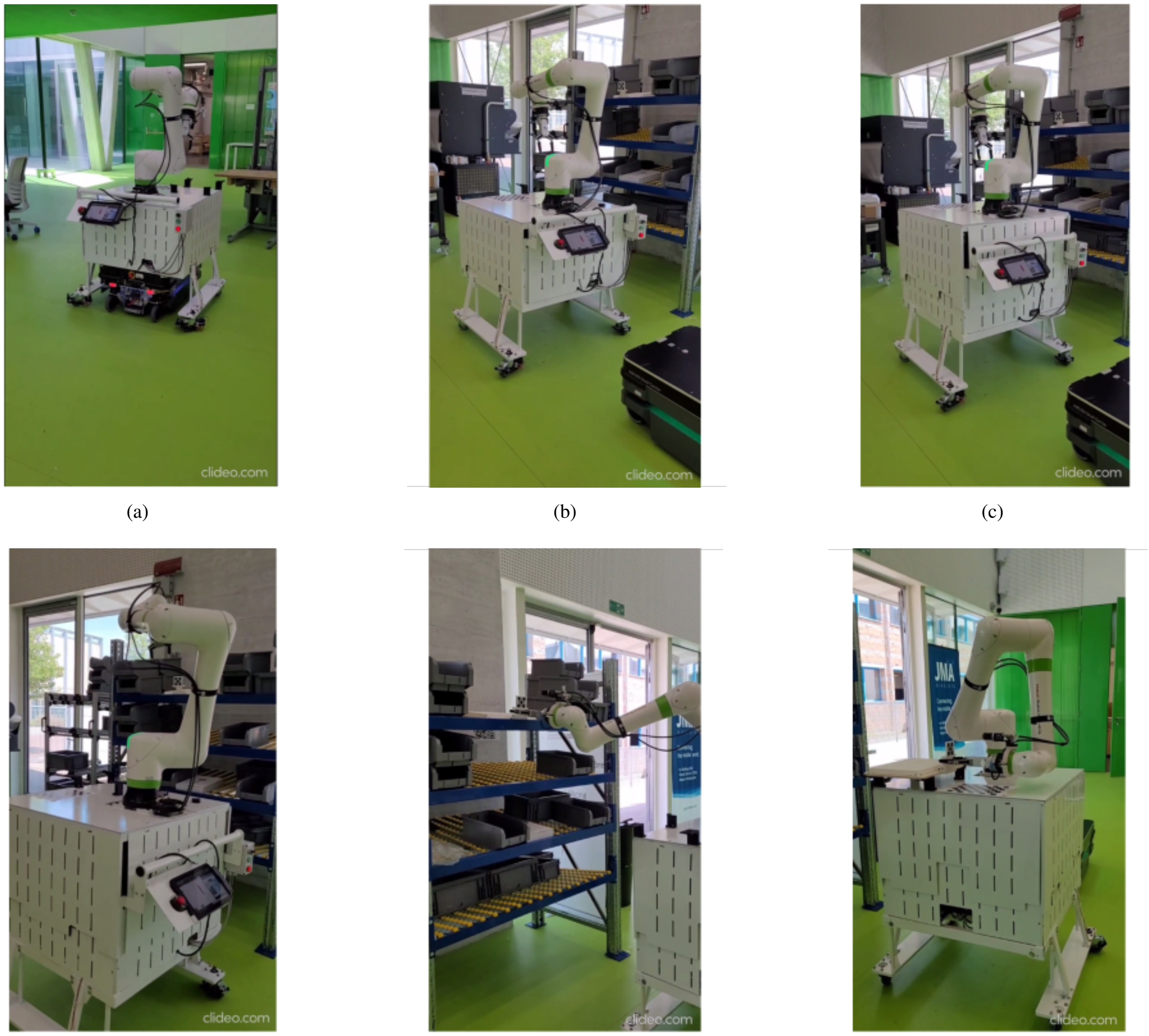
[8] https://www.st.com/en/evaluation-tools/32f3348discovery.html



(a) (b) (c)

(d) (e) (f)

Fig. 8. Working cycle phases: (a) the AMR anchors the mobile cart; (b) the AMR transports the cart to the warehouse and decouples from it; (c) the telescopic column is lifted; (d) the cobot snaps a photo of the ChArUco marker; (e) the tray is picked; (e) the tray is placed on the cart.

mobile base and the cart is guaranteed by the laser-scanner detection of the four asymmetric cylindrical legs;

3. brakes are disengaged to allow the free movement of the robotic system;
4. the MiR250 transports the mobile wagon to the warehouse; the mobile base positioning is in ”free space” since no physical marker helps this operation;
5. brakes are engaged to ensure safety and stability during the cobot manipulation;
6. the MiR250 decouples from the cart and proceeds to other logistic tasks (Fig.8(b));
7. the telescopic column lifts the working plane bringing the cobot to the suitable height for picking the target item (Fig.8(c));
8. being in a free space positioning, the spatial referencing process explained in Sec. 2.4 is required; so, the Fanuc CRX moves in a pre-recorded pose, and the KOWA camera snaps a photo (Fig.8(d));
9. the image is extracted and post-processed to recog-


(a)
(b)
(c)

Fig. 9. Mobile rack demonstration: (a) the AMR anchors the mobile rack; (b) the AMR transports the cart to the warehouse; (c) the AMR decouples from the mobile rack.

nize the cartesian position of the ChAruco marker; at this point, the cobot is able to pick and place the tray in a suitable support aboard the mobile wagon (Figs.8(e),8(f));

10. the cobot moves to a home position and the working plane is lowered;
11. the Mir250 couples with the mobile cart and brakes are disengaged;
12. the robotic system is transported to a different working station. Here, the MiR positioning is aided by a physical VL-marker, and as a result, the spatial referencing operation is not required;
13. the tray is placed on a table. It is noteworthy that, in this situation, the robotic system operates as a single mobile manipulator since the mobile base stays anchored to the cart, so no brake action is required.

To further increase flexibility and reconfigurability of the system, the coupling of the MiR250 with a mobile rack is also presented. The latter is composed of extruded aluminum profiles and it can contain different shaped bins, thanks to 4 shelves of rollers. It can be moved both from the MiR250 and the human operator, and a demonstration video is available in Tab.3. The mobile rack provides logistic support to the process as it can be moved and loaded while the AMR is decoupled from the cart. The demonstration is outined as follows (Fig.9):

1. the mobile rack stands in a free-space position of the working area;
2. the AMR anchors the wheeled cart (Fig.9(a));
3. the mobile rack is transported to the warehouse (Fig.9(b));
4. the MiR250 decouples from the wheeled cart (Fig.9(c));
5. the mobile rack is now available to provide logistic support to the cobot manipulation.

5 CONCLUSIONS

This paper presented the design of a reconfigurable mobile collaborative manipulator. With respect to commercial solutions, usually composed of a mobile base and a collaborative robot linked permanently together, the proposed robotic system consists of a collaborative arm installed on a wheeled cart the can be anchored to the mobile base only when its transport is required. In this way, it is possible to optimize working times, as the AMR is free to perform other tasks during the cobot manipulation. The study starts from the selection of the most suitable transport strategy, and continues with the design of automatic brakes for caster wheels to ensure safety and stability while the cobot is operating. The implementation of the most suitable lifting system is addressed that allows the collaborative robot to process items at different heights. A computer-vision algorithm is developed to compensate the error given by the MiR repeatability and, finally, details are given about the mechanical, electrical and architecture control design of the entire system.

The proposed solution allows two different working mode, one in which the collaborative arm and the mobile base work as one single mobile manipulator and the other in which they operate as two different entities. This peculiarity, combined with the above-mentioned features and the possibility of being transported by a human operator, gives a high level of flexibility and reconfigurability to the solution, making it suitable to work in varied working environments.

Despite these advantages, some limits are evident. In general, the process takes a long time to be concluded. Considering the use case showed in Sec.4, the cobot speed can be increased still remaining within collaborative limits, but a raise in the mobile base speed could bring to safety issue in case of brake emergency, as the mass of the mobile cart generates a great inertia. Improvements can be made also on the electrical side. The integration of higher capacity batteries will allow to pass from a 4h to 8h working autonomy that corresponds to an entire workday without the need of recharging.

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