Moderate Loads Handling & Transportation by COBOTs and AMRs: Discussion of Different Architectures to Increase Payload & Reach and to Improve Operators Ergonomics

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***Abstract* — Collaborative robots (cobot) open up many opportunities for industrial automation where interactions with Operators are required. These machines focus more on repetitive tasks, such as picking, to help workers focusing more on tasks that require problem-solving skills. Parts handling & manipulation, in production floor, logistics centers, etc. often require the combination of these two skills. In this paper, we present different architectures where cobots can cooperate with Operators to handle & manipulate moderate loads between 10kg-60kg and where the manipulation reach is further than 2 meters. Performing these loads repetitively only by Operators are the leading causes of injury and musculoskeletal disorders in production workplaces. The paper describes innovative methods for Operators-cobots interactions that require the minimal efforts for the Operator to successfully perform a load handling & manipulation task and leading to improved ergonomics in a workplace.**

Keywords – Cobots, Operator's ergonomics, load handling & manipulation, Gravity compensation, AMRs

I. INTRODUCTION

Collaborative robots, or cobots, can improve the working conditions of humans by decreasing the workload of human workers and by reducing the risk of workplace injuries such as Musculoskeletal Disorders (MSDs) [1]. Unlike the current traditional industrial robots, cobots are designed to provide more flexibility on the work floor and work safely alongside humans. In the human-robot collaboration paradigm, repetitive and precise tasks can be shifted to the robot while tasks that require more dexterity or problem solving ability can be assigned to the human [2]. An application where collaborative robots are useful, is the assembly task and more specifically the assembly of small batch size products with high variability. Currently available collaborative systems can be roughly categorized in two groups. The first group consists of light and compact cobots with a limited payload and reach, for example the UR3-5-10, KUKA LBR iiwa, ABB YuMi, Rethink Robotics Baxter/Sawyer, while the second group is formed by heavy and bulky devices with moderate payload and reach, like the Fanuc CR-35iA and Comau Aura. In between these two groups, there is a gap in the current commercial offers, for payloads ranging between 10 kg and 60 kg, and a large reach (> 2 meters) while retaining a compact solution. Market studies indeed confirm the largest growth potential for collaborative payloads to lie in the > 10kg payload range.

In a recent project [3], a research team represented by the authors of this paper, explored different innovative architectures to extend cobots payloads and spatial reach, while keeping a compact solution in an industrial floor. This paper summarizes these architectures, their implementations and achieved results.

The innovative contribution of this paper relies on extending a standard cobot' s payload and spatial reach by presenting different architectures to augment the cobots, both hardware and software wise, to make them compatible for moderate loads handling applications where operators stay strongly in the loop. A decision tree is also elaborated to facilitate the selection of one or a combination of architectures for a custom handling application with specific technical and safety requirements.

In Section II, studied architectures to increase cobots payload are described. In Section III, studied architectures to increase cobots spatial reach are summarized. Section IV discusses the experimental validation and achieved results. In Section V, a Decision Tree to facilitate the choice of one or combined architectures for moderate loads handling problems is presented and discussed. Conclusions are made in Section VI.

II. COBOTS ARCHITECTURES FOR INCREASED PAYLOADS

In this section, two architectures to increase cobot' s payloads beyond the specified payload of the cobot are discussed. Both architectures allow to augment the cobot with an extra system that shares the payload handling together with the cobot.

A. *Increased COBOT payload by gravity compensation*

In order to increase the payload of a cobot without changing its design, one solution consists of assisting the cobot with an additional structure that will handle most of the static torque due to the payload. A popular trend in robotics are gravity compensators which are either passive [4] or active [5]. These mechanisms can be placed directly on the joint and compensate for a payload (generally fixed if passive and variable if active). When placed on a joint directly, they have a torque-angle characteristic only function of the joint angle which is their main weakness as only few robot configurations (especially for robots with several degrees of freedom) have a static torque only dependent on one joint angle. More complex compensators can be used but they will generally require a change in the structure of the robot and are thus not discussed. Another option, close to what is already done for human Operators, is to combine a lifting platform with a cobot such as jib crane or a hoist. This interestingly creates a parallel structure (and not an open chain anymore) with a part of the system which can be fully actuated or under-actuated (jib crane) and another part actuated or even over-actuated (when 7 degrees of freedom are present in the cobot). Most of the work-space of the cobot is still available by using these platforms although this can cause a reduction of the number of degrees of freedom at the end-effector. A commercial solution based on this idea (CobotLift) already exists and increases the payload from 16kg (of a UR-16 cobot) to 30kg. The lifting system is a pneumatic one that has limitations in terms of kinematics. The first concept in our research proposes a passive lifting platforms using gravity compensators with improved kinematics [6]. A conceptual sketch of the combination of the proposed gravity compensation system and a cobot to increase the payload is show in Figure 1.

This compensation system acts as an advanced cantilever that compensates for the excessive weight above the cobot payload.

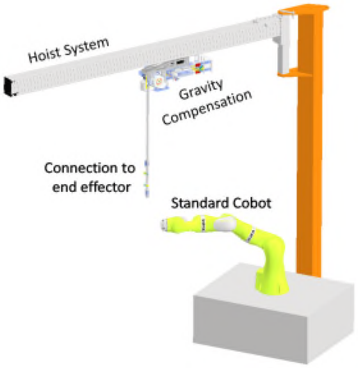

Figure 1. Sketch illustrating the proposed gravity compensation system to increase cobot payload

B. *Increased COBOT payload by industrial hoist*

The second concept of our research consists of combining the cobot with an industrial passive hoist system. The load is fully handled by the hoist while the cobot / robot acts as a guiding system. A conceptual sketch is illustrated in Figure 2. While the hoist compensates gravity, a robot with reduced payload guides a heavy load to a precise target position and orientation, for example during a transfer motion or an assembly process. A gantry supports the hoist, providing one or two degrees of freedom that are either passive or actuated. The robot could be replaced by a cobot. For extending its reach, the robot could be placed on a mobile platform (see Section III).

Different levels of integration between the motion controllers of the subsystems (gantry, hoist, robot, platform) are possible, resulting in different implementations for the overall task controller. A major concern is to protect the robot end effector against the occurrence of high forces due to modelling errors or disturbances (e.g., due to synchronization errors) in the overall motion control system. To this end, the robot end effector (red box in Figure 2) includes, besides a gripper, a 6D force/torque sensor and a 6D passive compliance.

III. COBOTS ARCHITECTURES FOR EXTENDED REACH

In this section, two architectures to increase cobot' s reach are discussed. Both architectures are based on setting cobots in a wheeled unit that allows unlimited reach.

A. *Extended Cobot Reach by instructable AMR*

Autonomous Mobile Robots (AMRs) enable flexible and changeable small series production where 87% of the production time is going in transporting parts and components [7]. For parts transportation and handling in production floor, AMRs enable automation of these tasks, as they benefit of both, a flexible moving platform to automatically move, and a flexible manipulator, typically through a high degree of freedom cobot.

While in theory, the autonomous mobile system of the AMR would allow an unlimited reach of the manipulator system, synchronizing these two high-tech systems to deal with complex handling of various tasks, parts & environments, as well as having intuitive interactions with Operators remain a challenge in practice.

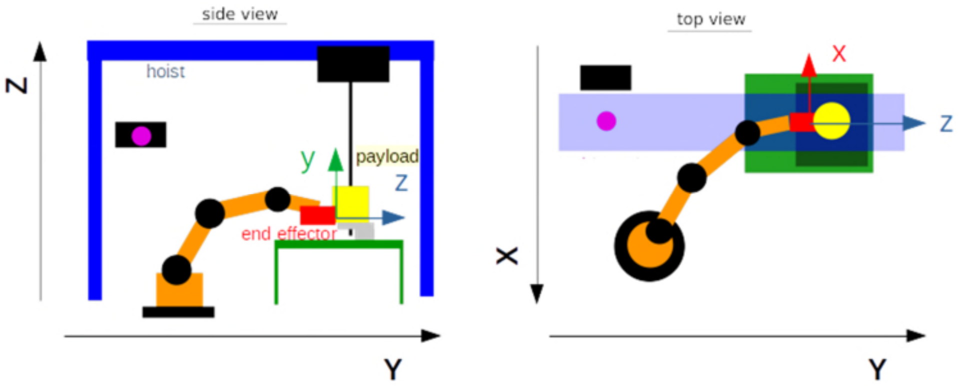

Figure 2. Schematic layout of robot-hoist co-manipulation

Our research platform consist of configuring a standard AMR by controlling individually or in synchro different parts of the AMR (i.e., manipulator / mobile platform) to physical support Operators, such that the AMR performs basic manipulation tasks (e.g., actively handling a part) while the Operators concentrate into precise actions (e.g., screwing parts to each other's). The first concept (Figure 3 - Left) consists of configuring an AMR to act as a 3rd hand supporting Operators to assemble parts (±10kg) in difficult poses. While the second concept (Figure 3 - Right) consists of configuring an AMR as a 'joystick' allowing Operators to organically interact with the full system in order to transport parts with moderate loads (±20kg) in an extended reach within a production environment.

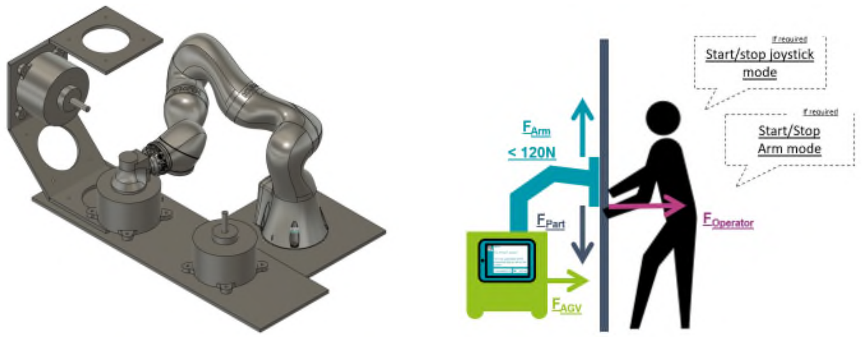

Figure 3. (Left) AMR configuration as a 3rd hand to support Operators, (Right) AMR configuration as a 'joystick' for part's transportation and handling with extended reach

The first case challenge consists of programing the manipulator to achieve difficult reach while smoothly collaborating with Operators, while the second case challenge deals with accurate control to synchronize between the manipulator & the mobile platform while interacting with Operators.

B. Extended Cobot Reach by Double Controlled AMR

Commercial AMRs (like the ones proposed in Section III.A) are provided with integrated mobile platform and manipulator and all safety around them. However, an AMR can also be achieved by combining a standard robot manipulator with a Wheeled Mobile Manipulator (WMM), designed from existing motorized wheels. On one hand, these WMM systems should be able to handle high payloads. On the other hand, they need to be able to move in a workspace only constrained by the environment. In case of shared control with a human Operator in order to carry heavy loads, this also requires that the platform can instantaneously move in all directions ("holonomic") and that the platform is able to quickly react to inputs of the human while jointly carrying a load. A typical solution is to use a highly powered, precise, holonomic platform, e.g., equipped with Mecanum wheels [8],[9]. These are however expensive, costly to maintain, and still limited with respect to the load they can carry. To avoid wheel slip, they also impose significant requirements on the floor on which the robot travels. Below, we present a control architecture that lessens the requirements imposed on the mobile platform such that a lower-dynamic platform with steered wheels can be used and wheel-slip can be tolerated, as long as an accurate pose estimate of the platform is available, even in cases where the platform needs to carry a heavy load. A control framework is proposed [10] that exploits the difference in the dynamics between the mobile platform and the robot manipulator in order to improve the accuracy and the bandwidth of the whole WMM. This framework uses two velocity-resolved constraint-based controllers using eTaSL [11], as shown in

Figure 4.

Both controllers use the same kinematic model of platform and manipulator and the same model of the human-robot interaction for jointly carrying load. The first controller ('platform eTaSL') however can only adapt the platform control input, i.e., desired velocity set-points for the mobile platform. It is not assumed that the mobile platform can execute these desired velocity set-points perfectly. It is however assumed that we can obtain a good estimate of the mobile platform pose and velocity via proprioceptive or exteroceptive sensors. The second controller ('arm eTaSL') determines the control input for all of the degrees of freedom of the manipulator, taking into account the measured mobile platform pose and velocity. The above results in a control architecture with two constrained-based controllers, one for the platform, one for the manipulator, where both controllers use the complete model of the robot system and task. For example, the platform eTaSL controller will also anticipate joint limits of the manipulator degrees of freedom by avoiding to move the platform in directions that will necessitate violating these limits. The manipulator controller will use its knowledge of the platform motion to compensate the errors of the platform eTaSL controller. Compared to a single constraint-based controller, this approach does not require additional modeling effort for the application developer since the same robot and task model is used for both controller.

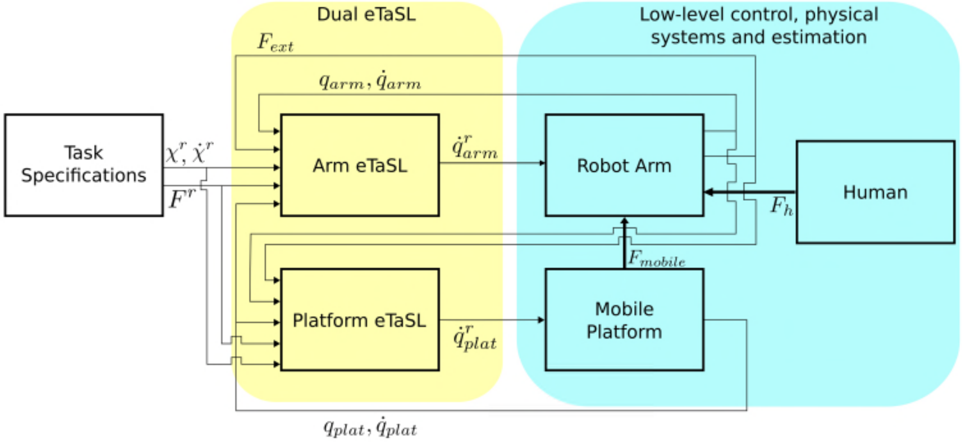

Figure 4. Control architecture for Wheeled Mobile Manipulator

IV. VALIDATION CASES AND ACHIEVED RESULTS

In this section, validation cases of all 4 architectures described in Section II & Section III are presented.

A. Gravity Compensation increases Cobot payload by x2 for light loads (<8kg)

The architecture presented in Section II.A, is implemented in Kuka Franka Emika Panda (payload 3kg). Using a jib crane, on which our gravity compensator is placed (Figure 5), the payload has been increased to 5,8kg. In this scenario, the gravity compensator can statically balance payloads between 0.8kg and 8.7kg over a stroke of 800mm which allows covering a large amount of the workspace of the cobot. Although the compensator can statically balance 8.7kg, due to internal friction, this is limited to 3kg dynamically as shown in Figure 6. This limitation is discussed in details in [6] and can be improved in future designs. By changing the level of compensation, the payload felt by the cobot can be kept minimal potentially allowing lower energy consumption for the cobot.

Scaling up the presented concept to deal with higher loads would require the redesign of the gravity compensators and use of more powerful motion components.

Figure 5. Jib crane with a gravity compensator (left – red dash line) coupled to a Franka Emika Panda Cobot (right). The payload of the cobot is initially 3kg (the gripper weighting already 0,8kg) and the manipulated load (black cylinder – green dash line) weighs 5kg

B. Industrial hoist + robot increases payload by x2 for moderate loads (>15kg)

The architecture discussed in Section II.B is implemented for heavy spools handling. As illustrated in Figure 2, the set-up includes a world reference frame *XYZ* and a robot end effector frame *xyz*. The robot is a 6 degrees-of-freedom (dof) KUKA KR16, with a payload of 16kg. The hoist is custom-made with one passive dof (along *Y*). The robot is equipped with an ATI/Schunk FTN-GAMMA force/torque sensor, a custom-made 6D passive compliance and a custom-made magnetic gripper which provided extra safety for the experiments (Figure 7). Both robot and hoist controllers are interfaced to a control pc on which the task controller is implemented in the *eTaSL* software framework for task specification and control of sensor-based robot tasks [11]. The interface to the robot reads its joint positions and sends desired joint velocities at 250 Hz with negligible delay. The interface to the hoist can only send on/off commands for up/down motions to the hoist controller. Hence, controlling the hoist from the pc is completely open loop. Moreover, the executed motion of the hoist is not completely deterministic, showing varying velocities and a considerable time delay which is also variable (~80ms). The poor-quality hoist interface and the high acceleration/deceleration of the hoist (up to 2.5 m/s^2) necessitated the use of the passive compliance in the gripper. We investigated three separate scenarios as reported below.

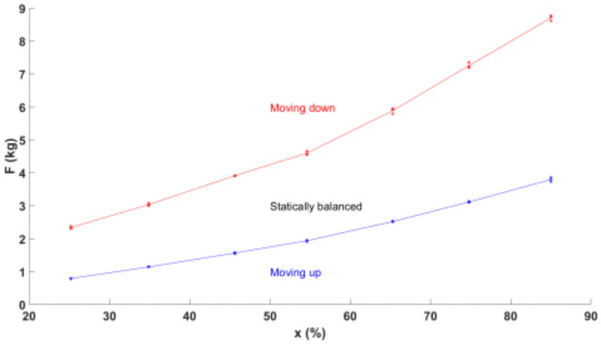

Figure 6. balanced weights versus gear ratio of the researched gravity compensation system

a) **Changing height of payload (Z)**

The main challenge for joint robot/hoist motion in the vertical direction was the synchronization between both motions. Our approach consisted of: 1) experimentally identifying the motion profile of the hoist and the variation of its time delay, and 2) controlling the end effector forces and torques to zero, while feeding forward the expected vertical hoist velocity profile to the robot. The measured vertical force for a payload of 11 kg and a change in height of 150 mm remains limited, both in executions where the open loop synchronization worked well (< 1N) or not (< 4N).

b) **Fast transfer motion along passive dof of hoist (Y)**

The main challenges were: 1) applying a suitably smooth motion profile for the payload to avoid oscillatory behavior (due to the dynamics of the passive hoist trolley subjected to a varying horizontal component of the cable force), and 2) avoiding large moments acting on the robot end effector. Accordingly, our approach consisted of: 1) applying a desired motion profile in translation that was continuous up to and including the derivative of acceleration, and 2) adding a desired orientation profile of the end effector about its *y* (i.e., nearly vertical) axis to bring the main direction of the end effector (z) more in line with the acceleration/deceleration force (in the world's Y-direction.

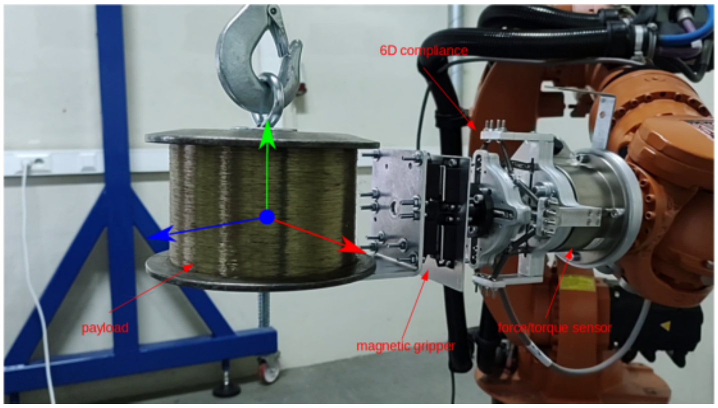

Figure 7. (Left) Experimental set-up with annotated components, (Right) QR code of a video with the realizations

This was inspired by how humans would 'pull' the payload while limiting the moment applied to their arm. The orientation profile was made proportional to the desired payload acceleration. The scaling factor determines the amplitude of the rotation. In the experiments we started and ended the trajectory with the end effector oriented perpendicularly to the translation direction Y, and allowed a rotation amplitude of Θ=30° during the motion, which reduced the moment by a factor (1-cosΘ), hence by 13%. The traveled distance was 1.5 m in 10 seconds, resulting in a peak acceleration of 0.11 m/s^2. We used payloads up to 25kg, producing acceleration forces up to 28N for the payload only, but the moment on the end effector remained limited (< 2.1 Nm) thanks to this approach. No significant oscillatory behavior was observed.

c) **Force-controlled placement into a container**

This scenario assumes the payload has been transferred along Y and lowered to a 'sub-target' position that represents an appropriate approach position for the final placement (below gantry) in a 'target' position (not below gantry) that is subject to uncertainty (Figure 2). This final placement consists of two force-controlled motions (in X- and Y-directions, respectively) towards a wall of the container, followed by a brief activation of the hoist to deposit the payload while staying in contact with the two walls. This scenario did not pose any further challenge.

To summarize, even though this case considered a simple set-up (passive DOFs of the hoist, poor-quality interface of the hoist controller with the overall task controller), it was shown that a robot, in combination with a hoist, was able to manipulate a payload that exceeded its own capacity in industrially relevant scenarios.

C. Instructable AMR allows an easy to operate mobile 3rd hand for Operators

The architecture described in Section III.A., allows a modular configuration of a standard AMR to an organic mobile 3rd hand for Operators in assembly stations. The realizations of the two concepts described above are illustrated in Figure 8. Both realizations have been achieved by the following main steps, (i) programing the AMR in a compliance mode for a smooth collaboration with Operators (ii) modular configuration using pre-programmed modules for basic tasks (e.g., parts pick-up & drop-off) and programming new modules to make the process as intuitive as possible (e.g., automated gripping, active load estimation), (iii) easy interactions and instructions with / by Operators such as using interactive HMI (e.g., tablet) or hands-free control through natural speech interaction.

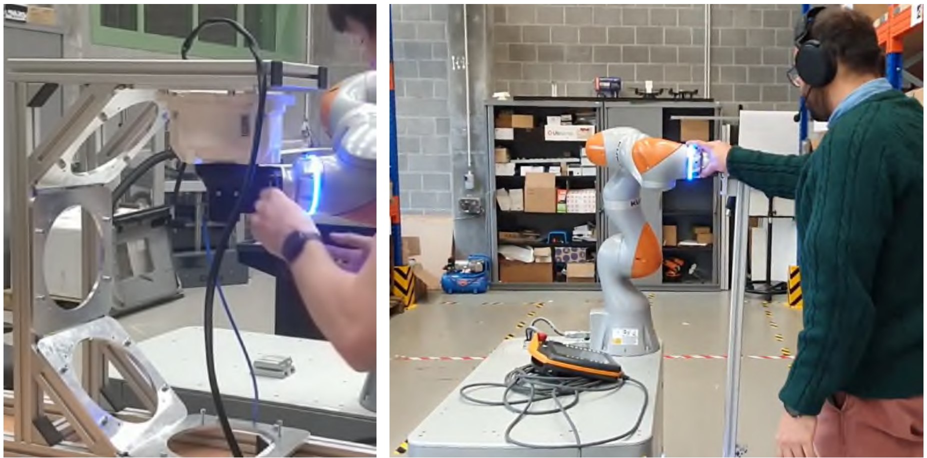

Figure 8. (Left) AMR in a 3rd hand configuration, (Middle) AMR in Joystick configuration, (Right) QR code of a video with the 2 realizations

D. Independent wheels control for illimited reach for heavy payloads

A mobile platform capable of carrying heavy payloads was designed using four wheel units. Two wheel units manufactured by KELO [12] were differentially actuated and two wheel units were passive caster wheels (cf. Figure 9-a). Each KELO unit has a payload of 125kg, which translates to a mobile platform evenly distributed payload of 500kg. Although this kinematic configuration is theoretically holonomic, significantly high wheel velocities can be necessary to move in directions perpendicular to the wheel axes of the drive units. These higher velocities can exceed actuator capability and can cause wheel slip, especially on uneven or dirty floors.

The architecture explained in section III.B can overcome the disadvantages of this kinematic design while at the same time being less expensive than e.g., Mecanum wheels and can handle uneven or dirty floors. To demonstrate this using an application where a load is shared between a wheeled mobile manipulator and a human Operator, a small Franka Panda 7-dof manipulator was mounted on top of this platform and two experimental cases were executed with good performance: one involving a pure positioning task and another involving a human-robot interaction on task.

Figure 9-b shows the results a motion of the platform where a significant disturbance occurs due to wheel reversal. It can be seen that the accuracy of the proposed dual controller architecture is significantly improved compared to a single constrained-based controller (85% in the motion direction and 57% in the other direction).

In a second case, an insertion under shared human-robot interaction has been performed (Figure 9-c) with significantly reduced interaction forces due to the imperfect motion of the mobile platform. Compared to a single constraint-based controller, the interaction forces in the vertical direction where dominated by the insertion forces and remained approximately the same, while there was a reduction of disturbance force of 50% in the motion direction and 25% in the direction perpendicular to the motion.

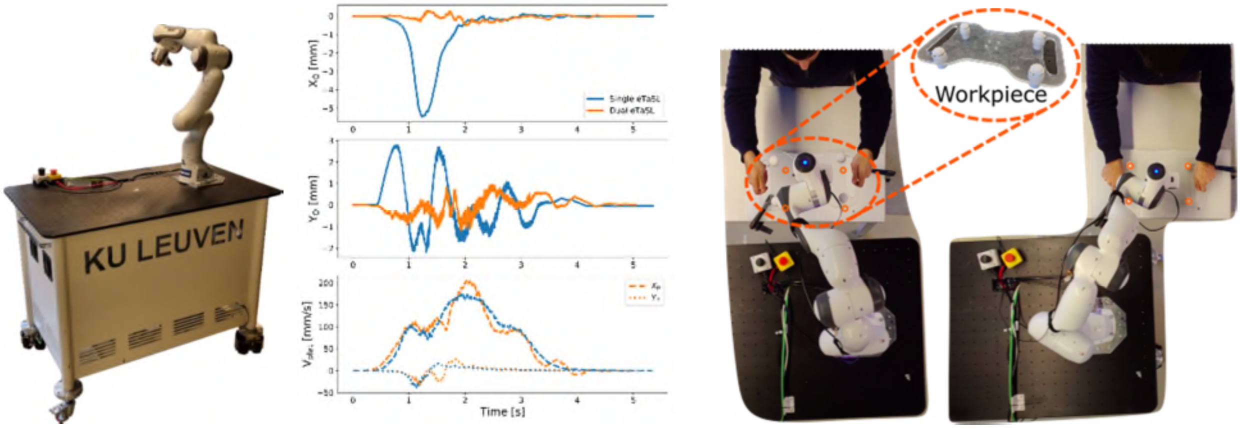

Figure 9. a) Wheeled Mobile Manipulator (WMM) set-up, b) Results for null space motion, c) Human robot interaction task.

V. DECISION TREE FOR COBOT BASED HANDLING ARCHITECTURE

Depending on the handling application, a specific cobot-based architecture can be chosen. A decision tree to facilitate this choice is illustrated in Figure 10.

The decisions are made based on 3 main criteria: (i) the spatial distance where the load to be handled should travel versus the spatial reach of the cobot, (ii) the weight of the load to be handled versus the cobot maximum payload, (iii) the level of interactions with the Operators.

If the spatial traveling distance (reach) is below 2m (standard cobot reach), a standard cobot can be used if the weight of the part to be handled is lower than the cobot payload. Otherwise, gravity compensation architectures (section IIA / IIB) can be used to augment the cobot payload. Selection between architecture (IIA) or (IIB) can be made based on the number of degree of freedoms needed during the handling of the load versus the design budget / maturity of the solution. Architecture presented in Section IIA can offer high degree of freedoms but requires more design efforts and dimensioning of the system for moderate loads. While the architecture presented in Section IIB offers a high industrial maturity but with limited degrees of freedom to handle the parts.

If the spatial reach is higher than the standard cobots reach, a motion system will be needed to extend the reach. Standard AMRs can offer a direct solution if one looks for a plug & play solution without changing system’s control and where enough budget is available (typically > 50k€).

If more flexibility is needed with regards the motion control of a cobot system, the architecture in Section IIIB presents a good decision. The mobile system can be configured and controlled in a custom way, with yet cost-effective components.

If more flexibility is needed for interacting with Operators, the architecture presented in Section IIIA presents innovative techniques to interact with a mobile cobot in terms of organic control and intuitive interaction.

Finally, the presented architectures can be combined to generate advanced custom handling systems driven by specific technical requirements, as well as by safety requirements with Operators in the loop.

VI. CONCLUSIONS

In this paper, we presented different architectures where cobots can cooperate with Operators to handle & manipulate moderate loads between 10kg-60kg and where the manipulation reach is further than 2 meters.

We explored different configurations that can be scaled-up for industrial usage starting from standard robots, cobots and mobile platforms. A summary of these configurations & how to select relevant one is given in the decision tree in Figure 10.

The paper describes different configurations illustrating how to make a standard Cobot and / or an AMR, flexible & smart handling systems that provide systematic and relevant assistance to Operators. Depending on the load to handle, the desired reach and the level of interactions with Operators, one single configuration or a combination of different configurations would be needed.

Future research will tackle limitations of current concepts and implementations to make them more suitable for large variety of loads & reaches, more modular in their control architectures to facilitate more interactions between multi-agents (cobot, mobile platform, Operator, etc.), as well as to make them more robust to deal with complex assembly parts, tasks and missions.

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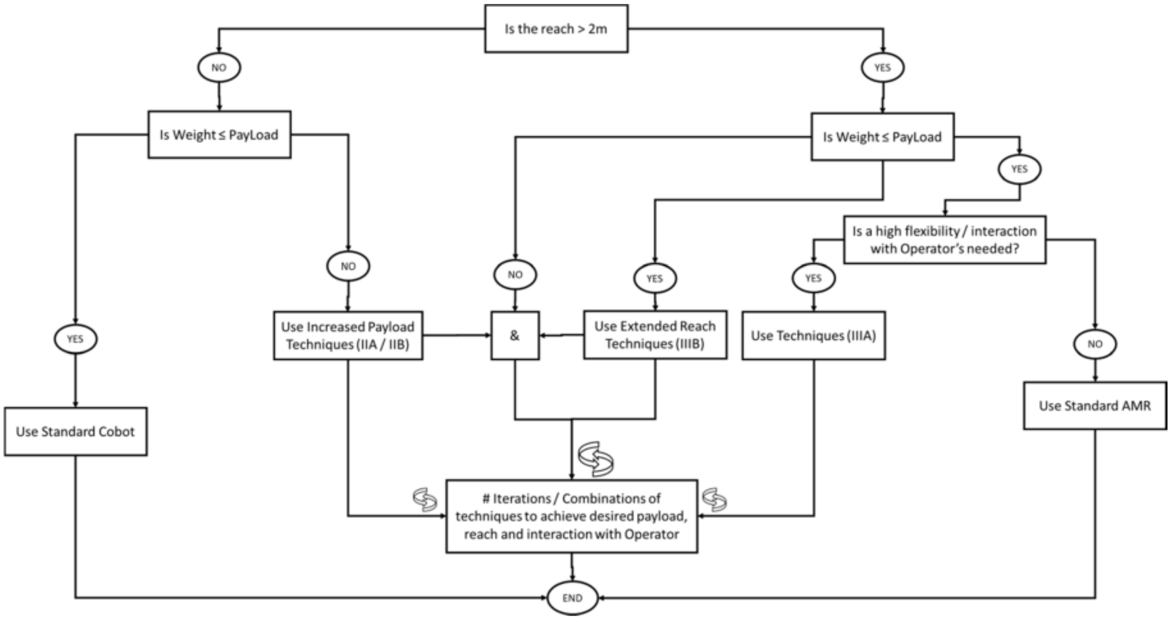

Figure 10. decision tree summarizing selection of relevant configuration for handling industrial parts based on desired load (weight), reach and interaction with Operator's

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