

Autonomous Collaborative Mobile Manipulators: State of the Art

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Abstract—*In order to extend the workspace of manipulators, the use of mobile platforms represents a good solution. This is the idea behind the concept of Mobile Manipulator (MM). In spite of their progresses, MMs have limitations, that can concern control or mechatronic design, the former being often covered in literature. Up to now, MMs are limited to specific applications and not widely spread in industry. One of the possible breakouts of these machines into industrial applications can be the collaborative way of performing some tasks.*

In this paper, a literature overview of different researches on collaborative MMs is presented to help understand the advantages of these machines, their background, the ongoing developments and their limits. A classification of these systems is presented along with definitions of each of their mechatronics components. The paper includes a focus on experimental architectures of MMs and a review of the limits of the current state of the art and finishes with possible enhancements and research topics that could be considered for future projects. This work will help in the project of designing and controlling new collaborative MMs for industrial and service applications.

Keywords: Robotic manipulation, mobile robots, mobile manipulators, collaborative robots

I. Introduction

Recent reports about the use of robotics in different fields are giving encouraging signs for developing such systems [1]. In this study, the authors specify that, while industrial robots are the most used in the world and have reached the highest number ever sold in 2013 with 178132 units sold (increase of 12% compared to 2012), professional service robots are gaining more of the market share (11% in 2013)

with a sale increase of 28% compared to the previous year. Different fields of use of these service robots are indicated such as construction, cleaning, inspection, etc. Among interesting applications of robots are collaborative tasks. In these applications, industrial robots, mainly manipulating arms, are equipped with special actuators and advanced control methods based on different kinds of sensors [2]. These modifications give the ability to the robot to detect the presence of obstacles in their workspace and avoid it or pause the work. Consequently, these robots can be used in tasks where they work together or with humans to perform a designed task [3,4]. The Paragrip project is a special case of four independent manipulators that may work together and co-manipulate a payload. In this project, objects can be manipulated by several manipulating arms used in parallel [5].

To enlarge their workspace, manipulators can be deployed on mobile platforms, thus becoming Mobile Manipulators (MMs). Different mobile platforms can be used, classified by their type of locomotion (crawling, walking or rolling), their speed or their maximal payload. Thus, MMs can collaborate to perform a lifting task, for example, with a certain degree of modularity allowing to adjust the position and the number of MMs in order to comply with payloads of varied shapes and masses [6].

Therefore, designing a universal solution where several MMs can be gathered will be very interesting, especially if the advantages of mobile platforms and manipulation robots can be kept and the disadvantages prevented. For example, one can imagine the use of several MMs in a manipulating task; the use of multiple manipulating arms for parallel manipulation generally enhances the stiffness compared to single arm manipulation, and maximizes the payload; additionally, the use of mobile platforms overcomes the problem of limited workspace.

In the DC²M³ project (Design and Control of Collaborative Modular Mobile Manipulators), the goal is to synthesize single MMs that can collaborate to create a complete

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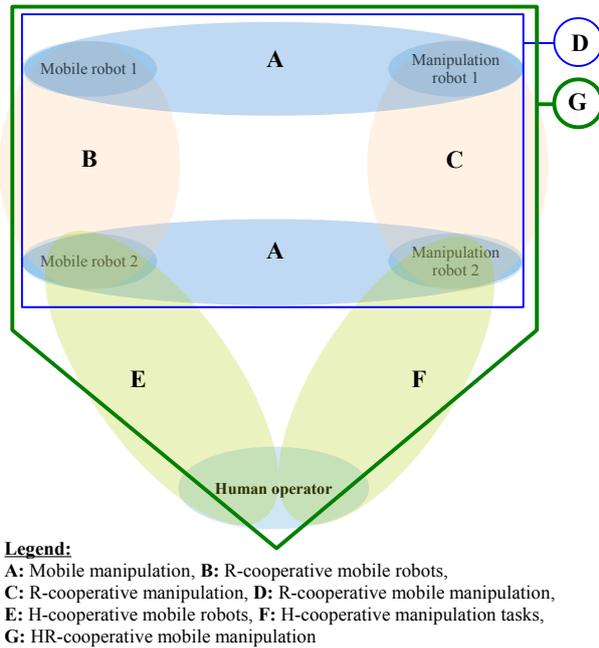


Fig. 1: Classification of autonomous or collaborative robotic tasks involving mobile robots, manipulating robots and human operators

robotic system for a specific task and workspace. Therefore, this paper intends to present an overview of the different existing solutions with their advantages and limits, comparing their characteristics and performances. This work will serve as a basis for designing innovative collaborative MMs.

First, collaborative MM components will be detailed by defining their mechatronic architecture, their use and their limitations. After that, a study of the literature on the use of multiple MMs in different configurations will be presented, with additional details on the proposed solutions. Finally, a review of the state of the art and the limits and possible tracks of development will be presented.

II. Background and definitions

In multiple robots groups, two different notions appear: cooperative and collaborative tasks. Tasks are qualified of cooperative use when robots perform tasks together without any intervention of human operators. On the other hand, collaborative tasks involve interactions between humans and robots to perform the designed tasks or simply open the robot workspace to human operators, which is a challenging constraint for the robot. Collaborative robots have to guarantee the security of the human collaborator while performing their tasks and, in case of errors, humans can be hurt. But the "collaborative" and "cooperative" terms may appear too similar, and therefore, three abbreviations

are used in this paper:

- H-cooperative: At least one robot is cooperating with at least one human operator.
- R-cooperative: Multiple robots are cooperating together to execute a common task.
- HR-cooperative: Several robots working together in presence and/or in collaboration with human operators.

Figure 1 represents this classification, representing several elementary robotic entities, human operators and possible combinations of them:

- *Mobile robots:* Mobile robots are sorted depending on numerous criteria. A first classification of mobile robots considers the environment in which they are supposed to evolve. Accordingly, there may be aerial, terrestrial, marine or submarine. In this paper, the focus is set on terrestrial MM. Therefore, only this category will be studied. Terrestrial mobile robots are further subdivided into different categories depending on their locomotion systems: wheeled, tracked, legged and crawling robots can be found. Each kind of locomotion has its own advantages and drawbacks as presented in [14]. Additionally, hybrid structures are being developed to gather the advantages of two or more locomotion types [15]. Most of the MMs are equipped with rolling mobile bases because they are intended to work on regular grounds, and rolling allows a better energy efficiency compared to other locomotion types. The bases can be holonomic (omnidirectional) or non holonomic; omnidirectional robots have no constraint on the direction of the movement. Furthermore, a terrestrial mobile robot has a planar workspace, so it needs three Degrees of Freedom (DoF) to be located on the ground.

- *Manipulation robots:* According to the online IFTToMM dictionary (International Federation for the Promotion of Mechanism and Machine Science), a manipulator is *a device for gripping and the controlled movement of objects* [16]. This machine is used for the remote handling of objects, whether in order to preserve the health of human operators by helping in moving heavy objects for example, or simply to gain time and lower costs. Manipulation robots were the first to appear on the market and are mostly used for industrial tasks. Generally, manipulators provide up to six DoF to successfully complete a task in space. Manipulators can be serial or parallel according to their kinematic architectures; "The serial kinematic chain is formed by links connected sequentially by joints. Links are connected in series as well as in parallel making one or more closed-loops in a parallel mechanism" [17].

- Serial manipulators: also called articulated arms, they represent the big part of manipulators because of their low cost, simple design and their important workspace compared to other robots. Their applications are very large, and for each application there is a corresponding architecture and control strategy. One of the recent versions of these robots are light and simple to control and are equipped with numerous sensors and actuators to allow them the work in

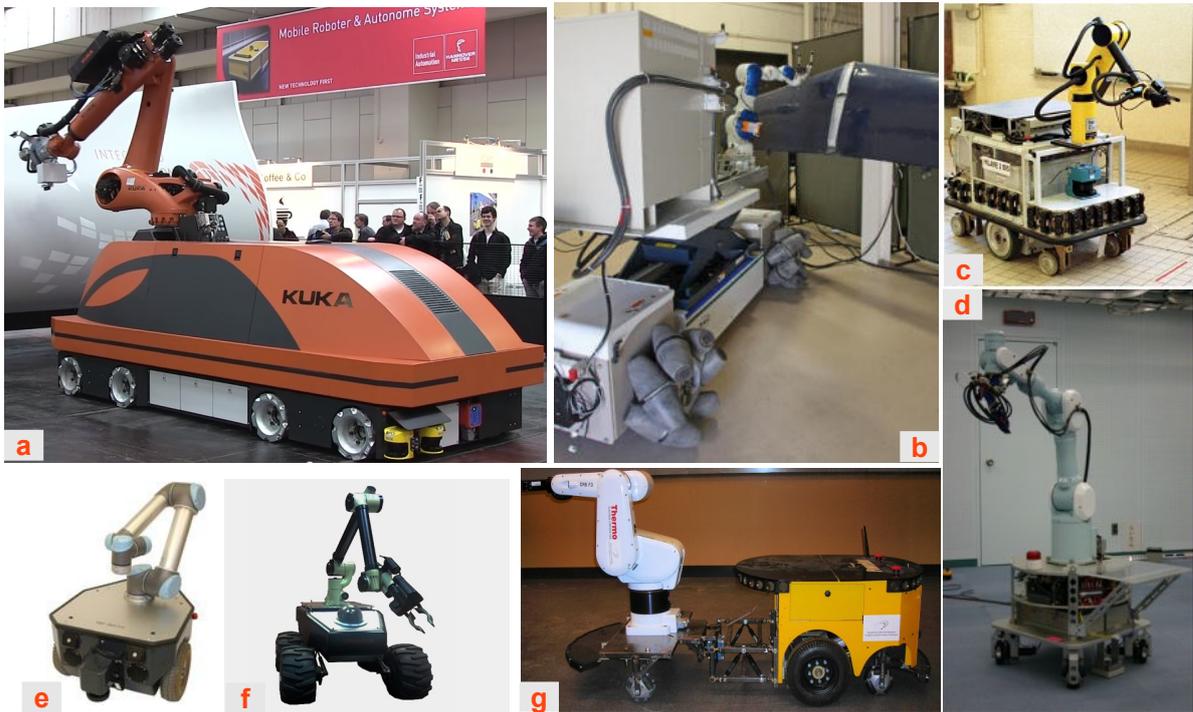


Fig. 2: Examples of mobile manipulators: a- *Kuka "Moiros"* for sheet metal manipulation [7], b- Southwest Research Institute mobile manipulator [8], c- *H²BIS* mobile manipulator [9], d- *ufmrp02* mobile manipulator [10], e- *MM-500* mobile manipulator [11], f- *Robotnik XL-Ball* mobile manipulator [12], g- University of Ontario mobile manipulator [13]

presence of dynamic obstacles. *Universal Robots* [2] and *Kuka LBR iiwa* robots [18] are good examples from this category.

– Parallel manipulators: Parallel manipulators have smaller workspace than serial manipulators of the same size and are difficult to control. However, using several limbs in parallel is a good way to benefit from a higher stiffness than the stiffness of a single limb. This rigidity allows them handling heavy payloads while being very steady during tasks. A survey of their use and examples is presented in [19]

– Hybrid manipulators: This kind of robots are the mix of the two previous categories. They are designed to gather the advantages of the two solutions, that is to say the rigidity of parallel manipulators associated with the simplicity and large workspace of serial manipulators.

• *Human operator*: In the majority of recent works, their presence is not necessary for operating the robots, that regularly gain in autonomy. Meanwhile, today's focus is on the use of robots alongside with humans in industrial, service or home applications.

The association between these different entities gives seven robotic cases:

• *Mobile manipulators (Fig. 1-A)*: Fig.2 presents some examples of MMs of different size and use. A MM is the association of one or multiple manipulation robots with a mobile robot. Different kinds of MMs can be found in multiple fields such as construction [34], military and security purposes ([35, 36]) or research platforms ([37, 38]). The size of the MMs depends on the tasks and on the environment. Large MMs are used, for example, to process surfaces (sanding, coating removal or painting) of large systems such as aircrafts or ships [8]. Moreover, small MMs can be used as well for automatic picking and transporting of small parts in assembly lines [11, 12]. In our current project, the interest is focused on medium-sized MMs. A review of this category is presented in [39], where specifications of different MMs are given with possible manipulators arms that can be associated.

• *R-cooperative mobile robots (Fig. 1-B)*: Mobile robots can be used together to accomplish simple tasks like moving an object by pushing it [40], lifting and transporting small payloads [6, 41], managing warehouse stocks [42] and exploring simultaneously the same area. They can also be used as heterogeneous swarms (*e.g.* rolling and flying

	Work	MMs	Mobile base	Manipulator DoFs	End effector	Cooperative tasks
Exp.	Khatib_1996 [20]	2	Omnidirectional	3	Gripper	PT / CL
	Sugar_2000 [21]	3	Mix	3 / 1 / 1	Fork-lift/ Plates	PT-lf
	Tang_2004 [22]	2	Non holonomic	2	Plate	PT
	Hirata_2005 [23]	2	Omnidirectional	7	Gripper	PT / CL
	Stroupe_2006 [24]	2	Omnidirectional	4	Gripper	PT
	Hichri_2015 [25]	2+	Non holonomic	1	Plate	PT-l
Sim.	Tanner_2003 [26]	2	Non holonomic	6	Gripper	PT-fo
	Chen_2006 [27]	3	Non holonomic	2	Gripper	PT
	Bolandi_2011 [28]	2	Non holonomic	5	Gripper	PT-o
	Andaluz_2012 [29]	3	Non holonomic	3	Gripper	PT-o
	Yang_2013 [30]	3	Non holonomic	2	Gripper	PT-o
	Chinelato_2013 [31]	2	Non holonomic	2	Gripper	PT / Manipulation
	Hekmatfar_2014 [32]	2	Omnidirectional	5	Gripper	PT-o
	Krid_2014 [33]	2	Non holonomic	3-4	Gripper	PT-o

TABLE I: Example of works on cooperative and collaborative mobile manipulators

Abbreviations:

MMs: Number of used mobile manipulators DoF: Degree of Freedom Exp.: Experimental Sim.:Simulation
 PT: Payload Transport; -l: large payload, -f: flexible payload, -o: presence of obstacle CL: Possible collaborative tasks

robots) to have a better overview of the environment and improve the precision of the task [43]. A survey of the task planning strategies is presented in [44]. Although these systems and strategies are efficient for relatively small and light payloads, handling larger objects may provoke instability and control difficulties due to their design, especially if the payload Centre of Mass (CoM) projection is located outside the robot supporting polygon.

- *R-cooperative manipulation (Fig. 1-C)*: The association of two or more manipulators in specific tasks can be valuable for assembly lines. In industry, lots of examples can be found, even for meat cutting and handling cooperative tasks [45]. A review of dual arms manipulation is presented in [46]. Meanwhile, systems with more than two manipulators also exist in car factories for the handling of a car body by two manipulators while a third one is painting it. This association allows an important profit for the time and cost of a single task, not to mention that the use of such systems eliminate dangerous jobs that humans used to do before. Yet, these systems are limited by their workspace, in addition to the cost of relocating and programming them for other tasks, which is very high. Another example for smaller scale R-cooperative manipulation is the PARAGRIP project, where multiple serial manipulators cooperate between them to handle a common object as a parallel manipulator [5].

- *H-cooperative mobile robots (Fig. 1-E)*: This category is the extension of the "R-cooperative mobile robots" by introducing the human operator in their workspace. For example, mobile robots for domestic use have to recognize the obstacles that face them, and in this context, humans are considered as dynamic obstacles that the robots are required to avoid [47]. Other applications needs the inter-

action between robots and humans, for instance, the *mule robots* where they follow the humans. For this kind of tasks, the robot has to be equipped with various sensors and efficient control strategy. Other strategies can be proposed where the human grabs a part of a passive mobile robot and the robot follows the human movement [48].

- *H-cooperative manipulation tasks (Fig. 1-F)*: This category is the result of adding the human operator to the "R-cooperative manipulation" category. Here, advanced security features are required to perform tasks, as recommended by the *ISO 10218-1* and *ISO/TS 15066* certifications which define multiple aspects of the collaborative tasks from the workspace set-up to the control made by the human operator. Multiple researches can be found on this topic. For example, in the *ICARO* project, researchers were interested to make a manipulator collaborate with a human operator to assemble a car part [3]. Two or more manipulators can be associated with this kind of tasks, as with some industrial applications, where multiple collaborative robots have emerged. For example, the solutions proposed by *ABB* [4] and *Rethink Robotics* [49] are designed to work side by side with human operators and share the same workspace. This collaboration is mainly made possible with the introduction of a new generation of light weighted serial manipulators.

As this paper focuses on collaborative and cooperative MMs, their uses and their limits will be presented in the next section.

III. Cooperative and collaborative mobile manipulators

The association of the previously presented entities can be gathered into two major categories:

- *R-cooperative mobile manipulators (Fig. 1-D)*: The idea

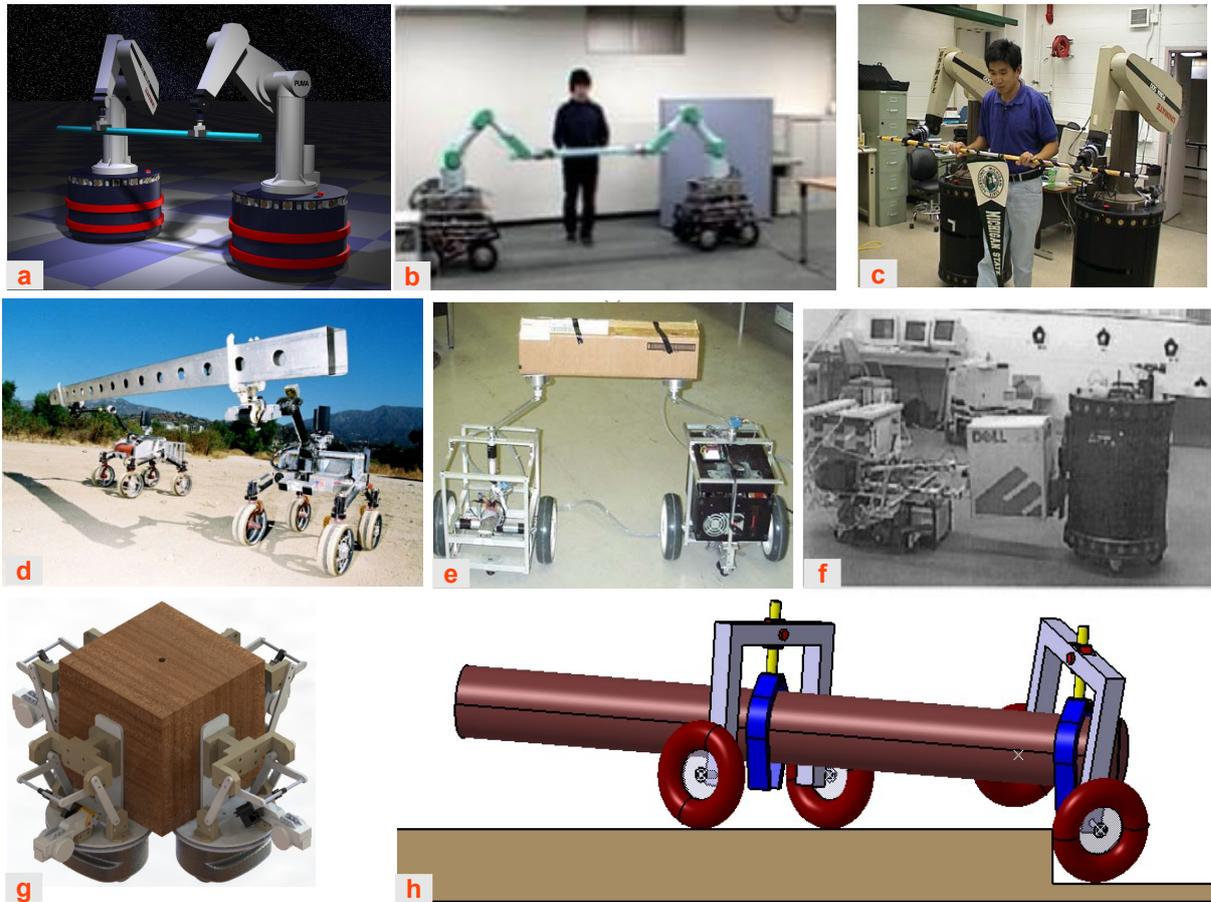


Fig. 3: Examples of collaborative and cooperative mobile manipulators: a- Stanford Assistant Mobile Manipulator (SAMM) [20], b- Collaborative experiments of the Systems Robotics Laboratory [23], c- University of Michigan cooperative and collaborative mobile platforms, d- JPL cooperative mobile manipulators [50], e- ARMLAB demonstrator of the cooperative payload transport project [22], f- Coordination of multiple and different mobile manipulators [21], g- Four C³Bots DGP (Dorsal General Payload) MMs lifting and transporting a payload on their back [6, 25, 51], h- Two C³Bots AT/VLP (All Terrain/Ventral Long Payload) MMs transporting a payload under their belly and crossing an obstacle [33, 52]

of associating MMs to perform a single task together arose since the beginning of the design of MMs. A cooperative strategy is needed when one MM can not perform the task alone. The widely spread demonstrated task is the cooperative transport of objects, where most of the research topics were about control strategies. Only few works consider re-designing the structure of MMs. For the C³Bots project (Collaborative Cross and Carry mobile roBots), two versions of MMs, both for dorsal transport of payloads of any shape (regular or irregular) and for ventral transport of long payloads (payloads that exceed the MM length and fit between wheels). In [6, 25, 51], the MMs are equipped with a specially designed single DoF manipulator that elevates the

payload when the MMs simultaneously push it (Fig. 3-g). In [33, 52], the payload is picked from the ground by a 4-DoFs manipulator and serves as a frame and counterweight during obstacle crossing (Fig. 3-h), using a control method in 18 steps that guarantees permanent stability.

- *HR-cooperative mobile manipulators (Fig. 1-G)*: The use of MMs alongside with humans can be very dangerous because MMs are relatively heavy, faster and stronger than humans, which will lead to serious injuries if the robot falls or operates without taking in account the human presence. The use of these systems must be taken with caution. Multiple examples of MMs collaboration with humans presented in [53–55].

It exists multiple examples of works on cooperative and collaborative mobile manipulation, as presented in Table I, where the upper part of the table is dedicated to fully experimental systems, that are represented in figure 3, and the lower part is for the simulation work that was done on the subject. The number of experimental platforms for cooperative and collaborative tasks is not very important. Few research institutes and projects seem to cover simultaneously mobile robots, manipulation and cooperation. The most cited in the literature are:

- *Stanford artificial intelligence laboratory* where the SAMM (Stanford Assistant Mobile Manipulator) is developed and experimented with cooperative and collaborative tasks [20] (Fig. 3-a).
- The *Systems robotics laboratory* of the School of Engineering of Tohoku University, Japan, developed experimental systems to validate cooperative tasks [56] as well as collaborative ones [23] (Fig. 3-b).
- *Jet Propulsion Lab "JPL"* (a research institute between *Caltech* University and *NASA*) designed and controlled multiple MMs in order to achieve payload transport and build simple structures by stacking beams transported cooperatively as presented in [24] (Fig. 3-d).
- *ARMLAB* which is attached to the *State University of New York at Buffalo* developed a project named "*Cooperative Payload Transport by Robot Collectives*" where different aspects of the cooperative handling of payloads were treated and with small prototypes experimental results [22] [57] (Fig. 3-e).

Meanwhile, there are multiple works that deal with the control and path planning of cooperative and collaborative MMs. Here are presented some of the researches:

- [58]: A design and a cooperative control method is proposed for the control of two MMs.
- [26]: A simulation of two MMs transporting a flexible object while avoiding obstacle.
- [27]: In this work, the authors presented an adaptive control algorithm based on neural networks to control a cooperative transportation made by three MMs. The algorithm was simulated based on small MMs.
- [29]: The authors proposed a method to cooperative control of three or more MMs. Their simulations take into account the obstacle avoidance and singularities avoidance. It's noted that the simulated system have a total of 6 DoFs, which makes it a non redundant system, therefore, the robot control will be much easier.
- [28]: The authors were interested in the problem of trajectory planning for two MMs transporting a payload in presence of obstacles.
- [31]: A modeling and control work was presented in order to control cooperative tasks performed by two MMs. The authors indicated that two phases were simulated; transport and manipulations tasks.
- [30]: A Control strategy was presented involving three 5 DoFs planar MMs with obstacle avoidance capacity.

- [32]: This work represents a control strategy to successfully complete the cooperative transport of the object while avoiding obstacles. As a base of simulations, the authors used the "youBot" MM platform ([38]).

IV. Review of the explored work

This brief literature analysis showed that most of the work deals with control strategies and path planning of MMs with the aim to optimize the energy consumption and the time needed to perform a task while assuring the cooperative aspect and the safety of the workspace, especially for humans. Meanwhile, some problems related to cooperative and collaborative MMs are obvious, amongst them:

- Design problems: This kind of problems concerns the structure of cooperative MMs presented in this paper, and can be expressed, although not limited to:

- Singularities: The association of several MMs while holding or transporting a common object forms a parallel system. Parallel systems are subject to specific singularities, that can be avoided in the case of MMs thanks to the additional mobilities of the mobile platforms. Though singularities were scarcely studied in the presented work, their analysis is compulsory for proper control of the MMs.

- Redundancies: They appear when the robotic system has more DoFs than those strictly needed to complete its task [59, chapter 11]. Away from its advantages of enlarging the singularity-free workspace, optimizing the energy consumption of the actuators and avoiding obstacles with the extra DoFs, redundancy represents a problem when controlling the end effector and the robot generally. For MMs, the total system made of the mobile base and the manipulator is redundant, independently from the task and the object, if it has more than six DoFs. In case of cooperative or collaborative tasks, most of the non-redundant MMs will form a redundant system. The challenge for this problem is to design multiple MMs that are less redundant while cooperating.

- Actuators: Using specific actuators that can be transformed to passive or semi-passive joints can reduce the actuating redundancy of the system. The problem of using this kind of actuators is that a single MM with lot of passive joints could not perform simple tasks alone. Example of this approach was the base of the *ARMLAB* project ([22], [57], etc.).

- End effectors: Most of the considered systems of cooperative and collaborative MMs are equipped with a simple gripper as an end effector. Such systems could be more efficient if equipped with more advanced end effectors like robotic hands and specific tools, along with a system for changing the tool depending on the task. These modifications would allow to adjust the complexity of the mechanical structure to the task. Manipulation tasks would benefit from advanced robotic hands, whereas simpler end effectors such as contact plates, forks or hooks could improve payload catching and overall stiffness during transport case.

An example of the latter category is the C³Bots project with one DoF manipulator that brings the payload on top of the robot [51].

- Control strategies and methods: This topic is the most viewed through the presented works and different strategies and methods are presented. Laengle and Lueth presented in [60] different control strategies that can be used for multi-agent systems. These control strategies can be used, alone or combined, in different parts of the system while controlling the manipulation arm and the mobile base, and especially when controlling simultaneously all the mobile manipulators. They can advantageously exploit perception systems, for instance multiple cameras like presented in [61]. Every control strategy can be realized based on different control methods (PID control, sliding mode control, Lyapunov-based control, etc.). Current issues in controlling distributed systems are related to the effective use of data of multiple sensors.

- Possible future works

- Task definitions: Although that most of these researches achieved their goals, MMs tasks were most of the time limited to payload transport. Defining new challenging tasks, closer to real applications for industry and service, appears to be necessary to bring MMs to the market.

- Design enhancements: Very few works try to redefine the MM mechatronic architecture, so as to differentiate from the archetype of a manipulating arm fixed on a mobile base. Rethinking the design of actual MMs can help them to be more efficient and ready to perform complicated tasks for robots. For this part, a study of the mobility of the MM and the possible singularities of the system are the first step to design an effective system for a specified kind of tasks.

- Experimental validations: Most of the models need experimental validation in realistic conditions to demonstrate the added value of using MMs in collaborative way.

V. Conclusion

In this paper, an overview study of cooperative Mobile Manipulators (MMs) was presented, with applications for service and industry. Through this paper, seven possibilities of combining manipulating and mobile robots for robot-robot and human-robot cooperation were considered. The focus was set on cooperative MMs, where multiple researches were presented and discussed. The considered studies combine most of the time two or three MMs for performing payload transport tasks. Obstacle avoidance is rarely considered and some works focus on large or flexible payloads. It can be noted that this particular field of robotics is still under exploration, and innovative mechatronic design can be imagined so new advances can be achieved in various areas such as singularities avoidance, agility through redundancy, reconfigurable actuators, interchangeable end-effectors and multi-agent control strategies.

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