A Method for Structural Synthesis of Cooperative Mobile Manipulators

Z.-E. Chebab, J.-C. Fauroux, G. Gogu, N. Bouton, L. Sabourin and Y. Mezouar

Abstract This paper deals with the design of cooperative mobile manipulators, that are not simply considered as the union of an existing mobile platform with an arm, leading to a highly redundant system, but as a system redesigned from scratch with an original minimal kinematics suitable for robot-robot collaboration. In order to design cooperative mobile manipulators adequate with the environment and the considered task, functional specifications are first expressed and partially translated into constraints on the structural parameters, both for single robotic units (m-bots) and the poly-robot resulting of the cooperation (p-bot). This method allows to obtain a set of robotic architectures that also verify other functional specifications.

Keywords Mobile manipulators · Robotic cooperation · Structural synthesis · Structural parameters

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1 Introduction

Factories of the Future are becoming a strong concern for European industry and research [3]. Industry 4.0 is also supposed to become the fourth revolution of the industry (after steam power, electricity and automation revolutions) by making the different industrial processes more modular, with real-time reconfigurability of production systems for customizable products. Different ways to achieve this revolution are considered. For example, the technical report [4] covers the domains and tasks that can be upgraded and how to perform them. In robotics, two major issues have been identified: collaborative robots and flexibility of conventional manufacturing processes. Therefore, in our DC^2M^3 project (Design and Control of Collaborative Modular Mobile Manipulators) both aspects are mixed with the goal of providing ground Mobile Manipulators (MMs) that can perform a wide range of tasks in a collaborative way by using different mobile manipulators called mono-robots (m-bots) and associate them to form a poly-robot (p-bot). The interest of the p-bot is that it can perform tasks not possible with separate m-bots and benefits from different properties. This project is the continuity of the previous C^3Bots project that dealt with payload transport using multiple mobile robots [6]. Additionally, the current project considers different manipulative tasks. Both the C^3Bots and the DC^2M^3 projects focus mostly on robot-robot cooperation, although human-robot collaboration could also be considered in future work. The interest of cooperative and collaborative systems is to help human operators for heavy duty tasks while performing them with more efficiency brought by the reconfigurability and modularity of the robots. A previous bibliographical study [2] has shown that most of mobile collaborative systems are classical MMs, which are the association of a conventional mobile platform with a manipulator arm, without a prior study on the mechanical structure. This kind of association of MMs is not optimized for cooperative use and task performance. Different methods of structural synthesis for parallel manipulators can be found in the literature [1, 5], but this paper focuses on cooperative mobile manipulators: a general approach and preliminary implementation of the structural synthesis is presented, both for elementary mobile manipulators (m-bots) and for their combination into a poly-robot (p-bot), including also hypotheses for contact joints of the wheels on the ground, considered as ordinary kinematic joints.

2 Specific Approach of Structural Synthesis of m-Bots and p-Bots

This section proposes the method that is based on structural parameters and applied to the specific case of designing m-bots that will be connected to form a p-bot. Several simplifying hypotheses will be presented for this brief paper.

2.1 Structural Parameters

Structural parameters are commonly used for specifying robotic systems. They define the mechanical characteristics of the considered kinematic chain in the robot: for instance, the serial chain that guides the end-effector of a manipulating arm, the parallel locomotion chains that support the platform of a mobile robot. Four structural parameters are used; connectivity, mobility, redundancy and degree of overconstraint. These parameters are here presented based on the definitions of the IFTOMM online dictionary [5, 7], whose notations are used for this paper:

- Connectivity: The connectivity S_F of a kinematic chain F is the number of independent displacements between its base and its end-effector. It represents the dimension of the operational velocity space of the kinematic chain R_F, with: $S_F = dim(R_F); 0 \leq S_F \leq 6$.
- Mobility: The mobility M_F, also called Degree of Freedom (DoF), of a mechanism F is the "*number of independent variables that must be considered for input motion*" [7] (definition 1.3.11). In the field of mechanical theory, the mobility is "*the number of independent finite displacements in the joints needed to define the configuration of the mechanism*" ([5], p. 79). The mobility depends on the kind and number of joints and the nature of links and is strongly related to the connectivity of the kinematic chain(s) that form(s) the mechanism, with: $M_F \geq S_F$
- Redundancy: A mechanism is called redundant when it exists "*more than one means for accomplishing a given function*" ([7], 13.3.18). The redundancy T_F of a kinematic chain F is "*the difference between the dimension of the joint space and the dimension of the operational space*", which is the difference between the mobility and the connectivity of the kinematic chain [5]: $T_F = M_F - S_F$
- Overconstraint: The degree of overconstraint N_F of a mechanism F is the number of kinematic constraints in excess with respect to the minimal number required to close the loops of the mechanism, with [5]: $N_F = 6q - r_F$ with q the number of independent closed loops and r_F the number of joints parameters that lose their independence in mechanism F.

2.2 Specifications of the m-Bots/p-Bots and Simplifying Hypotheses

The general structure of p-bot is presented in Fig. 1 and includes m m-bots. Each m-bot includes a mobile base supported by l locomotion chains connected to the ground and supporting several manipulation and connecting chains towards the payload or other m-bots.

- *Description of the environment*: In this paper, structured environments with flat ground will be considered such as industrial halls or construction sites for civil

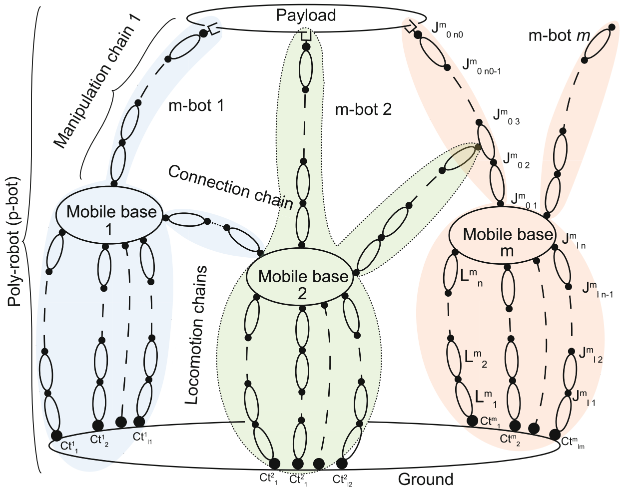

Fig. 1 General kinematic graph of a poly-robot (p-bot) based on multiple mono-robots (m-bots); *L* Links, *J* Joints

engineering applications. Future work will deal with other kinds of unstructured environments.

- *Number 'm' of m-bots*: In general, the number m of m-bots in a p-bot depends on the payload mass and the payload capacity of each m-bot, as well as the task to be performed. For this paper, the p-bot will contain no more than two identical m-bots ($m = 2$).
- *Locomotion*: In this paper, the locomotion device will be limited to wheels that are considered as the most efficient mean of locomotion in the considered environment. A previous study [8] calculated the mobility only of mobile platforms without specifying the wheel shape. In our work, mobility as well as the three other structural parameters are calculated for toric wheels specifically. In a reference frame where x represents the direction of advance of the wheel, z is opposed to the gravity and y is chosen as $z = x \otimes y$, the difference between cylindrical wheel and toric wheel is that the latter allows large rotations around the $\boldsymbol{x}$ axis (Fig. 2). Furthermore, longitudinal and lateral slipping are not allowed. Rolling without slipping hypotheses are made for $\omega_y \leftrightarrow v_x$ and $\omega_x \leftrightarrow v_y$, with ω for rotational and v for translational speeds. The contact joint (Ct) of a toric wheel with the ground has three DoF $f_{Ct} = 3$, with its operational velocity space $(R_{Ct}) = (\boldsymbol{v}_x, \boldsymbol{\omega}_x, \boldsymbol{\omega}_z)$.
- *Manipulation*: Each m-bot includes a manipulator with a manipulation chain supporting an end-effector. Their architecture depends on the required functional specifications of the task.
- *Connection capacity between m-bots*: It is achieved with a connection chain that can connect one body of m-bot i to another body of m-bot $i+1$. The body can be the mobile platform for simple attachment between m-bots. It can also be a body of the manipulation chain for manipulation reinforcement, similarly to a human that

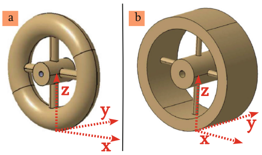

Fig. 2 Toric (**a**) and cylindrical (**b**) wheels

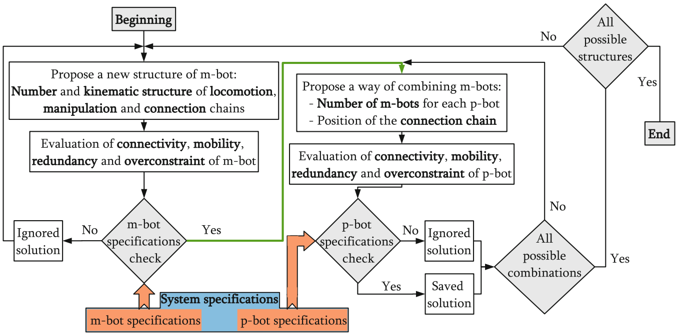

Fig. 3 The proposed structural synthesis approach

would catch its right wrist with its left hand for manipulating heavier payloads with the right hand (Fig. 1).

- *Description of the task*: In this project, the goal is to design a robotic modular system that can achieve various kinds of tasks, from machining to manipulating. For this paper, the considered task is to pick an object from the ground in a given pose A and transfer it to another location with pose B. This includes translational and rotational motions for manipulation. The industrial applications considered in this project are mechanical manufacturing and assembly. The m-bots will perform this task for small parts, whereas the bigger parts will be manipulated with a whole p-bot.

The considered approach of structural synthesis is presented in Fig. 3.

3 Application of the Approach for the Design of m-Bots/p-Bots

Some of the previous specifications may be now converted into constraints on structural parameters to be used into the structural synthesis approach. Two different sets of constraints will be defined: one for the m-bots and one for the p-bots. The index m will be used for the structural parameters of m-bots and the index p for the structural parameters of p-bots. The constraints only concern three of the four structural parameters as mobility M_F derives from redundancy T_F and connectivity S_F with $M_F = T_F + S_F$.

- *Constraints on m-bots*:
  - Connectivity: For the considered pick and place task on a plane ground, the operational velocity space needed for m-bots is $(R_m) = (\boldsymbol{v}_x, \boldsymbol{v}_y, \boldsymbol{v}_z, \boldsymbol{\omega}_z)$ $((\boldsymbol{v}_x, \boldsymbol{v}_y, \boldsymbol{\omega}_z)$ for the planar movement and $(\boldsymbol{v}_z)$ for picking and placing the payload) therefore $S_m \geq 4$. Choosing $S_m = 5$ or $S_m = 6$ can be useful for payload orientation and manipulation dexterity.
  - Redundancy: To simplify the control of the m-bots, a low redundancy is preferred. So, a zero degree of redundancy is chosen on m-bots ($T_m = 0$). This means that $M_m = S_m$. This redundancy is different from the operational redundancy that occurs when the number of mobilities $S_{m'}$ of the robot is superior to the required mobilities S_m to perform the task, e.g. $S_{m'} = 5$.
  - Overconstraint: The required degree of overconstraint is null ($N_m = 0$). Verifying this condition ensures that all the wheels maintain their contact with the ground, a necessary condition for rolling without slipping.

- *Constraints on the p-bot*:
  - Connectivity: The minimum required connectivity is the same as for the m-bots due to the same specifications (planar movement and task specifications), therefore $S_p = 4$
  - Redundancy: The more redundant the system, the more complex is its control. Consequently, platforms with the lowest degree of redundancy will be preferred. This condition regulates also the mobility of the system, where $T_p = M_p - S_p$ and $M_p \geq S_p$.
  - Overconstraint: The lowest degree of overconstraint is required to ensure a good association of m-bots that form the p-bot. A null N_p means all the wheels are in contact with the ground, a necessary condition to avoid longitudinal and lateral slipping.

After the definition of the specifications of both m-bots and p-bots, the structural synthesis approach proposed in Fig. 3 is used to get the wanted solutions. For this paper, and for demonstration purpose, only two specific configurations of two wheeled and tricycle mobile platforms are presented. Figure 4 represents the four proposed structures of m-bots (CAD model, kinematic chain and structural parameters). It is noted that the structural parameters are evaluated using Gogu's formulae [5].

Among the four proposed solutions, only the solution a_2 verifies the specifications made on m-bots, where the operational velocity space (R_m) can be obtained by transforming ω_y into v_z. Using this configuration, and for demonstration purpose, only one configuration of possible p-bots is presented in Fig. 5. The construction of the p-bot is done by connecting the end effector $3a$ of the m-bot$_a$ to the link $1b$ of the m-bot$_b$ (Fig. 5-1). The associated kinematic chain is represented in Fig. 5-2 and structural parameters are presented in Fig. 5-3.

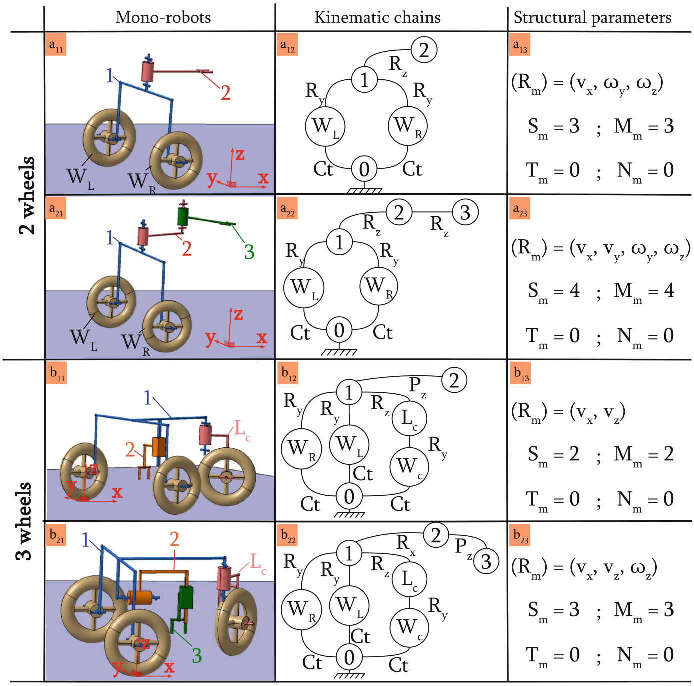

Fig. 4 Resulted mono-robots (m-bots) from the structural synthesis

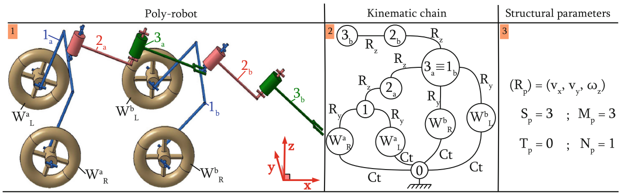

Fig. 5 Resulted poly-robot (p-bot) from the association of two mono-robots (m-bots)

The presented solution of p-bot doesn't respect the condition upon connectivity ($S_p = 1$). Arriving at this point, it is said that this configuration doesn't respect the specifications of the p-bot, and other ways of combining m-bots must be explored to get an adequate solution. If none of the ways of connecting the m-bots suits the p-bot specifications, another m-bot structure is proposed and the approach proposed in Fig. 3 is applied again.

4 Conclusion

The purpose of this paper was to present a method of structural synthesis of cooperative mobile manipulators. The process of structural synthesis began with the definition of structural parameters and specifications for mono-robots (m-bots) and poly-robots (p-bot) that had to be respected. Then, an approach of structural synthesis was proposed for designing m-bots and p-bots. A set of constraints on structural parameters was issued from functional specifications for both m-bots and p-bots in their environment and during their task. The proposed structural synthesis approach used these constraints on the structural parameters to select a group of solutions and to demonstrate the design process. The originality of the synthesis approach is to use mobility/connectivity as well as less used parameters such as redundancy or overconstraint indices. Contacts of non-slipping toric wheels on the ground are also treated as ordinary kinematic joints. In future work, a set of solutions that can pass all the process will be obtained and passed through another selection process that depends on constraints related to the task, technical feasibility and singularity analysis to finally converge to an adequate solution for a given task and environment.

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