Mobile Manipulators as Robot Co-workers: Autonomy and Interaction in the Human-Robot Collaboration

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Summary

In work environments, the use of dexterous mobile manipulators as co-workers poses several challenges with respect to the human-robot collaboration. On the one hand, its focus is in the autonomy (i.e. the mobile manipulators are required to cooperate with humans by performing autonomously complementary tasks while moving around in the human environment and in their presence). On the other hand, its focus is in the interaction (i.e. with a virtual interaction via teleoperation, or with a physical interaction through an object jointly handled). The project summarized in this paper deals with the development of planning, reasoning and control algorithms, and of the necessary software to provide mobile manipulators with the autonomy (mainly through the simultaneous planning of tasks and motions) and the capacity of interaction (mainly through teleoperation) to allow the cooperation with humans.

Keywords:
Robotics, mobile robots, robotic manipulators, manipulation tasks, path planning, teleoperation.

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1. Introducción

With the aim of facilitating the use of mobile manipulators as robot co-workers, the CoWo project has two main objectives:

a) to contribute to the increase of the **autonomy** of mobile manipulators, by developing simultaneous task and motion planning strategies to allow the finding of feasible plans, including manipulation motions, and human-like motions in the case of dual-arm anthropomorphic robots;

b) to contribute to the improvement of the **interaction** between human operators and mobile manipulators through teleoperation, by designing controllers, and by developing strategies to handle redundancy and to properly manage the singularity problem.

The contributions done to fulfil each of these two objectives are summarized in Sections 2 and 3. The experimental and simulation set-up is sketched in Section 4 and finally the conclusions are presented in Section 5.

2. Robot autonomy through planning

Regarding the autonomy required for mobile manipulators to play the role of co-workers, the current project focuses on planning issues, contributing to: a) at motion level, on the one hand, to the plan of human-like motions for the case of dual-arm anthropomorphic robots, and on the other, to the plan of motions with interaction with the environment; b) at task level, to the introduction of methods to simultaneously combine task planning, using heuristic search, with physics-based motion planning.

2.1. Human-like motion planning

The problem to be solved is the motion planning of a dual-arm system, looking for a reduction of the planning complexity, while trying to mimic the movements that a human does to solve a given task. With this aim, we propose the use of the synergies that exist in the dual-arm movements when humans solve different tasks. These synergies are employed to decrease the complexity of the planning phase

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through a reduction of the dimension of the search space, adapting, when possible, this space to the task to be solved. Besides, the resulting motions have human-like appearance.

The first approach in this line was proposed in (García et al., 2015a) that, as illustrated in Figure 1: a) captures the wrist poses of the operator's arms while performing different tasks; b) maps these poses to the joint space of a two-UR5 robotic system using the inverse kinematics; c) runs a Principal Component Analysis (PCA) and selects a reduced number of components (those with highest dispersion) to obtain a lower subspace; d) plans in this subspace using an RRT-connect planner (Kuffner and LaValle, 2000). The planning in this configuration subspace significantly reduces the complexity of the problem while preserves the human-like appearance. This approach is further explored in (García *et al.* 2017a), where a measure of the similarity of the movements needed to solve two given tasks is introduced and used to select the proper arm synergies for a given task, in order to improve the planning performance and the resulting path.

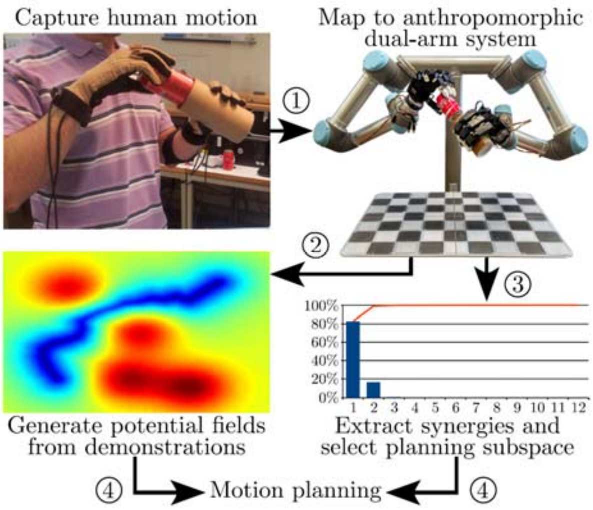

Figure 1: General schema of the motion planning approach.

In (García *et al.*, 2015b) an RRT*-based algorithm was introduced to minimize a user-defined cost function built as the combination of several potential fields. This idea was resumed in (García *et al.*, 2015c) by proposing the use of first-order synergies (correlations between velocities) to modify the growing directions of an RRT tree. For that, an automatic partition method was defined to optimally divide the configuration space into cells where first-order synergies are significantly different. The extension of this idea to the planning of human-like motions for a dual-arm system was introduced in (García *et al.* 2017b), using the KPIECE planner (Sucan *et al.*, 2010). In this case, the zero-order synergies are used to define the projection space that guides the tree coverage, and the first-order synergies, to define the tree extension procedure, that is adapted from a parameterless variant of the VF-RRT (Ko *et al.*, 2014). The following of the vector field defined by the first-order synergies obtained from the human captured motions, allows to obtain robot motions with a human-like appearance.

2.2. Physics-based motion planning

Robotic manipulation involves actions where contacts occur between the robot and the objects. In this context, the availability of physics-based engines allows motion planners to take into account the dynamics between rigid bodies, which is necessary for planning this type of actions. However, physics-based motion planning is computationally intensive due to the high dimensionality of the state space and the need to adopt a low integration step to obtain accurate solutions. On the other hand, manipulation actions change the environment and conditions further actions and motions. To cope with this issue, in (Muhayyuddin *et al.*, 2015a) the representation of manipulation actions using ontologies was proposed, together with a semantic-based inference process to alleviate the motion planning computational cost.

This ontological physics-based motion planning framework was extended in (Muhayyuddin *et al.*, 2017a) to linear temporal logic (LTL) problems in order to handle complex temporal goals. The proposal also included a simplification process for LTL formulas according to physical reasoning in order to detect unfeasible regions.

Complementarily, in (Muhayyuddin et al., 2015b) evaluation criteria were proposed to analyze the performance of several kinodynamic planners, which are at the core of physics-based motion planning, using different scenarios with fixed and manipulatable objects. The results showed that KPIECE computes the time-optimal solution with higher success rate, whereas, SyCLoP (Plaku *et al.*, 2010) the most power-optimal solution among the planners used.

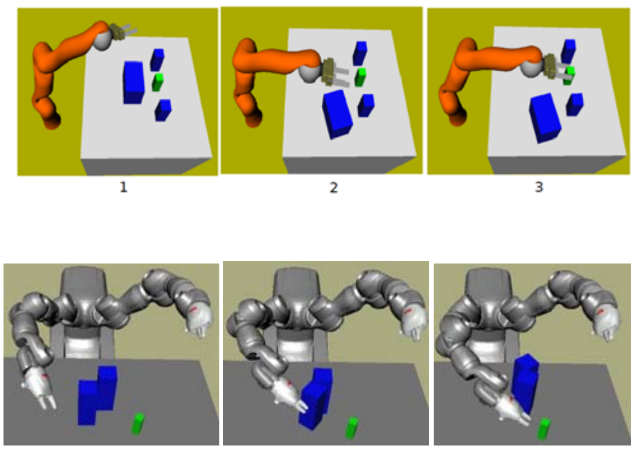

Figure 2: Motion planning for grasping allowing the interaction with obstacles.

This research line has also been extended to the motion planning for grasping in the presence of uncertainty (Figure 2). In (Muhayyuddin et al., 2017b) a knowledge-oriented physics-based motion planning approach has been proposed for a hand-arm system that uses a high-level knowledge-based reasoning to partition the workspace into regions to both guide the planner and reason about the result of the dynamical interactions between rigid bodies.

2.3. *Simultaneous task and motion planning*

Different approaches have dealt with different strategies to combine task planning (based on high-level symbolic reasoning) with motion planning (based on low-level geometric computations), with the aim of finding a feasible plan to solve a given task.

One approach to task planning, done in the planning space, is the Planning Graph (Blum and Furst, 1997), which is a graph that interleaves state-levels (involving a number of literals) and action-levels (representing a set of actions). Mutual exclusion relations are defined among actions as well as among literals (indicating how the combination of literals can be true at each state-level). Action-levels contain actions whose preconditions are met in the previous state-level, and they may add or delete some literals in the subsequent state-level. The construction phase is launched from a state-level that includes the initial state of the problem, and continues till a state-level is found where all goal conditions are satisfied. A modified version of the Planning Graph algorithm was proposed in (Akbari *et al.*, 2015a) to allow the retrieving of a number of potential plans that are then evaluated by a physics-based motion planner to find the least-cost feasible one. Then, the approach was modified to evaluate the feasibility of actions while planning (Akbari et al., 2015b), allowing to cut off some infeasible action branches at the task level.

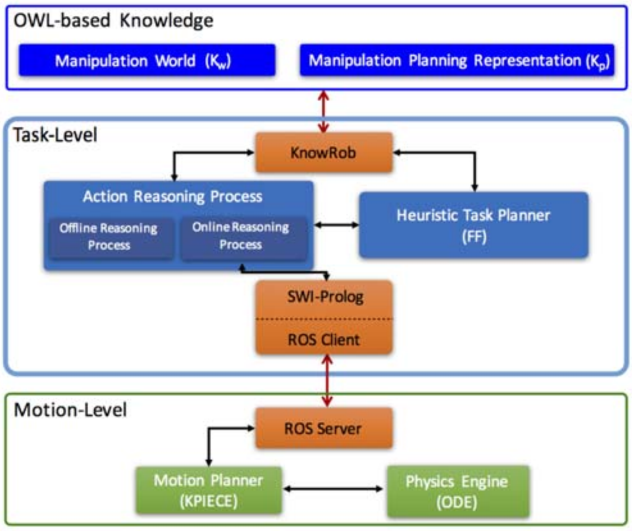

Figure 3: Task and motion planning framework.

Alternatively, task planning is done in the state space, like the Fast Forward (FF) method that uses a heuristic search. The heuristic is computed with the Relaxed Planning Graph (RPG), which is a Planning Graph that ignores the delete lists of actions, in terms of the estimated number of actions needed to reach the goal. Then, the state space exploration is done with the Enforced Hill-climbing method that selects the more promising successor state using the heuristic values. A modified version of the FF method was proposed in (Akbari et al., 2016a, 2016b) to mitigate the computational cost, in terms of number of calls to the motion planner, that the approaches based on the Planning Graph had. This FF variant uses physics information of the objects for the costs of actions during the RPG construction, and calls the physics-based motion planner only on the actions selected in the RPG plan computed to obtain the heuristic. The approach uses the geometric reasoning based on the connectivity of the configuration space to determine the pre- and post-conditions of the push and pull actions. As a result, an efficient combination of both levels of planning allows to obtain power-efficient feasible plans. These results are currently being extended to multiple robots and to robot manipulators with pick and place actions. Figure 3 shows the planning framework, that is further discussed in Section 4.

3. Human-robot interaction through teleoperation

Regarding the interaction with mobile manipulators acting as co-workers, the current project focuses on teleoperation issues, contributing to: a) the design of controllers for bilateral teleoperators without velocity measurements, the leaderless consensus and the leader-follower consensus of networks of robots in the operational space; b) the design of methods to exploit the redundancy of mobile manipulators; c) the development of efficient methods to solve the inverse kinematics of redundant manipulators and to cope efficiently with their singularities.

3.1. *Control of Bilateral Teleoperators and Networks of Robots*

This section presents the contributions on the control of bilateral teleoperators and of robot networks.

In bilateral teleoperators, the local and remote manipulators are interconnected through a communication channel that often imposes time delays in the transmitted signals. Controlling these systems has become a highly active research field. Most of the previous works along this line have tackled the problem of controlling a teleoperation system assuming that velocities are measurable. However, most of the commercially available robots, which can be used in teleoperation systems, are not equipped with velocity sensors, mainly to save cost, space, and weight. In this project, we have proposed (Sarras et al., 2016) a novel controller that is among the firsts that can guarantee position tracking capabilities in bilateral, not equipped with velocity sensors and with variable time delays in the communication cannel.

The solution presented in (Sarras et al., 2016) employs the recently proposed Immersion and Invariance observer to obtain an exponentially convergent estimate of the unmeasured velocities. Under the classical assumption that the human operator and the environment define passive, velocity to force, maps, it is proved that, with this observer and a Proportional plus damping controller, velocities and position error are globally bounded. Finally, in the case that the human operator and the environment do not exert forces, respectively, on the local and remote manipulators, global asymptotic convergence of velocities and of position error to zero is achieved. The theoretical results are verified with simulations using a couple of two degrees-of-freedom nonlinear manipulators.

In networks with multiple dynamical agents, the consensus control objective is to reach an agreement between certain coordinates of interest using a distributed controller. There are mainly two consensus problems: the leader-follower, where a network of follower agents has to be regulated at the given leader coordinate, and the leaderless, where all agents agree at a certain coordinate value. With regards to the different solutions provided, in the framework of this project, for the consensus of networks of robots, there are two main research lines: the control in the joint space and in the operational space.

The results about the control of networks of robots in the joint space, have been presented in (Nuño, 2017) and (Nuño and Ortega, 2017). The main contribution of (Nuño, 2017) is the inclusion of the Immersion and Invariance velocity observer to the Proportional plus damping injection (P+d) control scheme, to provide a solution to the leaderless and the leader-follower consensus problems in networks of fully–actuated robots. In the work (Nuño and Ortega, 2017) a novel controller that solves the same consensus problems as in (Nuño, 2017) is reported, but without requiring the complete knowledge of the robots dynamics. In both cases: i) the interconnection between the agents is modeled via a connected, undirected and weighted static graph; ii) these interconnections can exhibit asymmetric variable time-delays, with the only assumption that such delays are bounded and that the bounds are known; iii) the controller only depends on position measurements.

Three papers deal with the leaderless consensus and the leader-follower consensus in the operational space, namely, (Aldana et al., 2015), (Machuca et al., 2017) and (Nuño et al., 2017). The operational space is a subspace of the special Euclidean space of dimension three, denoted SE(3). The work (Aldana et al., 2015) solves the consensus problems in the presence of interconnection delays and it proposes a novel P+d scheme. The main contribution of (Nuño et al., 2017) is a novel controller that solves the leader–follower and leaderless pose consensus problems for heterogeneous robot networks with uncertain kinematic and dynamic parameters. The main features of the proposed scheme are the following: it estimates the kinematic and the dynamic physical parameters; it is robust to interconnecting variable-time delays; and, using energy-like functions, the controller synthesis follows a constructive procedure. In (Machuca et al., 2017) the same consensus problems are solved considering that the controller does not know any parameter of the robot. For this purpose, this work reports a radial basis Artificial Neural Network controller. In all cases, the unit-quaternions are chosen as the representation of the orientation because, in comparison with minimal representations (e.g., Euler angles), they are singularity-free. Further, the interconnection of the network of robots is assumed to be modelled by a connected, undirected, graph with fixed topology. The advantages of the proposed controllers, in comparison with others in the literature, are that they can deal with networks of kinematically and dynamically dissimilar robots and that the consensus problems are solved in the Cartesian space, where most robot tasks are defined. The applications of these controllers may span multiple application areas in service robotics, like in the interaction with a heterogeneous set of robot co-workers performing tasks in human environments.

3.2. *Exploiting the robot redundancy*

This section deals with the redundancy of the robotic systems, both regarding new applications of know techniques and exploring new approaches. The redundancy allows the robot to execute several tasks simultaneously, while preserving a predefined hierarchy between them (Siciliano *et al.*, 1991). For instance, a robot can track a desired position with its end-effector while moving along a trajectory far away from singularities.

One robotic system currently being explored consists of a mobile manipulator and an unmanned aerial vehicle (UAV) with a camera. The camera is used to give visual feedback to the operator, which controls the mobile manipulator using a haptic device. The rise of low-cost quadrotors opens new possibilities in the robotic field, like this.

In (Claret *et al.*, 2016) a framework to command both the TCP of a mobile manipulator and an UAV has been presented. The proposed algorithm, following (Dominjon *et al.*, 2005), allows the user to command both robots with a single haptic device (Figure 4). Further, a experimental study shows that, with minimal training, the algorithm does not increase the operator workload.

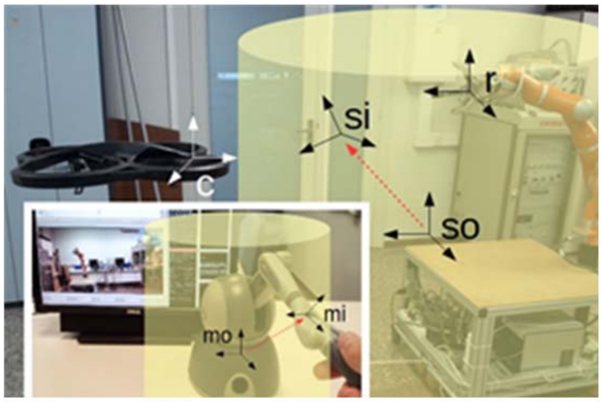

Figure 4: Teleoperation system.

Currently, the redundancy of the Barcelona Mobile Manipulator developed at our Institute (Figure 4), is being exploited to deal with three levels of task priority: joint limit avoidance, TCP tracking, and independent control of the mobile platform. This poses several challenges such as how to activate/deactivate new tasks and to deal with not fully activated tasks while still preserving the task priority hierarchy of the system (Mansard *et al.*, 2009).

Other works exploiting the redundancy of a robot have been implemented in a Pepper robot, a new humanoid robot from Softbank Robotics. In (Claret *et al.*, 2017) the first use of the null space of a robot to convey emotions to the user has been presented, along with a framework to map emotions to kinematic features of the robot. Further, in (Dubois *et al.*, 2017) the same framework has been used to study the influence of the robot proximity to the users to their responses.

3.3. *Inverse Kinematics and the singularity problem*

This section deals with the inverse kinematics of serial redundant manipulators and with the singularity problem.

Regarding the first one, a general method for analytically solving the problem for redundant manipulators has been developed. Manipulators of this kind are reduced to non-redundant ones by selecting a set of joints, denoted redundant joints, and parameterizing joint variables. While many authors like Hemami (1988) and Schrake *et al.* (1990) do not have any criterion for selecting these joints, the selection method proposed in (Zaplana and Basañez, 2017) is made through workspace analysis which also provides an upper bound of 2^m – with m the number of degrees of the redundancy - for the number of different closed-form solutions for a given pose. This number is significantly smaller than the upper bound of $C(n,m)$ – with n the number of degrees of freedom - given by the majority of authors. Once the joints have been identified, several closed-form methods developed for non-redundant manipulators can be applied for obtaining the analytical solutions. Finally, particular instances for the parametrized joint variables are determined depending on the purposes of the task to be executed, using different criteria and optimization functions.

In (Zaplana et al., 2017a) the inverse kinematics problem is solved using the tools provided by the conformal model of the Euclidean space geometric algebra. Geometric algebra is a field of mathematics devoted to the study of classical geometry with many applications to engineering and physics. In robotics, geometric algebra allows to describe the frames associated to each joint and the transformations between them using vectors of different dimension, denoted multivectors, instead of matrices. Moreover, the conformal model of the geometric algebra allows to describe the geometric entities and their relations using the same language. The benefits of such approach for the inverse kinematics are, among others:

- Less computational cost and execution time.
- Easiness in the development of geometrical solutions.

In particular, while recent approaches, like (Tordal et al., 2016), solve just the position problem for certain manipulators, (Zaplana et al., 2017a) solves the orientation and position problem for general redundant manipulators.

For the second problem, a general classification for the singularities has been developed as well as a procedure for obtaining the singular directions associated to a singularity. The classical approach is through the Jacobian matrix, which provides a relation between the Cartesian and configuration spaces in rate domain. However, in (Zaplana *et al.* 2017b) the identification of the singularities is made attending to the incidence relations of different geometric entities using again the conformal model of the 3D geometric algebra. These incidence relations are described in terms of the revolute and prismatic joint axes. Once the singularities have been identified, the extension of the Euclidean distance in the conformal model is used as a measure of how close to a singularity the end-effector of a serial manipulator is.

Finally, in (Zaplana *et al.* 2017c) a kinematic analysis of two redundant serial manipulators is performed. This analysis includes the derivation of the forward kinematics for both manipulators, as well as the solution of the inverse kinematic problem. For the Kuka LWR 4+ this solution is analytical whereas for the ABB YuMi an analytical and numerical approach is proposed. Besides, the singularities of the Kuka LWR 4+ are obtained symbolically and the singular directions associated are calculated. This study increases the kinematic knowledge of two actual redundant manipulators, and provides valuable information that can be used in the definition of different algorithms and control laws.

4. Experimental and simulation set-up

The experiments have been carried out at the robotics lab of the Institute of Industrial and Control Engineering (IOC). The hardware used is composed of: a) two omnidirectional mobile platforms (BMM1 and BMM2) each one with a Kuka LWR 4+ robot; b) an anthropomorphic dual-arm system composed of two UR5 robots equipped with Allegro mechanical hands; c) an anthropomorphic dual-arm ABB YuMi robot.

The software developments regarding the motion planning module have been done using The Kautham Project (Rosell *et al.*, 2014), an open source motion planning and simulation framework for teaching and research, developed at the IOC, that mainly uses planers from the Open Motion Planning Library (Sucan et al., 2012), and that is integrated with the Open Dynamic Engine (ODE) for the dynamic simulations.

The knowledge is coded in the form of an ontology, using the Web Ontology Language (OWL), that is accessed using the KnowRob software (Tenorth and Beetz, 2009), a potent knowledge processing tool that enables a flexible access to OWL knowledge. It is mainly developed in the Prolog language and provides fundamental predicates to fetch knowledge.

An open-source version of the FF planner implemented in Prolog has been used and modified accordingly. The communication between the task and motion layers is done using Robotic Operation System, ROS (Quigley et al., 2009). The motion planner is encapsulated as a ROS service and the task planner as a ROS client (using the SWI-Prolog library, (Wielemaker *et al.*, 2012)).

5. Conclusions

This paper summarizes the contributions done in the framework of the CoWo research project, centered at the development of methods and techniques to improve the human-robot collaboration of mobile manipulators in the role of co-workers, by increasing their autonomy through planning and the capacity to interaction with them through teleoperation. Regarding autonomy, simultaneous task and motion planning methods have been introduced to allow robots the finding of feasible executable plans and, in the case of dual-arm anthropomorphic robots, to move in a human-like manner. Regarding interaction, control strategies for bilateral teleoperators and networks of robots have been presented, as well as techniques to manage the redundancy and to efficiently cope with the singularity problem.

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