Dynamic Obstacle Avoidance for Omnidirectional Mobile Manipulators

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Abstract. The last decade witnessed an unprecedented spread of robotics. The production paradigm of Industry 4.0 and 5.0 yielded collaborative robots in production lines of all sizes. Also, the robots started leaving the industrial scenario to play a leading role in the field of personal assistance. These environments share a common challenge, i.e. the safety of people working and/or living around the robots. Collision avoidance control techniques are essential to improve such aspect, by preventing impacts that can occur between the robot and humans or objects. The paper extends algorithms already developed by the authors for robotic arms to the case of mobile manipulators. The control strategy, which has been refined in the contribution of the robot bodies, has then been tested in two simulated case studies involving an industrial mobile robot and the custom service robot Paquitop, developed at Politecnico di Torino.

1 Introduction

Due to the ever growing development in the field, the last years have been characterized by the diffusion of robots in every aspect of every-day life. Industry saw the wide spread of *collaborative robots* (or *cobots*), especially in small and medium enterprises (SME's) [1]. In fact, small batch production and high level of product customization make these industrial entities still based on the versatility of human labor. Cobots, for their part, had a chance to easily insert themselves in this productive paradigm for they have been specifically developed for coexistence and collaboration with people. In *non-productive* scenarios, robots made their part in the field of personal assistance: the ageing society is a very well known fact [2] which kept the attention of the robotics research community for the extremely wide field of applications that could be derived. Mobile robots in particular play a fundamental role in this field, for they represent the most

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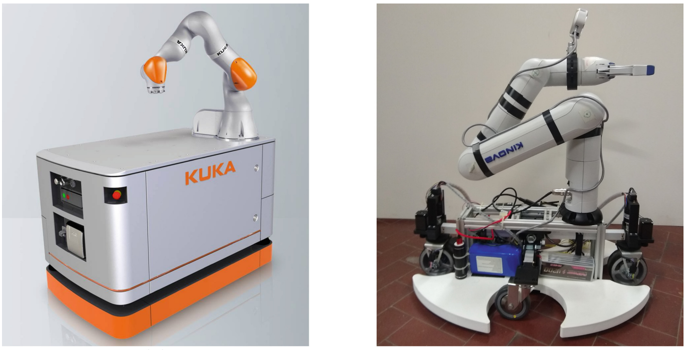

(a) (b)

Fig. 1. (a) Redundant industrial collaborative mobile robot KMR iiwa; (b) Paquitop.arm: mobile robot for personal assistance

natural manner to deliver services within a home environment with an as low as possible impact on the users' life.

In both cases, the coexistence of humans and robots is a key aspect to be kept in mind. As widely stressed in past literature [3–5], safety issues are central when the coexistence or collaboration between humans and robots is expected. Then, it is not surprising how the research community is focusing on the development of standards and methods used to validate and certify the non-dangerousness of a collaborative application. The perception of the environment is crucial too: simple 2D cameras can be used for detecting [6] and predicting [7] the motion of the human arm on a working surface, or to calibrate the user-frame of the robot [8]. Vision systems able to generate depth space images are typically used to perceive the human pose in the 3D space [9,10]; data from such sensors can be easily elaborated to extrapolate the coordinates of skeleton models replicating the human motion [11,12].

Aside dedicated hardware, the collaboration/coexistence of humans and robots implies specific control strategies, such as collision avoidance for dynamically varying environments: once fixed or moving obstacles are detected inside the workspace, the control must be able to modify the robot commanded trajectory to avoid impacts. Fixed obstacles can be thought of as objects inadvertently left inside the workspace, such as furniture pieces or mechanical tools, whereas dynamic moving obstacles may represent humans. The past literature offers several examples; a common approach exploits the same principles of the artificial potential fields method, typically used for the path planning of mobile robots [13,14]. This kind of approach was studied by the authors in [15,16] for two non-mobile collaborative robots.

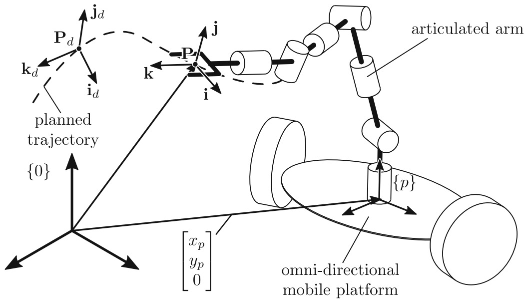

Fig. 2. Relevant parameters of a generic omni-directional mobile manipulator

From this starting point, the paper extends the collision avoidance strategy to mobile manipulators by taking into consideration the further degrees of mobility provided by mobile platforms. Firstly, the control algorithm is tested in simulated environment for an industrial redundant manipulator, the KMR iiwa by KUKA (Fig. 1-a), already analysed by authors without considering its mobile platform. The second test-study is Paquitop.arm (Fig. 1-b), a novel service robot developed at Politecnico di Torino. Interested readers are addressed to [17,18] for further details. The remainder of the paper synthetically recalls the control algorithm, introduces the parameterization used for both robots and, at last, shows simulated results for a couple of application scenarios.

2 Obstacle Avoidance Strategy

This section briefly recalls the obstacle avoidance algorithm extending it to the mobile-case. To such aim, it is possible to consider the velocity kinematics of a generic mobile manipulator as described by the contribution of two components: an omni-directional mobile robot, and an anthropomorphic arm. The former can be actuated by any combination of omni-wheels, steered wheels, etc., while the latter is actuated by a number of actuators greater or equal to 6 (depending on its degree of redundancy). In matrix form, the velocity kinematics of such system can be written as (Fig. 2):

$$\dot{\mathbf{x}} = \mathbf{J}\dot{\mathbf{q}} = \left[\mathbf{J}_p \; \mathbf{J}_a\right] \dot{\mathbf{q}} \tag{1}$$

where $\mathbf{J}_a$ is the $6 \times n$ arm Jacobian (with n number of the joints composing the kinematic chain of the manipulator, $n \geq 6$) and J_p is a 6×3 matrix describing the velocity contribution that the mobile platform provides the end-effector with. In such terms, the vector of joints variables is $\mathbf{q} = \left[x_p \; y_p \; \gamma_p \; q_1 \; \dots \; q_n\right]^T$ where x_p, y_p and γ_p respectively represent the two translations and the yaw of the mobile robot, and $q_1 \dots q_n$ are the n joints variables of the arm kinematic chain. With such notation, the Jacobian $\mathbf{J}_p$ is a trivial constant matrix (not shown here for space reasons), while $\mathbf{J}_a$ strictly depends on the kinematic structure of the manipulator. It should be remarked that, in this preliminary study, it is useful to keep $\mathbf{J}_p$ as simple as possible, bearing in mind that it can be easily translated on a specific actuation paradigm by a further (linear) Jacobian mapping among $\dot{x}_p$, $\dot{y}_p$, $\dot{\gamma}_p$ and the specific actuation scheme.

The formulation introduced by Chiriatti et al. in [16] is extended here to the above-described system. The inverse of the Jacobian $\mathbf{J}$ of the redundant system can still be obtained as a damped inverse:

$$\mathbf{J}^* = \mathbf{J}^T(\mathbf{J}\mathbf{J}^T + \lambda^2\mathbf{I})^{-1} \tag{2}$$

where λ is the damping factor, modulated as a function of the smaller singular value of the Jacobian matrix (for a full $\mathbf{J}$ rank matrix, λ is set to 0); the interested reader is addressed to [15,16] for further details. The inverse $\mathbf{J}^*$ can be used to compute the joint velocities needed to perform a given trajectory with a Closed-Loop Inverse Kinematic (CLIK) approach:

$$\dot{\mathbf{q}} = \mathbf{J}^* \left(\dot{\mathbf{x}} + \mathbf{K}\mathbf{e}\right) \tag{3}$$

where $\dot{\mathbf{x}}$ is the vector of planned velocities, $\mathbf{K}$ is a gain matrix (usually diagonal) to be tuned on the application, and $\mathbf{e}$ is a vector of orientation and position errors ($\mathbf{e}_r$ and $\mathbf{e}_p$), defined as:

$$\mathbf{e} = \begin{bmatrix} \mathbf{e}_r \\ \mathbf{e}_p \end{bmatrix} = \begin{bmatrix} \frac{1}{2}\left(\mathbf{i} \times \mathbf{i}_d + \mathbf{j} \times \mathbf{j}_d + \mathbf{k} \times \mathbf{k}_d\right) \\ \mathbf{P} - \mathbf{P}_d \end{bmatrix} \tag{4}$$

In Eq. (4) the subscript d stands for desired planned variable, $\mathbf{P}$ is the position of the end-effector, while $\mathbf{i}$, $\mathbf{j}$ and $\mathbf{k}$ are the unit vectors of the end-effector reference frame. It should be remarked that the term $\mathbf{K}\mathbf{e}$ is necessary in a real scenario since an open chain control law is virtually incapable to fulfill the planned trajectory.

The collision avoidance strategy is then implemented as a further velocity component (to be added to the trajectory joint velocities) capable of distancing the end-effector and the other parts of the robot from a given obstacle. In this manuscript, such contribution is function of the distance among the obstacle and every body of the robotic system. To this purpose, the bodies have been represented by means of two control points, $\mathbf{A}$ and $\mathbf{B}$ referring to Fig. 3. Called $\mathbf{C}$ the centre of a generic obstacle, the distance among it and the segment $\overline{AB}$ can be differently computed in three different scenarios:

- $(\mathbf{C} - \mathbf{A})^T\,(\mathbf{B} - \mathbf{A}) \leq 0$, Fig. 3-a: in this case the obstacle is closer to the $\mathbf{A}$ tip than to any other point of $\overline{AB}$; the distance d among the obstacle center and the line $\overline{AB}$ coincides with the length of $\overline{AC}$.
- $0 < (\mathbf{C} - \mathbf{A})^T\,(\mathbf{B} - \mathbf{A}) < |\overline{AB}|^2$, Fig. 3-b: the minimum distance d lies within points $\mathbf{A}$ and $\mathbf{B}$. In this case, it is:

$$d = \frac{|(\mathbf{C} - \mathbf{A}) \times (\mathbf{B} - \mathbf{A})|}{|\overline{AB}|} \tag{5}$$

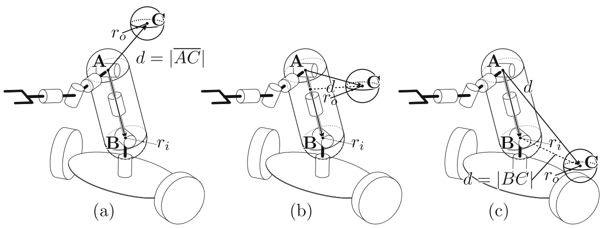

Fig. 3. Obstacle to robot body distance in the three considered cases

– $(\mathbf{C} - \mathbf{A})^T (\mathbf{B} - \mathbf{A}) \geq |\overline{AB}|^2$, Fig. 3-c: point **C** is closer to any other point, therefore $d = |\overline{BC}|$.

It is worth remarking that for this paper only spherical obstacles were considered, although similar approaches can be developed for objects of any shape starting from the distance primitives here defined.

Now the set of repulsive velocities for the ith body of the system can be introduced thank to the previous definitions as:

$$\dot{\mathbf{q}}_{r,i} = \psi v_r \left(k\mathbf{J}^*_{\mathbf{A},i} \frac{(\mathbf{A} - \mathbf{C})}{|\overline{AC}|} + (1 - k)\mathbf{J}^*_{\mathbf{B},i} \frac{(\mathbf{B} - \mathbf{C})}{|\overline{BC}|} \right) \tag{6}$$

where:

- ψ is an activation parameter, function of d, of the obstacle dimension r_o and the length r_i which characterize the body ith (as represented in Fig. 3, the dimension r_i defines a region around the line $\overline{AB}$ given by the intersection of two spheres centred in **A** and **C**, and a cylinder aligned with $\overline{AB}$, of radius r_i). The activation parameter can be a whatever function such that $\psi = 0$ if $i > r_i + r_o$, and $\psi = 1$ if $i \leq r_i + r_o$. Actually, such transition can be made smoother by the adoption of feasible functions (polynomials, logarithmic, etc.).
- v_r is a customized scalar representing the module of the repulsive velocity provided by obstacle to the body.
- k is a parameter which depends on the three cases of Fig. 3: in the first case $k = 1$ so that only the point **A** influences $\dot{\mathbf{q}}_{r,i}$; in the second case both **A** and **B** are considered proportionally to their distance from **C**, thus $k = 1 - (\mathbf{C} - \mathbf{A})^T (\mathbf{B} - \mathbf{A}) / |\overline{AB}|^2$; at last, in the third case $k = 0$ so that only the point **B** is relevant to $\dot{\mathbf{q}}_{r,i}$.
- $\mathbf{J}^*_{\mathbf{A},i}$ and $\mathbf{J}^*_{\mathbf{B},i}$ are the damped inverse of the Jacobian matrices of points **A** and **B**.

At this point, the CLIK control law Eq. (3) can be completed by the contribution Eq. (6) of each robot body obtaining:

$$\dot{\mathbf{q}} = \mathbf{J}^* (\dot{\mathbf{x}} + \mathbf{K}\mathbf{e}) + \sum_{i=1}^{m} \dot{\mathbf{q}}_{r,i} \tag{7}$$

being m the number of segments used to describe the mobile manipulator.

3 Test Cases

In this section two sets of analytical results concerning different mobile manipulators are shown. The two robots have been challenged in simulation with similar tasks. In particular, both have been controlled to maintain a constant end-effector orientation while moving along a linear trajectory. Two obstacles were put on the robots paths, one clogging the end-effector, the other hindering the mobile platform. Figure 4 shows some results about the performed simulations; for the sake of conciseness, the numerical details about the simulations and the robots geometrical parameters are omitted in this work: such aspects, however, do not actually affect the main result object of discussion, i.e., the fact that the proposed collision avoidance strategy can be successfully implemented on mobile manipulators owning different kinematic structure and dimensions. However, it is worth remarking that a specific characterization of each robot by means of the *segments paradigm* defined in the previous section is necessary.

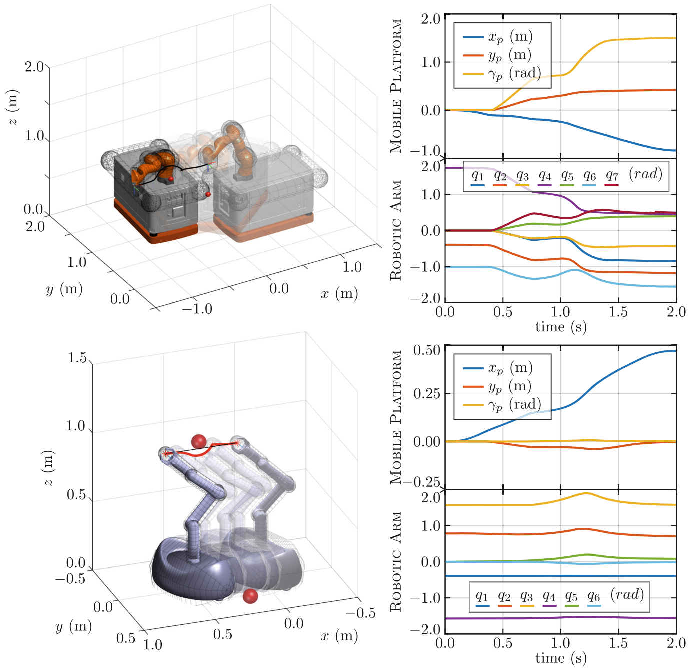

Fig. 4. Simulation results for the two considered test cases: the KUKA KMR iiwa industrial collaborative robot, and the prototype Paquitop.arm

Going a little into details, the CLIK control law of the KUKA KMR iiwa was built using 10 different segments (6 to cover up the robot arm, and 4 for the mobile platform: these latter in particular were placed along the platform perimeter at a variable height coincident with the possible obstacle height). Fewer lines were necessary for the Paquitop.arm prototype, namely 5 (4 for the arm and just a single segment for the mobile platform: this choice is due to its particular elongated shape, designed to better fit the small spaces of common houses, that allowed to cover it with just one element). At last it is worth reminding that the two machines have a different number of degrees of freedom, being the robotic arm of the KUKA a redundant manipulator with 7 active joints, while the manipulator mounted on the Paquitop platform is a low-weight KINOVA Gen3 Lite robot with 6 degrees of freedom.

The results of Fig. 4 allow drawing some simple qualitative conclusions, useful to drive the next steps of the research on these topics. The most evident among others is the fact that the Jacobian matrices of the two mobile platforms (previously called $\mathbf{J}_a$) deserve a further modeling effort: as visible for the KUKA robot, in fact, the CLIK as it is causes a huge amount of rotation of the platform which ends-up its motion with total yaw of about 90°. This fact may represent a relevant issue in case of limited maneuver space. Thus, the control law should prioritize translations above yaw rotations for this robot, while they could be more acceptable for Paquitop.arm due to its lower dimensions. Furthermore, the damped inverse of the Jacobian matrices shall consider the moving masses, or more precisely the change in momentum involved in the maneuver. As well desirable, in fact, the KUKA robot should prioritize the edging of obstacles by moving the robotic arm more than the moving platform (which is ca. 10 times heavier) in order to limit the kinetic energy of the system for both battery consumption and safety issues. Vice-versa, the robot Paquitop.arm owns comparable masses distributed along the arm and concentrated on the platform. This, together with the velocity limits of the KINOVA arm, causes a superior efficiency if the motion of the platform was preferred to that of the arm against a negligible effect on the whole kinetic energy.

4 Conclusions

The spread of robotics in industry and household environment brought the attention of the research community towards all the aspects concerning safety of people working or living in the same spaces of robots. This resulted in many innovations in terms of avoidance of uncontrolled collisions between robots and people/things. In such scenario, the manuscript extends a well-known obstacle avoidance control law to the case of mobile manipulators. The approach is at present purely kinematics and it was formulated for being adapted to several arm structures and mobile platforms owning different locomotion strategies. The algorithm has been tested in simulations on two machines, differing in both dimensions and purpose. The preliminary results shown here allow directing the further investigation efforts towards relevant aspects to be featured and specialized on specific applications.

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