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Preliminary observations for functional design of a mobile robotic manipulator

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Abstract. This paper presents the first steps approached for the functional design of a mobile robotic manipulator conceived for home assistance. The main characteristic of the mobile platform is that of owning an innovative architecture expressly conceived to enhance the dynamics performance offered by the present-day solutions for omni-directional planar motions. The mobile robot, named Paquitop.arm, is aimed at living and working in a domestic non-structured environment and it has been designed to mainly perform monitoring activities. As a matter of fact, the variety of tasks to whom it can be devoted significantly increases if an on-board manipulation ability is installed. Due to that, it is worth investigating what aspects could be to be taken into consideration while designing such a mobile manipulator. The manuscript approaches a simplified kinematics analysis to define and determine the most relevant parameters necessary for implementation of a commercial robot arm on the customized mobile platform Paquitop.

Keywords: personal assistance robot · mobile robot · mobile manipulator · collaborative task.

1 Introduction

The ageing society is a very well known scenario [1] which kept the attention of the robotics research community for the potential extremely wide field of applications that could be derived, especially for what concerns home and hospital personal assistance [2, 3]. Mobile robots in particular play a fundamental role in this field, for they represent the most natural manner to distribute services within a home environment with an as low as possible impact on the users life. The research in the field of mobile robotics produced many relevant results in the last years, to the point that almost any kinematic scheme and actuation layout was already analysed and exploited when possible [4]. At present, two main classes of machines seem to have reached the maturity level for being industrially exploited: full mobile robots with omni-wheels, and differential drive platforms. Pros and cons of both of them are well known and are mainly related to the offered mobility: the former can take advantage of high manoeuvrability,

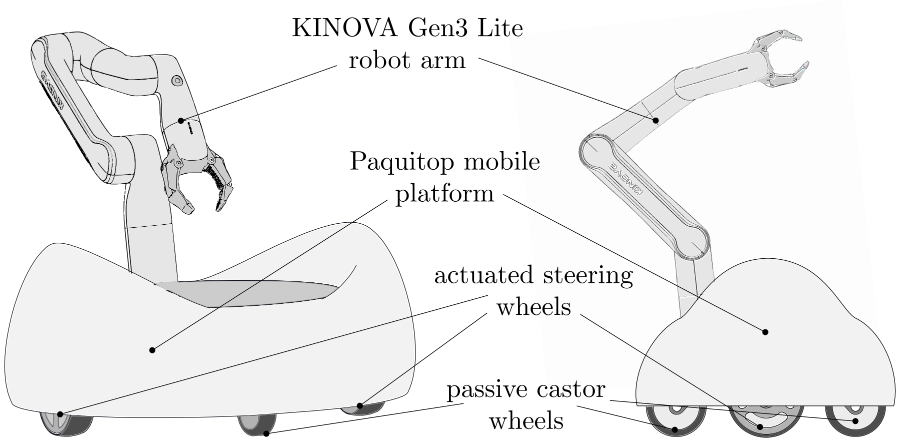


Fig. 1. The Paquitop mobile platform provided with the six degrees of freedom KINOVA Gen3 Lite collaborative manipulator.

but are poorly effective on non-structured environment and uneven grounds; the latter are more versatile in this sense, yet they cannot provide only two degrees of freedom motions. Among the most investigated applications, mobile manipulation is rising an ever-growing attention [5, 6], especially since the development of collaborative robotic arms [7, 8]. Such manipulators, in fact, fit almost perfectly the requirements for mobile purposes: low weight, moderate payload, and compatibility with the presence of humans in the workspace are some of the characteristics that have made them so attractive to both research and industrial communities. Even in this field, a lot has been said in almost every field of application, such as industrial [9], assistive [10], and medical [11] applications. The most studied aspects involve collision avoidance strategies for safety [12], and control algorithms for dexterous manipulations [13].

In such a crowded scenario, the researchers at Politecnico di Torino proposed in the recent past a novel mobile robot, named Paquitop, provided with full on-plane mobility [14]. The leading idea was that of designing it with a modular structure, eventually provided with a manipulation capability depending on specific requests. The platform is suspended on four wheels: two standard off-centred passive castor wheels and two driven wheels which are also provided with a steering degree of freedom. Such layout leads many mechanical design challenges, which has been tackled by authors in [15, 16]. A first prototype of the robot is at present under construction, and the manuscript presents the first design steps moved towards a further version of the robot, Paquito.arm, provided with manipulation ability thanks to the implementation of a collaborative robot arm on the Paquito main module, as shown in Fig. 1.

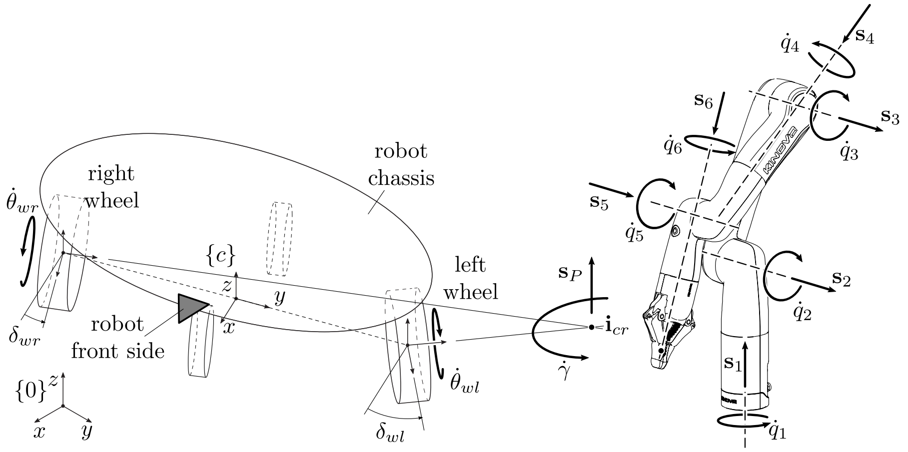


Fig. 2. Kinematics schemes of the mobile platform Paquitop, and the collaborative KINOVA Gen3 Lite arm.

1.1 Robot Concept

As aforementioned, the paper deals with the implementation of a commercial collaborative manipulator on the customized mobile platform Paquitop. The choice of a possible solution was performed by looking for a convenient compromise of cost, performance, and weight of the whole system. The final cost of the whole project, in fact, is an aspect not to be overlooked, since the expected final users are private persons interested in having available a help for simple yet needful daily tasks, such as helping the user to carry or collect small objects, or even to open doors on behalf of unable persons (such as elders who need walkers on a daily basis). Therefore, the performance of the manipulator (which needs to be collaborative for obvious safety reasons) takes a back seat with respect to the success of the entire project. High-level over actuated robots were then discarded a priori, although their extreme versatility should have brought substantial benefit either in terms of dexterity, or in terms of available payload. As a plus, however, low cost collaborative arms generally own a reduced weight with respect to over-actuated ones.

The final choice fell on the *KINOVA Gen3 Lite* robot, a six degree of freedom manipulator with on board controller. Such arm, designed for educational and mobile applications, owns a weight ($\sim 5.4\,kg$ declared by the constructor) compatible with the dimensions of the Paquitop platform, with an overall reach ($740\,mm$) sufficient for most parts of the above-mentioned tasks. The joints architecture of the robot is shown with its most relevant dimensions in Fig. 2. The allowable payload is definitely moderate ($0.5\,kg$), although it is in line with the performance offered by other commercial cobots of the same market sector.

2 Robot mobility

In this section, the mobility of the robotic manipulator together with the mobile platform is taken into consideration. To such aim, some simple observations can be drawn by composing the Jacobian matrix of the robot arm by means of the unit screws of its joints. The velocity of the end-effector of the arm, in fact, can be depicted as the linear combination of the velocities offered by all the joints composing its kinematic chain, proportionally to the rate of the joints themselves. Thus, it is:

$$\begin{bmatrix}\boldsymbol{\omega}_{ee}\\ \mathbf{v}_{ee}\end{bmatrix} = \sum_{i=1}^{n} \$_i \dot{q}_i \tag{1}$$

where $\boldsymbol{\omega}_{ee}$ and $\mathbf{v}_{ee}$ are the angular and linear velocities of the end-effector, $\dot{q}_i$ is the rate of the i^{th} of the n joints, and $\$_i$ is its unit screw. The unit screws of the six revolute joints are then composed by means of their axes, and mutual position with respect to the end-effector:

$$\$_i = \begin{bmatrix}\mathbf{s}_i\\ {}^{ee}\mathbf{p}_i \times \mathbf{s}_i\end{bmatrix} \tag{2}$$

being $\mathbf{s}_i$ the axis of the i^{th} joint, and ${}^{ee}\mathbf{p}_i$ the position of any point of such axis with respect to the end-effector. In brief, the Jacobian matrix of the manipulator can be worked out as a function of the six unit screws of the arm joints as:

$$\mathbf{J} = \begin{bmatrix}\$_1 \dots \$_6\end{bmatrix} \tag{3}$$

This quite basic result gains relevance if the mobility of the Paquitop platform is considered together with that of the arm. Due to its particular architecture, Paquitop is provided with a full on-plane mobility and it can exhibit any velocity in the plane. In other words, by rearranging the wheels steering angles δ_{wr} and δ_{wl}, and the respective angular velocities $\dot{\theta}_{wr}$ and θ_{wl}, the instantaneous center of rotation $\mathbf{i}_{cr}$ of the mobile robot can be placed anywhere, according to:

$$\mathbf{i}_{cr} = \frac{2a\cos\delta_{wr}}{\sin\left(\delta_{wr}-\delta_{wl}\right)} \begin{bmatrix}\cos\delta_{wl}\\ \sin\delta_{wl}\\ 0\end{bmatrix} \tag{4}$$

It is worth noticing that such relation can be obtained only considering the fundamental constraint that relates the two steering angles together with the actuation velocities: $\dot{\theta}_{wr}\sin\delta_{wr} = \dot{\theta}_{wl}\sin\delta_{wl}$. Such constraint, which basically represents the rigid body constraint of the robot chassis, provides an actuation law that the robot wheels must fulfil when non-null steering angles are used. Otherwise, the position of $\mathbf{i}_{cr}$ is located along the common axis of the two actuated wheels depending on the difference of velocity of the wheels. Also, (4) shows that when $\delta_{wr} = \delta_{wl} \neq 0$ the platform loses its ability to perform angular velocities around the vertical axis. In any case, Paquitop architecture was conceived to let it exhibit any velocity in the plane of motion. Thus, its instantaneous mobility can be described by a zero-pitch unit screw passing through the center of rotation $\mathbf{i}_{cr}$. The consequent velocity of the robot chassis is:

$$\begin{bmatrix}\boldsymbol{\omega}_c \\ \mathbf{v}_c\end{bmatrix} = \$_P \dot{\gamma} \tag{5}$$

where $\dot{\gamma}$ is the yaw rate of Paquitop main body (described by means of its reference frame $\{c\}$), while $\$_P$ is the aforementioned zero pitch unit screw, obtainable as:

$$\$_P = \begin{bmatrix}\mathbf{s}_P \\ {}^{ee}\mathbf{i}_{cr} \times \mathbf{s}_P\end{bmatrix} \tag{6}$$

If pitch and roll rotations are disregarded, the axis of the screw is merely vertical: $\mathbf{s}_P = \begin{bmatrix}0 \; 0 \; 1\end{bmatrix}^T$.

The velocity of the mobile platform contributes to that of the end-effector as far as the remainder of the actual joints of the arm. The resulting Jacobian is now:

$$\mathbf{J}^* = \begin{bmatrix}\$_1 \; \$_2 \; \$_3 \; \$_4 \; \$_5 \; \$_6 \; \$_P\end{bmatrix} \tag{7}$$

which is a quite typical shape for redundant manipulators with seven degrees of freedom. Such peculiarity lasts unless a singularity occurs, i.e. unless two or more unit screws become linearly dependent within $\mathbf{J}^*$. By construction, every articulated arm is affected by specific singular postures which have been widely investigated in the past and are well known in the field. Aside such configurations, others can be added by the presence of the mobile platform. In particular, it is worth taking into consideration the screw $\$_1$ of the first revolute joint of the arm.

The position and orientation of $\$_1$ are actually a design problem that should be carefully addressed to obtain the best possible performance from the system. Usually, the first joint of mobile manipulators is placed vertically, especially when redundant arms are used (as done, for example, by KUKA for the well known *KMR iiwa*). In the specific case of Paquitop, the use of a low cost six degrees of freedom arm can benefit from a different concept of coupling. The main idea is that of maintaining the redundant platform-arm system as distant as possible from singularities by avoiding the overlapping of the two screws $\$_1$ and $\$_P$. To maintain such screws independent one can act in two directions: by keeping away the centre of rotation of the platform from $\mathbf{s}_1$, or by providing the system with non parallel $\mathbf{s}_1$ and $\mathbf{s}_P$ by placing the first joint of the robot arm with a fixed non-null orientation with respect to the vertical axis.

The first solution moves the issue from mechanical design to motion planning and control of the manipulator. Therefore, it represents a possible limitations in the use of the robot which should be as far as possible avoided. The second option, which is basically effortless from the point of view of realization, does not require any made on purpose actuation strategy and significantly improves the usability of the robot arm.

From the point of view of position kinematics, in fact, dealing with a redundant manipulator instead of a classic one allows approaching in a more efficient way many issues typical of collaborative robots, such as that of obstacle avoidance. In other words, maintaining a redundant architecture provides the motion planner with more configurations to be exploited for avoiding obstacles within the workspace. As a matter of fact, the optimal solution in this sense should be that of having $\mathbf{s}_1 \perp \mathbf{s}_P$. In that case, when the two axes intersect in $\mathbf{i}_{cr}$, the three screws $\$_1$, $\$_2$, and $\$_P$ form a spherical joint permitting the redundant platform-arm system the widest possible range of configurations for each point of the workspace.

This simple concept is shown in Fig. 3 for four different mutual arrangements of the arm over the Paquitop platform. For the sake of simplicity, the representation considers a simple three degrees of freedom manipulator, comparable to a wrist-less robot arm. The dimensions of such simplified arm where set-up equal to the dimensions of the KINOVA Gen3 Lite. Fig. 3(a) refers to parallel $\mathbf{s}_1$ and $\mathbf{s}_P$: whatever the yaw angle of the platform is, the arm can reach the target point with only one configuration (two, if the second assembly mode proper of the three axes manipulators is considered). Fig. 3(d) shows the dual situation, when $\mathbf{s}_1 \perp \mathbf{s}_P$. In this case, the arm can advantage of infinite possible configurations by positioning the proximal and the distal links onto two conical surfaces. Such wide range of configurations can be usefully exploited to avoid particular regions of the workspace, as in the case of the presence of obstacles. Fig. 3(b) and Fig. 3(c) depict intermediate mounting assets, with reduced conical surfaces with respect to Fig. 3(d).

3 Task Oriented Optimization

According to the observations of the previous section, one is led to suggest to adopt an horizontal configuration as the best solution for the robot arm placement. Actually, the obtainable manipulability is not the only aspect that must be kept into consideration, since the final performance of the system with respect to the tasks it is required to fulfil shall heavily depend on the choices made at this design step. The most relevant aspects to be considered are the arm behaviour within its workspace, and its reach with respect to both the mobile platform and the external environment. To such aim, the simple wrist-less kinematics used in the previous section was used again to figure out what the result could be of settling the robot arm over the Paquitop platform. In Fig. 4 such aspects are graphically represented by means of the 2-norm condition number of the Jacobian matrix. In particular, to obtain a parameter bounded within a fixed zero-one bound, it was considered the condition number:

$$cn = \frac{\sigma_{min}\left(\mathbf{J}\mathbf{J}^T\right)}{\sigma_{max}\left(\mathbf{J}\mathbf{J}^T\right)} \tag{8}$$

with σ_{min} and σ_{max} minimum and maximum eigenvalues of the matrix $\mathbf{J}\mathbf{J}^T$: by definition such parameter is always bounded in the range $0 \leq cn \leq 1$. Also, for a better representation, cn was normalized within the workspace with respect

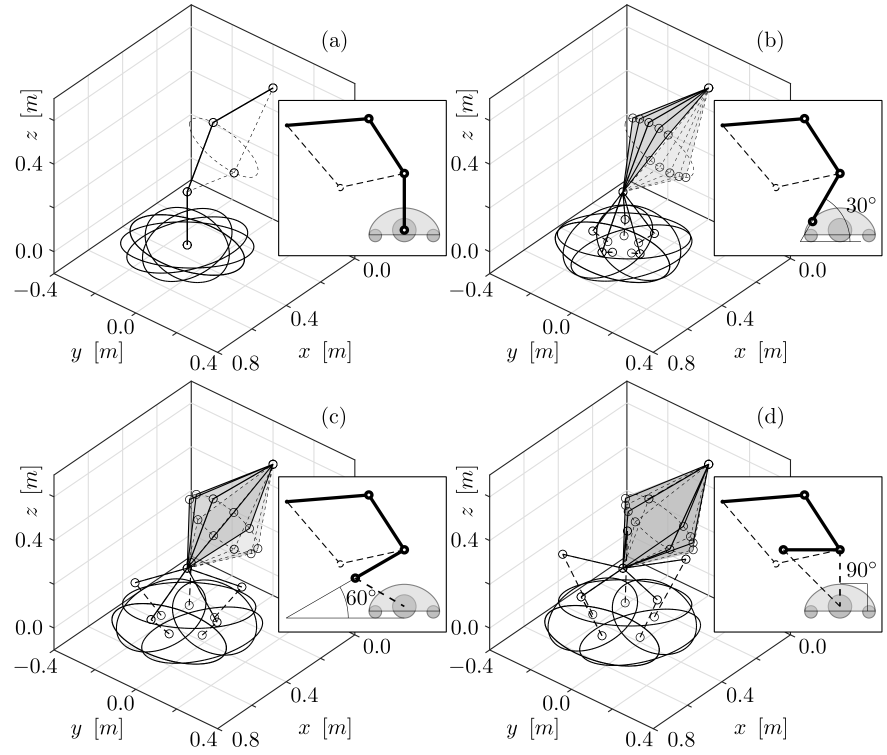
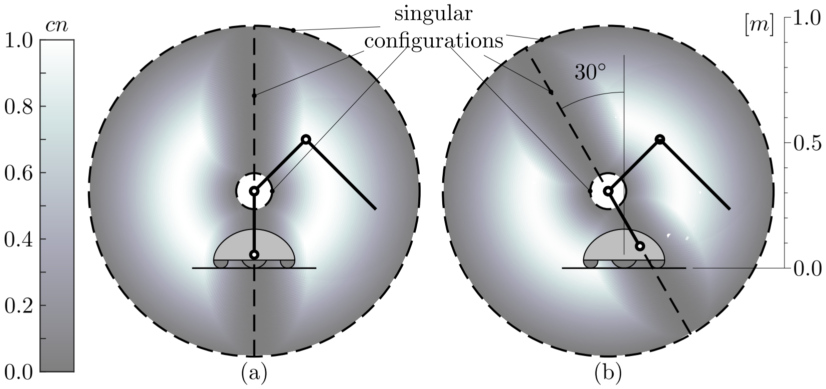


Fig. 3. Raange of possible configurations for different inclination of $\mathbf{s}_1$ with respect to the vertical direction: (a) $\mathbf{s}_1$ vertical (only one configuration possible, (d) $\mathbf{s}_1$ perpendicular to the vertical (complete cones of configurations); (b) and (c) depict intermediate configuratons of 30° and 60°.

to the maximum value assumed. Doing so, cn vanishes when singularities occur, while it is $cn = 1$ in the point characterized by the higher kinematic performance.

The maps of Fig. 4 can be useful to understand what is the effect of an initial orientation of the arm base with respect to the mobile platform. Fig. 4(a) shows a non-tilted configuration: as visible, the lighter regions of the cn map (corresponding to higher values of the parameter) are located in front and behind Paquitop chassis. Due to the height of the system, which is about 30 cm, such configuration do not valorise the actual possibilities offered by the manipulator due to the expected eight of the robot targets. The tasks to whom the robot is oriented, in fact, involve human-sized spaces and heights (planes of tables, chairs, etc) for which an higher placement of the arm should be preferable. Unfortunately, the arm base cannot be indefinitely raised up, for the sake of machine compactness and for mass distribution issues. The set-up can be improved applying a fixed orientation, as in Fig. 4(b), where the first joint of the robot arm was rotated of 30° around the y axis of the reference frame $\{c\}$. Such rotation, aside the



(a) (b)

Fig. 4. Condition number of the Jacobian matrix around the mobile platform for two assembly configurations of the arm with inclination null and equal to 30°.

advantages discussed in the previous section, moves the region characterized by higher values of *cn* in more useful portions of the workspace, allowing a more effective exploitation of the arm. Furthermore, the region adjacent to the robot back own the higher values of *cn* close to the ground surface, improving the arm ability to manipulate objects lying on the ground.

4 Conclusions

The paper shows some preliminary observations useful for the installation of a commercial robot arm on the customized mobile platform Paquitop. The platform, which owns itself a redundant set of actuators, can be exploited to enhance the mobility of the robot arm, by providing it with a further degree of freedom. This characteristic can be exploited to augment the arm space of configurations, which is a non-negligible feature under the point of view of dexterity and obstacle avoidance. A basic mobility analysis has been proposed to prove the advantages that can be brought by a non-vertical orientation of the first axis of the robot arm. Also, such rotation can enhance the reach of the gripper with respect to the task of the arm-platform system, as shown in the last part of the document. In future, such considerations must be kept into practice by installing a Kinova Gen3 Lite manipulator on the Paquitop prototype, whose mechanical design was already presented by authors.

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