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From robotic arms to mobile manipulation: on coordinated motion schemes

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Abstract

The task definition for mobile manipulators is presented. Then, a generic formulation of global instantaneous kinematics is proposed for wheeled mobile manipulators. It is compared with the classical kinematic modelling of robotic arms. In particular, it is shown that many tools of classical manipulation can be re-used in this new framework. Finally, simulation results and experiments are presented and the remaining industrial challenges are mentioned. So, this article provides comprehensive bases for the use of such systems in an industrial context.

Keywords: mobile manipulation, instantaneous kinematics, nonholonomy, motion generation

1. Moving products and robots

Mobile manipulation is an activity human perform every day. So, it is very unnatural to separate locomotion and manipulation in human tasks. On the other side, automation has been historically organized by explicitly separating the motion of products and the action of manipulators with fixed basis. The main drawbacks of this kind of organization are due to the inherently bounded workspace of classic robotic arms or automatic machines. Finally, their geometric reachability is extremely limited. So, when dealing with relatively small products (car, electronics, etc.), this paradigm leads to move the products inside a fixed bank of robotic manipulators by any kind of conveyors. At least two cases are not really consistent with this kind of organization:

- operations (painting, stripping, welding, etc.) on **large products** like ships, planes or cranes need to move the tools around them since moving a plane or a ship requires much space and energy.
- More generally, in a context where the products change quickly or need updates or customization, fixed basis robotic manipulators impose hard constraints on the production cycle, and possibly waste of ressources.

So, it became natural to consider robots that have motion and manipulation capabilities. The most famous are humanoids. Nonetheless, the problems they give rise in terms of complexity, cost or stability, disqualify them for a genuine use in manufacturing or production solutions in the near future. Instead, autonomous wheeled vehicles already are in the factories and some laboratories have worked on the coupling of these wheeled mobile bases with industrial robotic arms. Even more, some cases of industrial use of this *wheeled mobile manipulators* appeared. These compound systems have some common features:

- Mobile base provides an infinite workspace.
- The combination of both subsystems generally give rise to a global system possessing more actuators than required locally by the task.
- Wheeled vehicles are nonholonomic and are difficult to feedback stabilize. Moreover, when they are not omnidirectional, they impose manoeu-

vers that have to be taken into account at the environment design stage.
- Since reference frame supporting the tool is moving, real-time calibration is necessary and requires exteroceptive sensors (laser rangefinder, ultrasonic sensors, vision) and associated feedback laws.
- Since mobile manipulators are compound systems, one of the question concerns the coordination of motions of subsystems: is it necessary to use actuators of both subsystems at the same time? Do some tasks need only the motion of the arm or the motion of the mobile base? What are the advantages and drawbacks related with coordination or hierarchization strategies?

The objectives of this paper are to clarify what kind of tasks can be defined in weeled mobile manipulation and then how to perform these tasks. First, it is shown how the manipulation task and the environment constraints can be taken into account. Then, the need for coordination and the models underlying each strategy are discussed. The coordinated motion strategy is emphasized together with the models derived from the classic models of wheeled mobile platforms and robotic arms. Finally, experiments and simulation show the effectiveness of the approach. Concluding remarks are devoted to the gap between these laboratory experiments and industrial implementation.

2. Mobile Manipulation Tasks

A Manipulation Task as it is defined for robotic arms is only related to the motion of the end-effector and to the torque/force exerted on it. It is imposed by the user in the so-called *operational space*. A point in this space is the *location* of the end-effector (EE) denoted by the $m \times 1$ vector $\boldsymbol{\xi}$. It is characterized by a set of *operational coordinates* that correspond to the value of the position and the orientation of a frame attached to the EE at a particular point of this EE. Both values are measured with respect to a fixed reference frame. The tasks are mainly of two types: *regulation* or *tracking*. In a task of regulation, the goal is to reach a desired value of the EE location. In a task of tracking, one needs to realize a given velocity of this location, *i. e.* a given operational velocity, to follow a prescribed operational motion. Remark that when force/torque are imposed by the task, the same representation is used.

So, imposing location of the EE defines *equality constraints*. Of course, other constraints due to the environment and to construction limits (articular bounds) define *inequality constraints*.

Generally, in automatic motion generation, cluttered environments are tackled by a planning process defining forbidden regions or, more often, intermediate passing configuration points with a given clearance. Reachability constraints due to construction limits are considered by taking locally lower bounds on reachable space.

There are few works devoted to redundant manipulators, and also few redundant industrial manipulators since they are more expensive to build and because the whole organization scheme of production lines did not require them. In mobile manipulation, redundancy is the rule and decomposing the task by considering subsystems may appear as a useful recipe. The first experiments, in laboratory ([1] e.g) and industry, explicitly break down the task into sequences of pieces esssentially devoted to locomotion (motion of the platform) or to manipulation (motion of the arm with platform keeping a fixed location). Of course, this static decomposition does not allow to use all the capabilities of these systems. It is necessary to consider tasks for which all the actuators are used at the same time in order to provide a synchronized motion of the mobile manipulator. Moreover, due to the environment and to the inherent manoeuvering nature of the vehicles, a question arises naturally: is it necessary to impose a path for the vehicle - as *equality constraints* - to avoid obstacles? Or is it possible to solve the problem by the sole consideration of the *inequality constraints* the environment and the articular bounds of the arm define? So, even in a synchronized motion of the mobile manipulator, there are two main ways to define the task:

- hierachy: defining a subtask for the platform and then a subtask for the arm,
- coordination: defining a main task for the end-effector without explicitly imposing equality constraints on the motion of the platform.

2.1 Hierarchy

Here one reference motion is given as equality constraints for the platform. The task for the platform consists in moving its location and the task for the arm is relative to the frame attached to the platform. Here, it is necessary to have two models: the first one that link actuators of the platform to its location evolution on one side, and the second that link end-effector evolution with respect to the first body of the arm to its actuators. First, remember that nonholonomic platform cannot follow any path by definition. Thus, the first problem is to define a feasible path for the platform, or to define path for which it is ensured that the mobile base will remain in a given neighborhood of it. Then, the arm must adapt its motion. This hierarchical decomposition emphasizes nonholonomic constraints of the platform. In this approach, let us mention the works concerning transverse functions that allow to bound the region the platform traverses [2,3]. In these works, it can be observed that decomposition and hierarchization does not provide an easy to use solution and is of limited efficiency.

2.2 *Coordination*

On the contrary, it can be assumed that the non feasible directions of the wheeled platform will be compensated at the end-effector level by the degrees of freedom of the arm. Such an approach requires a global modelling and the definition of a main task for the end-effector without explicitly imposing equality constraints on the motion of the platform. In that case, it is necessary to have global models that link the end-effector evolution to all the actuators of the compound system. In this approach, it is supposed that the platform will "follow" the end-effector. So, it is necessary to avoid large of the platform, platform collisions and to insure that tool is never at the boundary of its workspace relative to the base of the arm. All these inequality constraints can be taken into account as *secondary tasks* the whole redundant system will satisfy. When looking at the global mobile manipulator, the kinematic constraints of the platform may be compensated by an adequate generalized velocity of the arm to realize a prescribed end-effector task. In that case, nonholonomy of the platform is somewhat hidden in the global instantaneous kinematics. This approach is presented in the following sections.

3. Global Modelling

Recently some contributions concerning modelling and control of generic nonholonomic mobile manipulators ([4,5]) have been proposed. Based on these proposals, it is now possible to consider modelling and control of mobile manipulators on a unified basis and a comparison can be made with classical manipulation. Manipulation and mobile robotics literature both provide modelling tools to solve this problem. On one hand, kinematics and instantaneous kinematics of robotic arms with a fixed base are now a very classical material. The associated notions of redundancy, singularity, and manipulability [6,7] are also parts of the classical background of manipulation. On the other hand, wheeled mobile platforms were properly described and modelled by [8]. Though less classical and less used in the robotics community, these notions are of great interest in the case of wheeled mobile manipulators.

For the sake of simplicity, the case of mobile manipulator composed of a mobile platform with two independent driving wheels and a serial manipulator with n_b joints is considered. Such a system is depicted on figure 1 in a $3-$dimensional version used for our experiments or on figure 2 in the planar version used in simulation. Some kinematic modelling results regarding mobile manipulators based on [5,9,10] are sum up first.

Figure 1. H_2bis: a 3D mobile manipulator.

3.1 *Mobile manipulator kinematics*

The configuration of such a mobile manipulator is completely defined using vector $\mathbf{q} = [\,\mathbf{q}_b \;\; \mathbf{q}_p\,]^T$ where $\mathbf{q}_b = [\,q_{b1} \;\ldots\; q_{bn_b}\,]^T$ and $\mathbf{q}_p = [\,\theta_r \;\; \theta_l \;\; x_{O_p} \;\; y_{O_p} \;\; \vartheta\,]^T$ respectively represents the arm configuration and the platform configuration (see Fig. 2). Its end-effector location (*i. e.* location of $\mathcal{R}_{EE} = (O_{EE}, \vec{x}_{EE}, \, \vec{y}_{EE}, \, \vec{z}_{EE})$ in the reference frame $\mathcal{R} = (O, \; \vec{x}, \; \vec{y}, \; \vec{z})$) can be described using a minimal set of parameters $\boldsymbol{\xi} = [\,\xi_1 \;\ldots\; \xi_m]^T$. $\boldsymbol{\xi}$ is expressed as a non linear function of $\mathbf{q}$. Differentiating it, the relation between $\dot{\boldsymbol{\xi}}$ and $\dot{\mathbf{q}}$ is given by:

$$\dot{\boldsymbol{\xi}} = J(\mathbf{q})\dot{\mathbf{q}} \tag{1}$$

with $J(\mathbf{q})$ a $m \times n$ matrix and $n = n_b + 5$.

In addition, the components of $\dot{\mathbf{q}}$ are constrained by the nonholonomy of the platform (*i. e.* the wheels cannot slip). Then, one can define a vector $\mathbf{u} = [\,\mathbf{u}_b \;\; \mathbf{u}_p]$ of $\bar{n}$ independent parameters (*i. e.* taking the nonholonomic constraints into account) such as:

$$\dot{\mathbf{q}} = T(\mathbf{q})\mathbf{u}. \tag{2}$$

Defining $\bar{J}(\mathbf{q})$ as:

$$\bar{J}(\mathbf{q}) = J(\mathbf{q})T(\mathbf{q}), \tag{3}$$

equation (1) becomes :

$$\dot{\boldsymbol{\xi}} = \bar{J}(\mathbf{q})\mathbf{u}. \tag{4}$$

Equation (4) completely describes the mobile manipulator kinematics.

When $m < \bar{n}$, the mobile manipulator is said to be kinematically redundant. This property provides the capability to choose a particular kinematic control vector $\mathbf{u}$ among those giving the prescribed end-effector velocity $\dot{\boldsymbol{\xi}}$ by using the relation:

$$\mathbf{u} = \overline{J}(\mathbf{q})^{\sharp}\dot{\boldsymbol{\xi}} + (I - \overline{J}(\mathbf{q})^{\sharp}\bar{J}(\mathbf{q}))\mathbf{z}, \tag{5}$$

where $\overline{J}(\mathbf{q})^{\sharp}$ is any generalized inverse of $\bar{J}(\mathbf{q})$ and $\mathbf{z}$ any $\bar{n} \times 1$ vector.

Access to the kinematic redundancy of the system is given by the second right-hand term of equation (5)

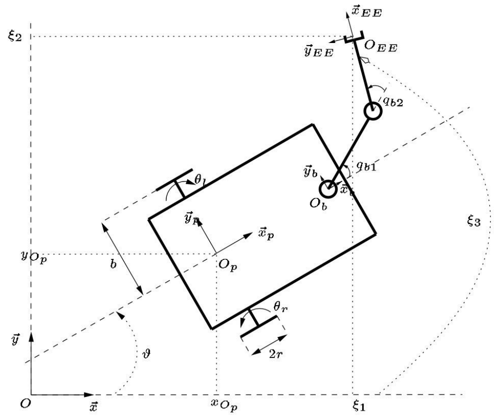

Figure 2. A planar mobile manipulator.

also called the internal motion control term since it does not provide any end-effector motion. Remark that practically, it is sufficient to choose the *generalized inverse* among the so-called *weighted pseudo-inverses* [11] for having any interesting behavior. Finally, at kinematic level, global system modelling leads to a model that has the same form as the one used for fixed redundant manipulators [1]. So, the same main control techniques can be used and adapted.

3.2 *Operational kinematic controllers*

Given $\dot{\boldsymbol{\xi}}^*$ and $\boldsymbol{\xi}^*$ desired end-effector speed and location to track, and a positive definite weighting matrix W_{reg}, the control vector defined by:

$$\mathbf{u} = \overline{J}(\mathbf{q})^\sharp(\dot{\boldsymbol{\xi}}^* + W_{reg}(\boldsymbol{\xi}^* - \boldsymbol{\xi})) + (I - \overline{J}(\mathbf{q})^\sharp \bar{J}(\mathbf{q}))\mathbf{z}, \tag{6}$$

ensures an asymptotic decreasing of $e = \boldsymbol{\xi}^* - \boldsymbol{\xi}$ toward 0.

In order to take advantage of the kinematic redundancy of the system, $\mathbf{z}$ can be chosen such as to minimize a scalar function $\mathcal{P}(\mathbf{q})$, also called *potential function*. The "*gradient descent*" local optimization method consists in choosing $\dot{\mathbf{q}}$ such as:

$$\dot{\mathbf{q}} + W_{grad}\nabla\mathcal{P}(\mathbf{q}) = 0, \tag{7}$$

where $W_{grad} \in \mathcal{R}^{n \times n}$ is a positive definite weighting matrix and $\nabla\mathcal{P}(\mathbf{q})$ is the gradient of $\mathcal{P}(\mathbf{q})$. This choice ensures an evolution of the system configuration tending to locally minimize $\mathcal{P}(\mathbf{q})$. However, $\dot{\mathbf{q}}$ components have to be independent which is not the case for a mobile manipulator. Thus, one have to adapt this method by choosing $\mathbf{z}$ as:

$$\mathbf{z} = -T(\mathbf{q})^+ W_{grad}\nabla\mathcal{P}(\mathbf{q}). \tag{8}$$

where $T(\mathbf{q})^+$ denotes the pseudo-inverse of $T(\mathbf{q})$.

When the task imposes end-effector force, the global model can be used for adapting classic scheme generally used for holonomic arms. For example, hybrid speed / force controller used for the following experiments is a modified version of the well known work presented in [12].

Once the contact is established, the robot's end-effector cannot independently exert a displacement and a force in the same direction. The control vector is then calculated as the sum of three terms:

$$\mathbf{u} = \mathbf{u}_s + \mathbf{u}_f + \mathbf{u}_r, \tag{9}$$

with:

$$\mathbf{u}_s = \overline{J}(\mathbf{q})^\sharp S\dot{\boldsymbol{\xi}}_s, \tag{10}$$

$$\mathbf{u}_f = \overline{J}(\mathbf{q})^\sharp (I - S)\dot{\boldsymbol{\xi}}_f, \tag{11}$$

$$\mathbf{u}_r = (I - \overline{J}(\mathbf{q})^\sharp \bar{J}(\mathbf{q}))\mathbf{z}. \tag{12}$$

$\dot{\boldsymbol{\xi}}_s$ and $\dot{\boldsymbol{\xi}}_f$ are the control vectors whose simple versions are given by:

$$\dot{\boldsymbol{\xi}}_s = \dot{\boldsymbol{\xi}}^* + W_{reg_s}(\boldsymbol{\xi}^* - \boldsymbol{\xi}), \tag{13}$$

and:

$$\dot{\boldsymbol{\xi}}_f = W_{reg_f}(\mathbf{f}^* - \mathbf{f}), \tag{14}$$

where W_{reg_s} and W_{reg_f} are two positive definite weighting matrices, and S is a $m \times m$ diagonal selection matrix where ones or zeros are placed on the diagonal respectively to indicate whether the component of $\boldsymbol{\xi}$ corresponding to the line in S is velocity or force controlled.

3.3 *Use of redundancy*

Here a set of functions to optimize using internal motion is presented. Many other functions may be used but these ones are relevant according to the presented results.

3.3.1. Manipulability maximization The manipulability notion was first introduced for manipulators (*cf.* [7] for a detailed presentation of this notion) but was also extended to mobile manipulators in [5]. The different manipulability measures are quantitative indicators representing the ease to instantly move the end-effector in any direction. Maximizing any of these indicators tends to avoid singular configuration of the system and thus to avoid high joints speed. Arm Manipulability measure is also useful for avoiding configurations close to workspace boundary of the arm.

3.3.2. Impact force reduction During the transition tasks between free space motion and contact motion, it is interesting to re-configure the mobile manipulator

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[1] When the platform features steering actuated wheels, it can be shown that the model is slightly different but keep its main properties. At dynamic level, many analogies that allow to use known techniques are also obtained by an adequate choice of variables [10].

using internal motion so as to give it good inertial properties. Results concerning holonomic mobile manipulators are presented in [13]. Using the dynamic model of the global system (*i. e.* the model establishing the relation between physical effects of motion, actuating torques and contact forces at end-effector level), it can be shown that the magnitude of the impact force is configuration dependent. So, redundancy can be used to provide convergence toward a configuration that minimizes this impact force magnitude.

3.3.3. Collision avoidance Techniques to avoid obstacles have extensively been studied in the case of mobile robots. However, the problem to solve here depends on the nature of the task to perform. Is the goal to follow an obstacle (like during a writing task on the wall) or to go around an obstacle (like in free space end-effector motion)? Different potential functions have been defined depending on what kind of collision avoidance is expected.

4. Simulation and experiments

Simulation and experiments have been conducted on two different mobile manipulators :

- The first one is depicted at the figure 2. It has been used in simulation in order to illustrate numerous strategies based on redundancy resolution on the basis of local/reactive potential function.
- The second one, H_2bis, has been used for demonstrating a complex mission realization including free-space and contact tasks.

4.1 Simulation framework

The simulator has been developed using *Matlab* and *Simulink*. The robot is modeled at kinematic and dynamic level. In particular, load torques due to dynamic effects of motion or due to contact, saturations of the actuators, low level digital PID, noise and inaccuracy of the end-effector force sensor together with its limited bandwidth are taken into account.

Contact between the end-effector and the environment is locally modeled either as a {*spring // damper*} system (*i. e.* Kelvin-Voigt visco-elastic model) or as a spring system and the values of the parameters characterizing the contact are unknown or poorly estimated.

4.2 Simulation results

4.2.1. Simulation 1: go to the wall among obstacles and follow it applying a normal force The task to realize consists in two main phases: first, the end-effector motion is imposed along a straight line and the environment may comprise low obstacles the robot will sense as motion progresses; in the second stage, the end-effector must follow a line on the wall and apply a given normal force (see figure 3).

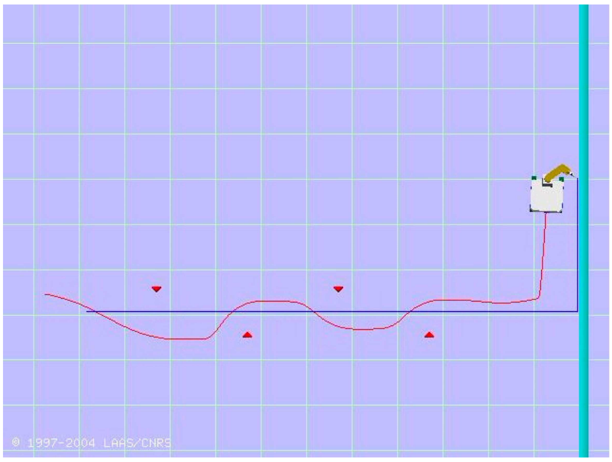

Figure 3. Go to the wall and follow it

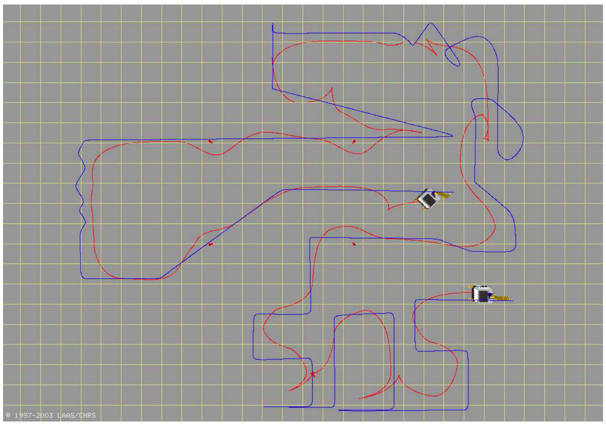

Figure 4. Interactive real-time end-effector setpoint

Here the end-effector motion is imposed and the mobile base has to avoid low obstacles reactively. There is only a local information about the location and number of obstacles. The dynamic sequencing scheme switchs automatically between indices: manipulability, obstacle avoidance, inertia, etc. The imposed end-effector motion is made of the two blue straight lines and the path of the middle of the rear axle of the mobile base is depicted in red. $\boldsymbol{\xi}$ is chosen as the end-effector position and $\mathbf{u} = [\,\dot{\theta}_r \;\; \dot{\theta}_l \;\; \dot{q}_{b1} \;\; \dot{q}_{b2}]^T$. Once the contact is established, the normal direction is force controlled whereas the tangential direction is velocity controlled.

4.2.2. Simulation 2: interactive joystick Here, the control scheme is used interactively since the end-effector velocity is imposed in real time. Again, the real-time imposed end-effector motion is in blue whereas the path of the middle of the rear axle of the mobile base is depicted in red (see figure 4). This simulation shows the robustness of the control scheme and the ability to realize totally reactive behaviour with a nonholonomic mobile manipulator. In particu-

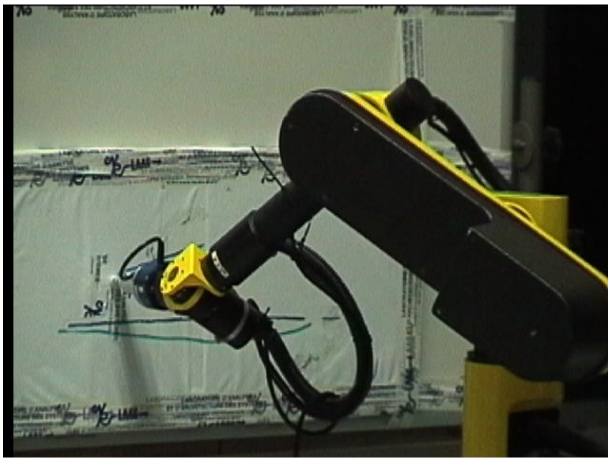

Figure 5. Coordinated Writing on a board

lar, cusps or manoeuvers are automatically generated. This mode shows how simple is to control the wheeled mobile manipulator in real time. In particular, use by human operator for cooperative tasks is particularly easy.

4.3 Experimental results

The mobile platform is actuated using two independent driving wheels. The manipulator is a 6R serial arm called GT6A. The robot is endowed with localization devices such as ultrasonic sensors, a telemeter and a black and white camera, an odometer system, the manipulator's incremental coders and a $6-$axis *GIROBO* force / torque sensor. Control algorithms are implemented using $G^{en}om$, a generator of software control modules developed, as well as the robot, in the *RIA* team of the LAAS laboratory.

The task simulated in 4.2.1 has been tested experimentally and the end-effector has been equipped with a pen so as to visualize the path of the end-effector and the action of the normal force. The figure 5 shows the end of the mission obtained by global coordination of mobile manipulator including a transition phase during which configuration is adapted for impact force minimization.

5. Concluding remarks

It is shown in this paper that classic control schemes can be revisited for wheeled mobile manipulators by choosing adequate global modelling and coordinated control. At present, the industrial use of these robots is limited by at least two factors, technological and organizational:

- technological: challenges are on real-time precision on geometric measures relative to the location of the robot in the environment.
- organizational: a fleet of mobile manipulators will, for example, totally change the rules of production sequencing, of reorganization on small series. All is to be redefined, including PLM software tools!

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