

## VIRTUAL TELEOPERATION AND REACTIVE MOTION OF A WHEELED MOBILE MANIPULATOR

Vincent Padois, Jean-Yves Fourquet, Pascale Chiron

*Laboratoire Génie de Production, ENIT, Tarbes, France  
vpadois,fourquet,pchiron@enit.fr*

Abstract: The work presented in this paper is devoted to the coordinated control of wheeled mobile manipulators in the particular case where operational trajectory is not planned but generated in real-time during the mission. We present a kinematic control scheme that can be used for operational control and that also gives access to the redundancy of the system. Redundancy as well as set-point filtering and actuators' input scaling are used to take into account all the secondary constraints associated to mobile manipulation mission. *Copyright © 2006 IFAC*

Keywords: : wheeled mobile manipulators, redundancy, reactive motion generation

### 1. INTRODUCTION

Robotic missions are getting more and more complex. From manipulators executing highly specific and simple tasks in structured environments, they have evolved to missions implying larger workspace than before. This workspace extension is due to bigger expectations in terms of what a robot should be able to do : explore planets and oceans, manipulate dangerous products, move in dynamical environments; examples are numerous.

These new types of missions are characterised by poorly calibrated environment and goals of different nature : operational trajectories to follow, operational force to exert or combinations of both. Moreover, they require the combination of both locomotion and manipulation means and the term *mobile manipulation mission* is often used to describe these types of robotic missions. Robots used to fulfil these missions are called *mobile manipulators* and we here focus on wheeled mobile manipulators that are systems combining a wheeled mobile platform and one or several robotic arms.

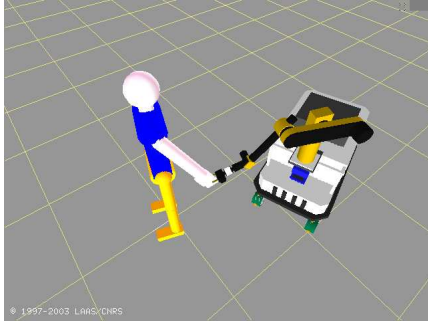
The operational control of wheeled mobile manipulators, *i.e.* the control of the end-effector, requires to take into account their inherent characteristics:

- wheeled mobile platforms, and by extension wheeled mobile manipulators, are nonholonomic systems;
- they are often kinematically redundant regarding the operational task to be achieved;
- sub-systems that compose the whole systems present very different dynamics.

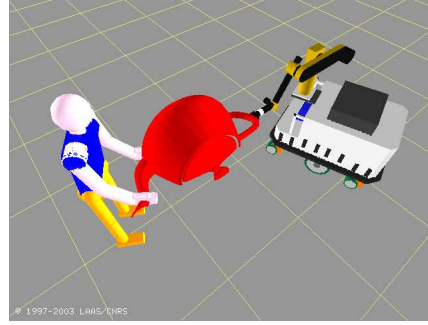
It also requires to identify constraints associated to the mission itself :

- obstacles avoidance;
- joint limits avoidance;
- rated inputs for the actuators;
- numerical singularities.

From this set of constraints and characteristics, a first class of approaches has been proposed to solve the operational control of wheeled mobile manipulators. It is based on a theoretical corpus widely explored for simple robotic manipulators



(a) Trajectory teaching



(b) Collaborative object handling

FIG. 1. Two examples where operational trajectories are generated on-line

and, considering their inherent characteristics, extended to the case of those systems. This class of approach assumes that the only input of the control problem is the operational trajectory to be followed or the operational force to be exerted by the end-effector of the system. Among the contribution to this class of approach, work in (Yamamoto and Yun, 1993) and (Seraji, 1993) concerns modeling and coordinated control of a particular type of wheeled mobile manipulator. Coordinated control, *i.e.* control of the system as a whole, is also handled in (Kang *et al.*, 2001) and (Umeda *et al.*, 1999) but from the operational force point of view. Regarding reactive obstacle avoidance in the case of an operational task to be accomplished, it is treated in (Brock *et al.*, 2002) where redundancy of the system is used to allow the mobile platform to avoid obstacles. The unified kinematic modeling issue is treated in (Bayle *et al.*, 2003). It is based on the classification of wheeled mobile platforms presented in (Campion *et al.*, 1996).

The second class of approaches relies on the observation that the controllability properties of non-omnidirectional wheeled mobile platform induce an explicit definition of the platform trajectory that comes as a supplementary input to the operational control problem. This is the case of the work in (Fruchard *et al.*, 2005) that is based on the *transverse function approach* introduced in (Morin and Samson, 2003).

With regard to the realisation of mobile manipulation complex missions, our previous work presented in (Padois *et al.*, 2004b; Padois *et al.*, 2004a) focused on the operational control of wheeled mobile manipulators by dynamic sequencing of local tasks whose nature is different from an operational point of view but also from the angle of the constraints (listed hereinbefore) that have to be met at a given instant. Operational trajectories (movement and/or force) are in that case planned before the mission and adapted during the mission. This paper discusses the case of operational control with operational

trajectories generated on-line. Teleoperation, trajectory teaching, collaborative object handling are example of applications of this particular topic illustrated on figure 1.

This paper is organized in four sections. The first one introduces models. Control laws used to compute actuators set-points are also presented. In the second one, we propose solutions especially based on the system redundancy to respect the different constraints associated to the mission. The third section presents the principle of the developed application. We finally show results associated to a particular example and analyse these results.

## 2. OPERATIONAL CONTROL OF A WHEELED MOBILE MANIPULATOR

We consider the case of a wheeled mobile manipulator composed of a wheeled mobile platform with two independent driving wheels and a planar serial manipulator with two revolute joints such as depicted on figure 2. Actuators are velocity controlled and thus, we rely on a kinematic control scheme.

### 2.1 Kinematics

The configuration of such a system is completely defined using vector  $\mathbf{q} = [\mathbf{q}_b^T \mathbf{q}_p^T]^T$  where  $\mathbf{q}_b = [q_{b1} \ q_{b2}]^T$  and  $\mathbf{q}_p = [x \ y \ \vartheta \ \varphi_r \ \varphi_l]^T$  respectively represents the manipulator configuration and the platform configuration. The situation of the end-effector is defined as a  $m$ -dimensional vector  $\boldsymbol{\xi}$ . We consider in this paper that the orientation of the end-effector is not to be controlled and we have  $m = 2$  and  $\boldsymbol{\xi} = [x_{EE} \ y_{EE}]^T$ . From a geometric point of view,  $\boldsymbol{\xi}$  can be expressed as a non linear function  $\mathbf{f}(\mathbf{q})$  of vector  $\mathbf{q}$ . Differentiating  $\mathbf{f}(\mathbf{q})$ , the relation between  $\dot{\boldsymbol{\xi}}$  and  $\dot{\mathbf{q}}$  is given by :

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

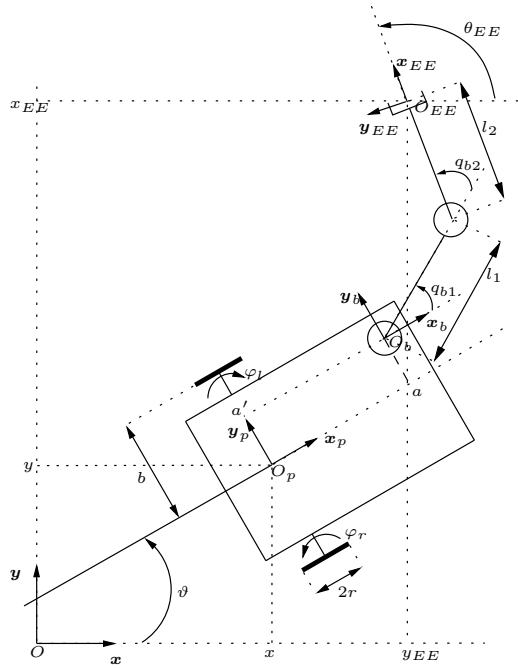


Figure 2. A planar mobile manipulator with  $J(\mathbf{q})$  the Jacobian matrix of  $\mathbf{f}(\mathbf{q})$ . Relation (1) does not take nonholonomic constraints on the platform wheels (rolling without slipping) into account. Actually components of vector  $\dot{\mathbf{q}}$  cannot vary independently. However, one can define a vector  $\mathbf{u} = [\mathbf{u}_b^T \ \mathbf{u}_p^T]^T$  of independent  $\delta_{mob}$  control parameters, related to vector  $\dot{\mathbf{q}}$  by a configuration dependent matrix  $S(\mathbf{q}_p)$  such as:

$$\dot{\mathbf{q}} = S(\mathbf{q}_p) \mathbf{u}.$$

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

$$\bar{J}(\mathbf{q}) = J(\mathbf{q}) S(\mathbf{q}_p),$$

equation (1) becomes :

$$\dot{\boldsymbol{\xi}} = \bar{J}(\mathbf{q}) \mathbf{u}. \quad (2)$$

Equation (2) completely describes the system kinematics. A natural choice for  $\mathbf{u}$  is  $\mathbf{u} = [\dot{\mathbf{q}}_b^T \ v \ \omega]^T$  where  $v$  and  $\omega$  are respectively the linear velocity of point  $O_p$  along vector  $\mathbf{x}_p$  and the angular velocity of the platform with respect to vector  $\mathbf{z}_p$ . In our particular case the system is said to be kinematically redundant of degree two. This property provides the ability to choose a particular vector  $\mathbf{u}$  among those giving the prescribed end-effector velocity  $\dot{\boldsymbol{\xi}}$ . Solutions are given by the following relation :

$$\mathbf{u} = \bar{J}(\mathbf{q})^\# \dot{\boldsymbol{\xi}} + (\mathcal{I} - \bar{J}(\mathbf{q})^\# \bar{J}(\mathbf{q})) \mathbf{u}_0, \quad (3)$$

where  $\bar{J}(\mathbf{q})^\#$  is any generalized inverse of  $\bar{J}(\mathbf{q})$  and  $\mathbf{u}_0$  any  $\delta_{mob} \times 1$  vector.

## 2.2 Kinematic Redundancy

Access to internal motions of the system is given by the null space projection term of equation (3).

This term is associated to the system kinematic redundancy and corresponds to motions that do not provide any end-effector motion. From the dynamic point of view, this is only true for a particular choice of  $\bar{J}(\mathbf{q})^\#$  (cf. (Khatib, 1987)).

*Remark 1 :* A particular set of generalized inverses of  $\bar{J}(\mathbf{q})$  is called the set of weighted pseudo-inverses. When  $m \leq \delta_{mob}$  and  $\text{rank}(\bar{J}(\mathbf{q})) = m$ , these generalized inverses are defined as :

$$\bar{J}(\mathbf{q})_{M_x}^* = M_x^{-1} \bar{J}(\mathbf{q})^T \left[ \bar{J}(\mathbf{q}) M_x^{-1} \bar{J}(\mathbf{q})^T \right]^{-1},$$

where  $M_x \in \mathcal{R}^{\delta_{mob} \times \delta_{mob}}$  is a positive definite symmetric matrix. Replacing  $\bar{J}(\mathbf{q})^\#$  by  $\bar{J}(\mathbf{q})_{M_x}^*$  in (3) leads to the solution minimizing the  $M_x$ -weighted euclidean norm of  $(\mathbf{u} - \mathbf{u}_0)$ . For  $M_x = \mathcal{I}$ ,  $\bar{J}(\mathbf{q})_{M_x}^*$  is called the pseudo-inverse of matrix  $\bar{J}(\mathbf{q})$ . Detailed results and proof regarding generalized inversion are presented in (Doty *et al.*, 1993) and (Ben Israel and Greville, 2003).

## 2.3 Operational kinematic control

Given a desired end-effector trajectory  $\boldsymbol{\xi}(t)^*$  and assuming that actuators' low-level control loops can ensure rejection of perturbations associated to unmodeled dynamics, the following operational kinematic control law :

$$\mathbf{u}(t)^* = \bar{J}(\mathbf{q})_{M_x}^* \left( \dot{\boldsymbol{\xi}}(t)^* + W(\boldsymbol{\xi}(t)^* - \boldsymbol{\xi}(t)) \right) + (\mathcal{I} - \bar{J}(\mathbf{q})_{M_x}^* \bar{J}(\mathbf{q})) \mathbf{u}_0$$

ensures the convergence of error  $e_{\boldsymbol{\xi}} = \boldsymbol{\xi}(t)^* - \boldsymbol{\xi}(t)$  to 0 if  $W$  is a positive definite matrix.

## 3. MISSION CONSTRAINTS SATISFACTION

The listed constraints are not always active during the mission. Thus one has to first define activation/deactivation threshold values for each constraint. These threshold values are, for example, a distance or a joint angle. Arbitration has to be done so that there is only one active constraint at each time. This arbitration is based on the evolution of indicators (distance to obstacle, joint angle value) with respect to their associated threshold value. It is also based on priority of each constraint relatively to the others. Switchings between active constraints is based on this arbitration.

In order to take advantage of the kinematic redundancy of the system, constraints that are not directly associated to the operational movement can be modeled as scalar function  $\mathcal{P}(\mathbf{q})$  called *potential function*. Using local optimisation methods such as the *steepest descent* method we can ensure the local optimisation of these functions. Considering a potential function  $\mathcal{P}(\mathbf{q})$  to be minimised,

one has to ensure  $\dot{\mathcal{P}}(\mathbf{q}) \leq 0$ . To do so,  $\mathbf{u}_0$  can be chosen as :

$$\mathbf{u}_0 = -K \left( \nabla^T \mathcal{P}(\mathbf{q}) S(\mathbf{q}_p) (\mathcal{I} - \bar{J}(\mathbf{q})_{M_x}^* \bar{J}(\mathbf{q})) \right)^T,$$

where  $K$  is a positive definite matrix. To ensure rated acceleration of the redundancy term,  $\mathcal{P}(t)$  has to be of class  $\mathcal{C}^2$  and to switch smoothly between two potential functions, a transition function can be created. Defining  $t_{ti}$  and  $t_{te}$  respectively as the time when the transition begins and the time when it ends, we have :

$$\beta(t) = \begin{cases} 0 & \text{if } t < t_{ti} & (a) \\ \left( \frac{1}{(t_{tf} - t_{ti})} \right) (t - t_{ti}) & \text{if } t_{ti} \leq t < t_{tf} & (b) \\ 1 & \text{if } t \geq t_{tf} & (c) \end{cases},$$

and :

$$\mathcal{P}(t) = \begin{cases} \mathcal{P}_{old}(t) & (a) \\ \mathcal{P}_{new}(t)\beta(t)^3 + \mathcal{P}_{old}(t)(1 - \beta(t)^3) & (b) \\ \mathcal{P}_{new}(t) & (c) \end{cases}.$$

Regarding inputs for the actuators, we must ensure rated acceleration and speed. If the desired operational trajectory is defined on-line, a solution is to filter this desired trajectory so that operational acceleration and speed are rated. Their maximum values can be calculated in the worst case in order to comply with the maximum values associated to each actuator and by extension to control vector  $\mathbf{u}$ .

We also have to ensure that the sum of the term associated to the operational motion and the term associated to the kinematic redundancy of the system is such that actuators' inputs maximum values are respected. A solution is to scale dynamically the term associated to the kinematic redundancy. Given the following notations :

$$\mathbf{u}_p = \bar{J}(\mathbf{q})_{M_x}^* \left( \dot{\xi}(t)^* + W(\xi(t)^* - \xi(t)) \right),$$

$$\mathbf{u}_{red} = (\mathcal{I} - \bar{J}(\mathbf{q})_{M_x}^* \bar{J}(\mathbf{q})) \mathbf{u}_0,$$

a scaling factor  $\alpha$  is obtained using the relation:

$$\alpha = \min(\alpha_{scale}, \alpha_{max}),$$

where :

$$\alpha_{scale} = \left( \frac{|\mathbf{u}_{max,i} \cdot \text{sign}(\mathbf{u}_{red,i}) - \mathbf{u}_{p,i}|}{|\mathbf{u}_{red,i}|} \right)_{i=1 \dots \delta_{mob}}.$$

In the worst case,  $\alpha = 0$ . It means that the operational task does not let any margin to optimise the potential function associated to the active constraints (one or more components of  $\mathbf{u}$  is fully dedicated to the operational task). In the best case,  $\alpha = \alpha_{max}$  where  $\alpha_{max}$  is a value chosen so that the term associated to the optimisation of the potential function is not exaggeratedly magnified (it is, for example, no use to generate large maneuver of the system in order to avoid an obstacle very far from the system, even if the actuator limits are far from being reached). In case of a

small  $\alpha$  (potential function is slowly optimised), one can scale the operational movement in order to allocate more power of actuation to the internal movement. A way to do this is to slow the operational movement. The geometric path followed by the end-effector remains the same but the speed of movement along this path is reduced for a better optimisation of the active constraint.

The control law is then given by :

$$\mathbf{u}(t)^* = \bar{J}(\mathbf{q})_{M_x}^* \left( \dot{\xi}(t)_f^* + W(\xi(t)_f^* - \xi(t)) \right) + \alpha (\mathcal{I} - \bar{J}(\mathbf{q})_{M_x}^* \bar{J}(\mathbf{q})) \mathbf{u}_0,$$

where  $\dot{\xi}(t)_f^*$  can be written as a function of :  $\dot{\xi}(t)^*$ ,  $\dot{\xi}_{max}$  (associated to  $\mathbf{u}_{max}$ ),  $\ddot{\xi}_{max}$  (associated to  $\dot{\mathbf{u}}_{max}$ ),  $\mathcal{P}(t)$  and  $\alpha$ .

#### 4. VIRTUAL TELEOPERATION OF A WHEELED MOBILE MANIPULATOR

In this paper, we consider the case of on-line generated operational trajectory. This trajectory is filtered to comply with the actuators' limits but also to slow down the operational movement to the benefit of the active secondary constraint optimization.

We have developed a simulator using *Matlab / Simulink* software. This simulator allows the simulation of the system kinematics and dynamics (continuous) as well as the various control loops (discrete time) : low level PID of each actuator, operational control law, operational trajectory filtering. The operational trajectory is generated in real time by a user interacting with *Simulink* via a software joystick. A 3D visual feedback of the scene is generated using *GDHE* software. The principle of this application is given on figure 3.

For filtering purpose, we have chosen a first order filter (low pass)  $F(s)$ :

$$F(s) = \frac{K_f}{1 + \tau s}, \quad (4)$$

such as :

$$\dot{\xi}(s)_f^* = F(s) \dot{\xi}(s)^*, \quad (5)$$

where  $\dot{\xi}(t)^*$  is the norm of the operational speed set-point generated by the user using the joystick and  $\dot{\xi}(t)_f^*$  the norm of the filtered operational speed set-point. Maximum operational speed is dynamically set using  $K_f$ , a function of  $\dot{\xi}_{max}$ ,  $\mathcal{P}(t)$  and  $\alpha$ . Using relations (4) and (5) and choosing  $\dot{\xi}(t)_f^*$  to the maximum value  $\dot{\xi}_{max}$ , parameter  $\tau$  is given by :

$$\tau = \frac{K_f \dot{\xi}(s)^* - \dot{\xi}(s)_f^*}{\ddot{\xi}_{max}}.$$

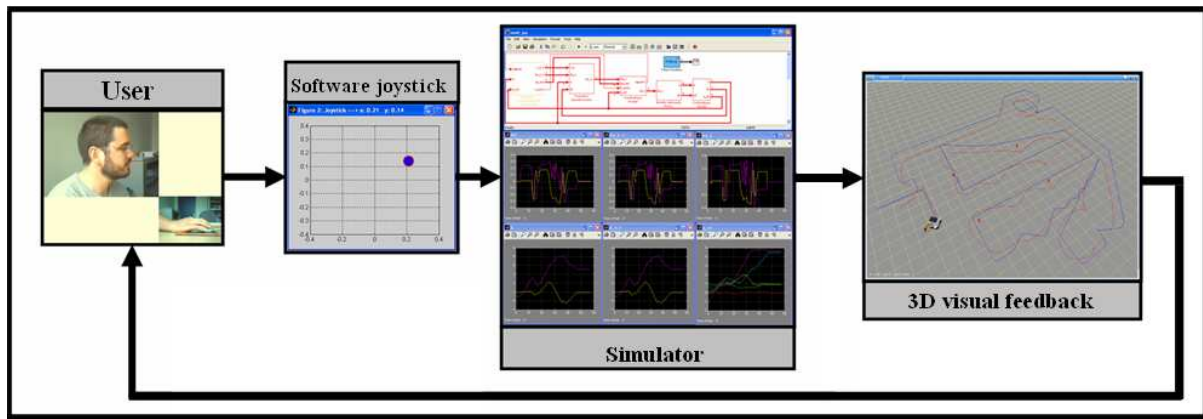


FIG. 3. Principle of the virtual teleoperation of a wheeled mobile manipulator

## 5. RESULTS

Here are presented the results of a simulation. For real time interaction purpose, simulation of the robot dynamics is simplified. Three different types of potential functions are considered:

- one for low obstacles avoidance; this potential function aims at maximising the distance between the wheeled mobile platform and the obstacles; it also aims at generating a tangential movement of the platform with respect to the obstacle;
- one for each joint limit avoidance; these functions are bowl-shaped and take their maximum values around the joint limit values. They have to be minimised ;
- one for numerical singularities avoidance; these singularities occur when  $\bar{J}(\mathbf{q})$  is rank deficient or has a bad condition number ; maximising the manipulability of the system is a way to avoid singular configurations.

Figure 4 presents the effect of filtering the operational speed set-point issued from the joystick. The five time zones where the filtered speed is really lower than the unfiltered one are those where the active constraint is obstacles avoidance. In this particular simulation no joint limit avoidance was needed and when redundancy is not used to avoid low obstacles, it is used to maximise manipulability. This figure also presents signal  $\mathbf{e}(t)_f^* = \dot{\xi}(t)^* - \dot{\xi}(t)_f^*$ . This signal shows the effects of operational speed set-point reduction as well as the difference induced by the respect of maximum operational acceleration.

Figure 5 gives a planar view of the whole movement (blue curve : path of the end-effector, red curve : path of point  $O_p$  of the platform). In this example, obstacles (green points) are, without loss of generality, modeled as points (no specific shape or size). These obstacles are efficiently avoided using a totally reactive control scheme. This robust reactive behaviour is also enlightened by the

platform trajectory that exhibits not explicitly planned cusps.

## 6. CONCLUSION

We propose an application of coordinated control for a wheeled mobile manipulator. Two types of constraints are present. The first one is the respect of the operational trajectory generated on-line by a user via a virtual joystick. The second one corresponds to all the secondary constraints that have to be respected when dealing with mobile manipulation. Using redundancy and local optimisation methods, we are able to switch between those constraints according to their importance at a given instant during the mission and thus to optimise the right constraint at the right time. Respect of actuators' limits is also achieved using set-point filtering and input scaling.

## REFERENCES

- Bayle, B., M. Renaud and J.-Y. Fourquet (2003). Nonholonomic mobile manipulators: kinematics, velocities and redundancies. *Journal of Intelligent and Robotic Systems* **36**, 45–63.
- Ben Israel, A. and T.N.E. Greville (2003). *Generalized Inverses : Theory and Applications, second edition*. Springer. ISBN 0-387-00293-6.
- Brock, O., O. Khatib and S. Viji (2002). Task consistent obstacle avoidance and motion behavior for mobile manipulation. In: *Proceedings of the ICRA*. Washington DC - USA. pp. 388–393. ISBN 0-7803-7273-5.
- Campion, G., G. Bastin and B. D'Andréa Novel (1996). Structural properties and classification of kinematic and dynamic models of wheeled mobile robots. *IEEE Transactions on Automatic Control* **12**, 47–62.
- Doty, K. L., C. Melchiorri and C. Boniveto (1993). A theory of generalized inverses applied to Robotics. *The International Journal of Robotics Research* **12**(1), 1–19.

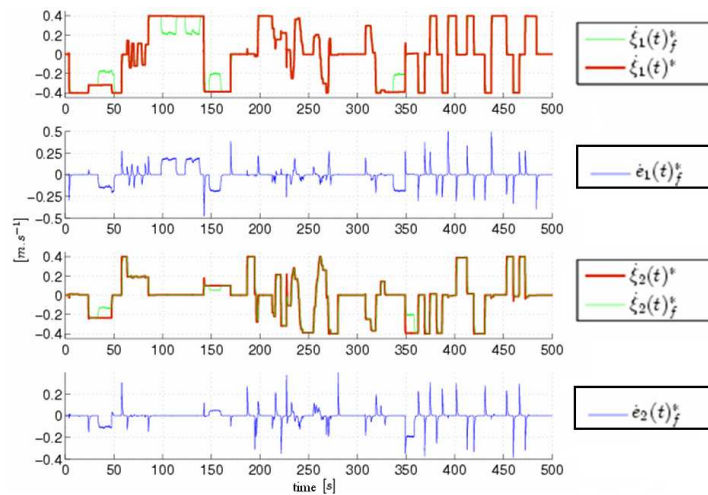


FIG. 4. Effects of filtering operational speed set-points issued from joystick

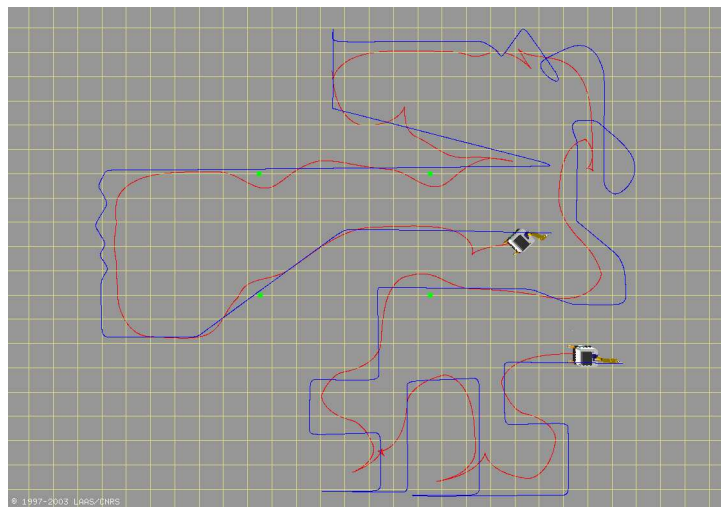


FIG. 5. Planar view of the movement of the system during the mission (grid size :  $0.5 \times 0.5$  m)

Fruchard, M., P. Morin and C. Samson (2005). A framework for the control of nonholonomic mobile manipulators. In: *INRIA Research Report N° 5556*.

Kang, S., K. Komoriya, K. Yokoi, T. Koutoku and K. Tanie (2001). Utilization of inertial effect in damping-based posture control of mobile manipulator. In: *Proceedings of the 2001 IEEE ICRA*. Seoul, Korea. pp. 1277–1282.

Khatib, O. (1987). A Unified Approach for Motion and Force Control of Robot Manipulators: The Operational Space Formulation. *IEEE Journal of Robotics and Automation* **3**(1), 43–53.

Morin, P. and C. Samson (2003). Practical stabilization of driftless systems on Lie groups: the transverse function approach. *IEEE Transactions on Automatic Control* **48**, 1496 – 1508.

Padois, V., J-Y. Fourquet and P. Chiron (2004a). Motion Coordination of a mobile manipulator for contact transition tasks. In: *Proceedings of the 10th IEEE International Confer-*

*ence on Methods and Models in Automation and Robotics*. Vol. 2. Miedzyzdroje - Pologne. pp. 967–972. ISBN 83-88764-04-7.

Padois, V., J-Y. Fourquet, P. Chiron and M. Renaud (2004b). On contact transition for non-holonomic mobile manipulators. In: *Proceedings of the 9th ISER*. Singapore.

Seraji, H. (1993). An on-line approach to coordinated mobility and manipulation. In: *Proceedings of the 1993 IEEE ICRA*. Atlanta, USA. pp. 28–35.

Umeda, Y., D. Nakamura, T. Mukarami and K. Ohnishi (1999). Hybrid position/force control of a mobile manipulator based on cooperative task sharing. In: *Proceedings of the 1999 IEEE ISIE*. Bled, Slovenia.

Yamamoto, Y. and X. Yun (1993). *Recent trends in mobile robots (Y. F. Zheng)*. Chap. 6: Coordinating locomotion and manipulation of a mobile manipulator, pp. 157–181. World Scientific.