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Dynamic control of pushing operations

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SUMMARY

The goal of this paper is to present a new method to control pushing operations with several fingers. We take into account some dynamical aspects that have not yet been investigated in pushing studies such as the object's center of mass acceleration correction and optimal force distribution. To do this, we use a general method for multi-chain mechanisms[1] based on a dynamical control with finger coordination. We first detail the problems encountered in this type of manipulation and the way to take these points into account with specific constraints definition for the support contact. According to the parameters of the model such as optimization criterion and object characteristics, we present simulation results of object pushing with two fingers for a rotational and translational motion.

KEYWORDS: Pushing task; Dynamic control; Multi-chain mechanism; Model parameters; Finger coordination.

1. INTRODUCTION

In the last fifteen years, many researchers have developed computational models for the pushing task. (A task during which an object is slid on a planar surface through a fence or point contacts). According to the literature, such operation consists in controlling the sliding of an object on a planar surface through various devices. Some authors have studied such strategies for part orienting in the industrial field,[2–4] while others have treated object's pushing trajectory planning and control without[5–8] or with obstacles.[9–13] The high versatility of the hand allows us to perform a wide range of object manipulation within the hand or take advantage of the environment. In the latter case, graspless strategies, including pivoting,[14] tumbling[15–20] and especially pushing have some interesting properties in comparison with classical pick-and-place operations. Forces involved are smaller robotic systems can be simpler, and pushing can be performed when an object has low accessibility. However, the environment plays a key role in the equilibrium definition and makes these manipulations less stable. During a pushing operation, the object is in contact not only with fingers but also with the environment. The object's dynamic equilibrium equations encompass both of them because forces exerted by the environment on the object dictate its motion. They can't be actively controlled and the fingers' forces amplitude are linked to them. The problem is to coordinate the action of several fingers in order to push an object according to a predefined path taking into account the mechanical interaction with the support. Based on works by Gorce,[1] we propose a method to solve this problem with an object trajectory tracking using an acceleration correction and an optimal force distribution. The technique used allows us to take into account contact with the environment, finger forces and the object's dynamics during the pushing operation while relaxing the quasi-static assumption made in the majority of the works.[5,8,22,23] The latter hypothesis states that the applied forces on the object (equal to the support friction forces) are just necessary to produce a motion and dynamic phenomena are neglected. To model the object/support interaction, we follow an approach inspired by Howe and Cutkosky[21] and Lynch et al.[6] Mason[5] in 1986 has developed a numerical procedure to find the motion of a pushed object by a single point contact assuming a known pressure distribution using results from Prescott[24] and MacMillan.[25] Then, Mason proposed a method to predict the rotation sense that depends only on the object center of mass location. Peshkin and Sanderson[22] following the work of Mason[5] gave bounds on the rotation sense by a center of rotation (*COR*) locus. Lynch[23] extended the results in the case of several contacts and provided a method to determine all the possible object's motions with a kinematic and force analysis. The concept of the limit surface which is a smooth convex surface in (f_x, f_y, m_z) space which encompasses the force motion relationship during a sliding motion was studied in tribology by Goyal and Ruina[26] and Liu and Paul.[27] To deal with the uncertainty of the pressure distribution which is needed to construct the limit surface, some useful approximations have been provided by Lynch et al.[6] with an ellipsoid and Howe and Cutkoky[21] with an ellipsoid, a cone or a pyramid. Also, some works have been devoted to the experimental determination of the friction parameters.[21,28,29] According to the pushing mechanics some planners have been developed. They allow one to reorient objects on a conveyor with a fence,[3,5] or with a parallel jaw gripper,[2,3,9] and align an object along a wall.[12,13] Some other works deal with object's displacement to a goal configuration, with one[6,10] or two contacts.[8] In particular, Akella and Mason[7] have used the concept of stable pushing in which an object is brought to a defined location by linear pushes. The exact motion is not known but at the end of each push the object is aligned with a fence. Terasaki and Hasegawa[9] studied pushing strategies to escape from a situation where an object can't be grasped and planned manipulator motion according to geometrical information about the environment. Kurisu and Yoshikawa[10]

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used optimal control techniques to move an object among obstacles with one contact using an approximation of the pressure distribution with a set of discrete support points. Lynch et al.[6] investigated manipulation and active sensing by a pushing control system using tactile feedback and a model of the limit surface. Lynch and Mason[30,31] discussed controllability issues to perform open loop plans for pushing a polyhedral object among obstacles.

This paper is organized as follows: In section 2 we describe the general architecture. In section 3, we present the force constraints for the pushing operation according to the sliding mechanics. In section 4, the coordinator level is described and the way to produce finger coordination is provided. Finally, in section 5, we present simulation results that show the effectiveness of the proposed method.

2. CONTROL ARCHITECTURE

The basic idea of the method is to control the object's center of mass acceleration and the force distribution to determine the optimal joint torque distribution for closed multichain mechanism when the trajectories are completely known. This approach has been used in references 1 and 32 for polyvalent grippers, in reference 33 for flexible grippers design, in references 11 and 34 for object graspless manipulation, in references 35–37 for biped standing posture control under external perturbation, in reference 38 for bipedal stepping motion, and in reference 39 for biped walking under external perturbation.

The main principle of the method is to coordinate the action of several fingers in order to obtain a desired object's motion. The hand is decomposed in several articulated chains fixed to a common body (the object) and connected to the palm. We first coordinate the individual action of each finger through contact forces using an optimization method and then obtain at the joint level action for each finger using their inverse dynamic model.

According to this formulation the control architecture is composed of three levels (Figure 1). It starts with a high level called "*the supervisor*" which role is to set the different trajectories, first for the object center of mass, and second for all the fingers of the hand. The intermediate level, called the "*coordinator*" deals with the finger coordination, and insures the object stability, contact forces distribution, and trajectory tracking. Finally, the lower level called "*the finger level*" exploits information coming from the "*supervisor*" and "*coordinator*" levels to compute the joint torque needed to obtain the desired contact forces using each finger inverse dynamic model.[40,41]

In this paper, we will stress the coordination level; the two other levels ("supervisor" and "finger level") have been

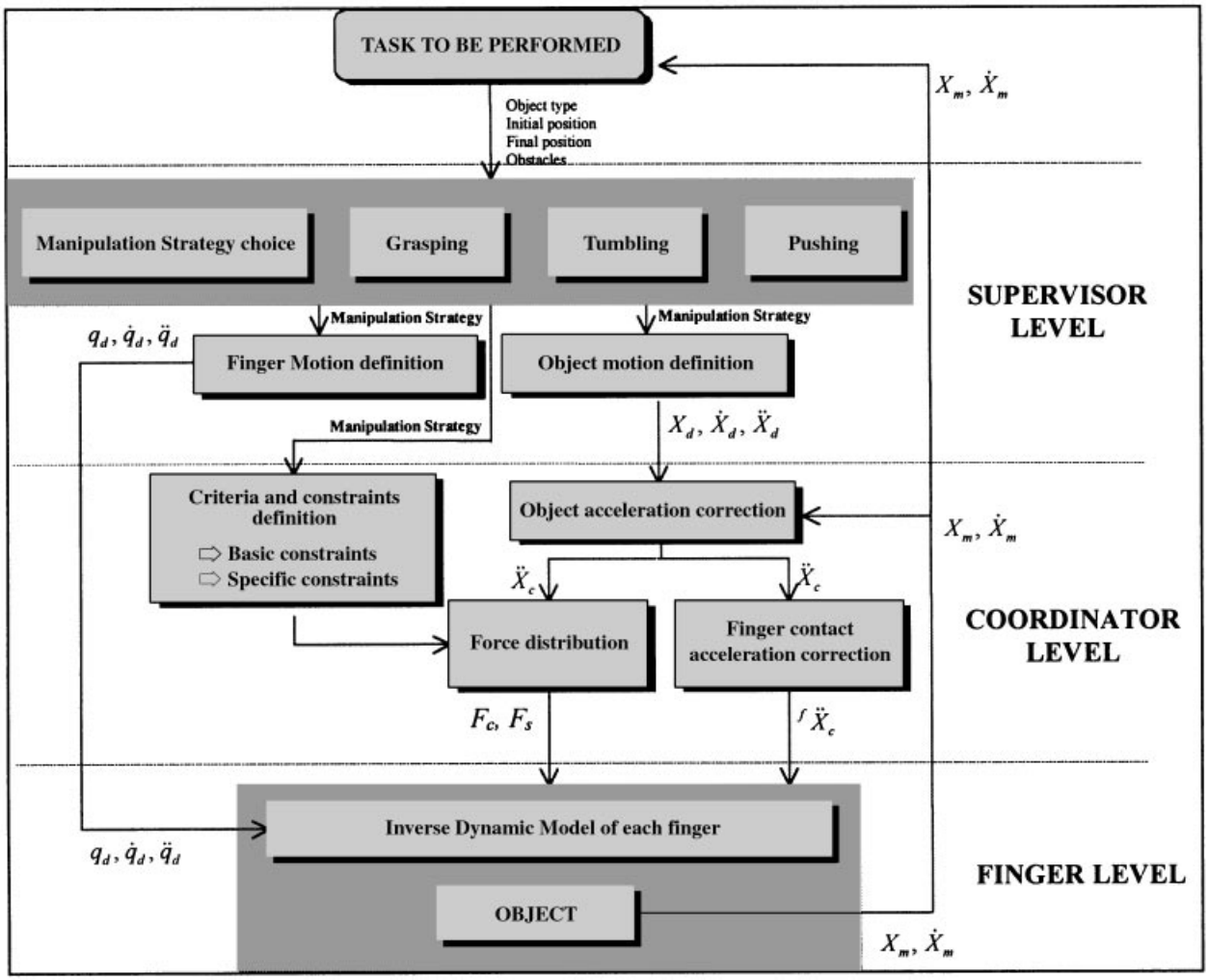


Fig. 1. Global view of the control architecture.

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Constraints	Dynamic Equilibrium	Positivity	Bounds on forces	Friction
Expression	Equation (1)	$f_{zi} \geq f_{z\min} > 0$	$f_{zi} \leq f_{z\max}$	$f_{xi}^2 + f_{xi}^2 \leq \mu_{ci}^2 \cdot f_{zi}^2$
number of constraints	6	n_c	n_c	$4 \times n_c$

Fig. 2. Basic finger constraints.

developed in more detail respectively in references 11, 34 and 1.

3. MANIPULATION CONSTRAINTS

In this section, we define the constraints chosen for finger and environment contacts. We derive two different sets of constraints: a basic set which concerns the object dynamics and the finger contacts and a specific set for the pushing strategy.

3.1 Basic constraints

3.1.1 Dynamic equilibrium. During the object's motion, the dynamic equilibrium equations must be satisfied giving 6 scalar constraints. If we consider the dynamic fundamental principle applied to the center of mass of the object C_0 relative to the reference frame expressed in the object frame (R_{C0}) centered at C_0, we obtain the following equations:

$$[M].[\ddot{X}] + [B] = [F_o] + [F_E] \tag{1}$$

$$[M] = \begin{bmatrix} J_3 & 0 \\ 0 & {}^0I_0 \end{bmatrix}, [\ddot{X}] = \begin{bmatrix} {}^0a_{c0} \\ {}^0\dot{\omega}_{c0} \end{bmatrix},$$

$$[B] = \begin{bmatrix} -m_0.{}^0g \\ {}^0\omega_{c0} \wedge ({}^0I_0.{}^0\omega_{c0}) \end{bmatrix}, [F_0] = \begin{bmatrix} {}^0F_0 \\ {}^0M_0 \end{bmatrix}, [F_e] = \begin{bmatrix} {}^0F_e \\ {}^0M_e \end{bmatrix} \tag{2}$$

where

m_o is the object mass, ${}^0I_0$ the object inertial matrix of dimension $[3\times3]$, ${}^0a_{c0}$ the object absolute acceleration expressed in the object reference frame $[3\times1]$, ${}^0\dot{\omega}_{c0}$ the object angular acceleration $[3\times1]$, ${}^0\omega_{c0}$ the object angular velocity $[3\times1]$, ${}^0g$: gravity acceleration, ${}^0F_0$ and ${}^0M_0$: resultant force and moment at the object center of mass extered by the fingers $[3\times1]$, ${}^0F_e$, ${}^0M_e$: resultant external force and moment at the object center of mass $[3\times1]$, and J_3 the identity matrix $[3\times3]$.
Also,

$$[F_0] = [W][f] \tag{3}$$

$[W]$ is the grasp matrix of dimension $[6\times(6\times n_c)]$ and $[f]$ is the concatened vector of contact wrenches of dimension $[6\times n_c]$ (n_c is the number of contacts).

3.1.2 Basic constraints. The basic constraints concern the finger-object contacts and the object's dynamic equilibrium. These constraints are classical in the literature,[1,42] and are surveyed in the work of Shimoga[43]. They concern some physical and mechanical properties that have to be satisfied and are summarized in Figure 2.

In the next section, we detail the specific constraints derived for the pushing operation.

3.2 Pushing specific constraints

3.2.1 Pushing mechanics. For a pushing operation, the contact between the object and the environment is planar with friction. The motion of the object is constrained in a plane, and has three degrees of freedom, two translations in the plane and one rotation around an axis perpendicular to the support plane. The instantaneous body motion can always be kinematically described as a pure rotation (clockwise or counterclockwise) about a particular point called the instantaneous center of rotation (*COR*). The overall surface interaction can be evaluated in a particular point called the weighted center of friction.[5,6,21,22] If we make the assumption that the sliding forces exerted on the object are constrained to lie in an horizontal plane we have:

$$f^T_{env/obj} = [f_x, f_y, f_z, 0, 0, m_z] \tag{4}$$

f_z being the vertical ground reaction which equals the object weight, f_x, f_y and m_z the frictional forces at the support plane. For a given *COR* location during a sliding motion we have a total frictional force expressed in the weighted center of friction frame given by:

$$\boldsymbol{f}_t = \begin{bmatrix} f_x \\ f_y \end{bmatrix} = -\iint_A sign(\omega)\mu_s.p.\boldsymbol{V}_{\boldsymbol{unit}}\, dA \tag{5}$$

and

$$m_z = = -\iint_A sign(\omega)\mu_s.p.[\boldsymbol{r}\times\boldsymbol{V}_{\boldsymbol{unit}}]dA \tag{6}$$

Where
ω: represents the instantaneous angular velocity of the object around the vertical axis perpendicular to the plane,
$\boldsymbol{V}_{\boldsymbol{unit}}$: represents the direction of the linear velocity of each infinitesimal contact area dA,
$\boldsymbol{r}$: represents the vector from the *COR* to the weighted center of friction.
P: represents the pressure distribution between the object and the support surface.
μ_s: represents the friction coefficient between object and support surface. We consider that the static and dynamic friction coefficient are equal and constant for each point of the surface.

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Assuming a defined *COR* location, the relationship between sliding motion and total friction force can be computed by summing up the contribution of frictional forces at each point across the contact surface using (8) and (9). This approach implies that the pressure distribution between the object and support is known or can be approximated.[28,29]

3.2.2 Limit surface. As the friction cone for the point contact, the limit surface for a sliding object encompasses the whole force motion relationship and is a closed, convex, origin-enclosing surface in (f_x, f_y, m_z) space.[26] For a given reference point, it is the boundary of the sum (or integral) of the frictional force and moments that each of the object's individual support point (or differential element of support area) can apply to the support plane for any given *COR* in the plane (Figure 3). The limit surface has an interesting property which is that during a sliding motion the object's velocity represented by the general vector (V_x, V_y, ω_z) is normal to the limit surface at a point (f_x, f_y, m_z) on the limit surface corresponding to the associated friction forces.

To cope with the uncertainty of the pressure distribution which may change, an approximation with an ellipsoid can be used.[6, 21] To construct it, we only need to determine or estimate the maximum force and moment due to friction. The maximum friction forces can be obtained for a translation placing the *COR* at infinity and the maximum moment placing the *COR* at the weighted center of friction.[4] The approximating ellipsoid (Figure 4) is given by the equation (7):[6]

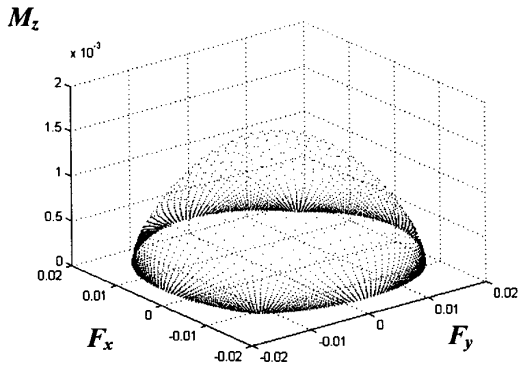


Fig. 3. Example of limit surface of a square object

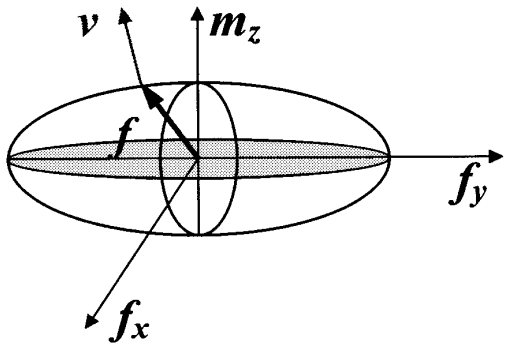


Fig. 4. Limit surface approximation with an ellipsoid, f is the generalized friction force, and ν the generalized velocity vector.

$$\left(\frac{f_x}{f_{\max}}\right)^2+\left(\frac{f_y}{f_{\max}}\right)^2+\left(\frac{m_z}{m_{\max}}\right)^2=1 \tag{7}$$

Defining the parameter $c=m_{max}/f_{max}$ the relationship between forces and velocities is straightforward for an ellipsoid and is given as follows:

$$\frac{V_x}{\omega}=c^2\frac{f_x}{m_z} \tag{8}$$

$$\frac{V_y}{\omega}=c^2\frac{f_y}{m_z} \tag{9}$$

If the pressure distribution is asymetric (when m_z is maximum f_x and f_y are not zero), an ellipsoid with a tilted axis can be constructed.[21] However, some differences may exist between the limit surface and the approximating ellipsoid especially for certain pressure distributions (for a rectangle with a length much greater than width for example). In general, as a contact patch becomes narrow in any direction there is a flattening of the limit surface in the orthogonal direction.[21]

3.2.3 Constraint definition. In our problem, we have to set constraints on the object-environment contact in term of interaction forces. We follow the approach proposed in reference 21 which states that given the object's velocity it is possible to compute the sliding forces. For that, we use the approximation of the limit surface with an ellipsoid proposed in the works from Howe and Cutkosky,[21] and Lynch et al.[61]

(i) The maximum frictional force and moment have to be evaluated either by experiment[21, 28, 29] respectively with a pure translational motion (*COR* at infinity) and rotational motion about center of pressure (*COR* at the origin of object frame) or using equations (5) and (6).

(ii) Given the object's velocity, we compute the frictional forces and moment according to (7), (8) and (9). So we have:

if $\omega\neq 0$

$$f_x=\frac{A\cdot|f_{\max}|\cdot|m_{\max}|}{\sqrt{(A^2+B^2)\cdot m_{\max}^2+f_{\max}^2}} \tag{10}$$

$$f_y=\frac{B\cdot|f_{\max}|\cdot|m_{\max}|}{\sqrt{(A^2+B^2)\cdot m_{\max}^2+f_{\max}^2}} \tag{11}$$

$$m_z=\frac{|f_{\max}|\cdot|m_{\max}|}{\sqrt{(A^2+B^2)\cdot m_{\max}^2+f_{\max}^2}} \tag{12}$$

with $A=\frac{V_x}{c^2\cdot\omega}$, and $B=\frac{V_y}{c^2\cdot\omega}$

otherwise:

$$f_x=-\frac{V_x}{|V|}\cdot f_{\max} \tag{13}$$

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$$f_y = -\frac{V_y}{|V|} \cdot f_{\max} \tag{14}$$

(iii) We state that at each time step during the sliding motion the support reaction is equal to the forces obtained in step (ii).

4. THE COORDINATOR LEVEL

The coordinator has a double role: first, determine the manipulation forces during the task and second insure the coordination between the different fingers, each of these acting together during the task. Our approach based on works from Gorce[1] relies on the center of mass acceleration correction and on the contact forces optimal distribution.

In our formalism the object trajectory is predefined (desired trajectory), it is represented by three vectors of six components (3 positions and 3 orientations) and noted $X_d(t)$, $\dot{X}_d(r)$, $\ddot{X}_d(t)$. During the task's execution, the object follows a real path noted $X_m(t)$, $\dot{X}_m(t)$. Under external perturbation or dynamic phenomena, the measured trajectory deviates from the desired trajectory. The principle of the object acceleration correction is to add to the desired object acceleration a correctional term in order to minimize the difference between the desired and measured trajectory. This term takes into account the measured position and velocity of the object at time t to calculate the modified acceleration consign at time $t+1$. Thus, this correction is expressed as follows:

$$\ddot{X}(t+1) = \ddot{X}_d(t+1) + \mathbf{K_p}.[X_d(t+1) - X_m(t)] + \mathbf{K_v}.(\dot{X}_d(t+1) - \dot{X}_m(t)] \tag{15}$$

where

$\ddot{X}(t+1)$: is the object center of mass acceleration correction at time $t+1$,

$\mathbf{K_p}$ et $\mathbf{K_v}$: are two real constant gain matrices (position and velocity) that guarantee the asymptotic stability $[6\times 6]$.

If we apply the acceleration correction at time $t+1$, the interaction forces between object/fingers and object/environment become in (1):

$$[M].[\ddot{X}(t+1)] + [B] = [F_o(t+1)] + [F_e] \tag{16}$$

At this level, the unknowns of the problem are the interaction forces at the finger. To solve this problem we use a linear optimization method: the simplexe algorithm.[1,11,32,34] Because the simplexe method is linear we have to modify the non finger sliding constraint which is quadratic. Therefore, we use the linear modified[42] Coulomb friction law that bounds the tangential friction forces relative to the normal force and the friction coefficient between object and finger:

So the general formulation of the Linear Programming problem is:

$$\text{Minimize } C = \sum_{i=1}^{n_c} f_{z_i}$$

subjected to

(16)

positivity for $i = 1..n_c$

Bounds on forces for $i = 1..n_c$

no finger sliding for $i = 1..n_c$

and

(10, (11) *and* (12) *if* $\omega \neq 0$

or

(13) *and* (14) *if* $\omega = 0$

where **C** is the cost function to be minimized and n_c the number of contacts on the object. Minimizing the normal forces exerted by the fingers implicitly minimizes all fingers trough the non finger sliding constraints (Figure 2).

As we can see in equations (11) through (14) the object velocity is needed to compute the sliding forces. To do this, we use the measured rather than desired velocity. As the sliding forces depend on the object trajectory, in other words the *COR* location, we give a better estimation of the sliding forces. Nevertheless, this correction is made with a delay of one step. In fact, during the task, at time t we determine the contact forces leading to an object displacement (the measured trajectory) using the estimate of the support sliding forces at time $t-1$ because the support forces depends on the measured velocity obtained at the previous step. If we make a trade-off between the calculation time and the time step precision, and if we choose smooth trajectories we consider this approach as valid.

5. RESULTS

In this section, we present simulation results, that show the force evolution at finger/contact and on the environment during a pushing operation. After this, we display finger contact and environment forces and the resulting object motion compared with the desired trajectory.

5.1 Simulation principle

First, we describe the simulation principle we have retained. We consider a pushing task of a rectangular object of mass m = 0.5 kg. We assume that the contact positions are known (Figure 5), and that the object is already in contact with the fingers. The object desired trajectory is previously determined and is considered as input data. During the task's process, once we have computed the object acceleration correction and made the distribution, we compute the actual object displacement and velocity using a numerical integration method. The object's trajectory is given using cycloid form which insures that the object desired velocity and acceleration will be equal to 0, at time $t = t_{start} = 0$, and $t = t_{end}$. This choice is dictated by the fact that we want to avoid large velocity or acceleration changes which may lead to

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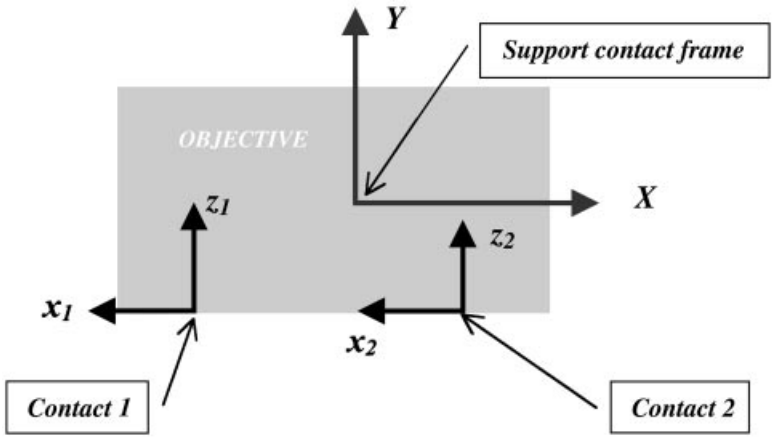


Fig. 5. Contact and support frames.

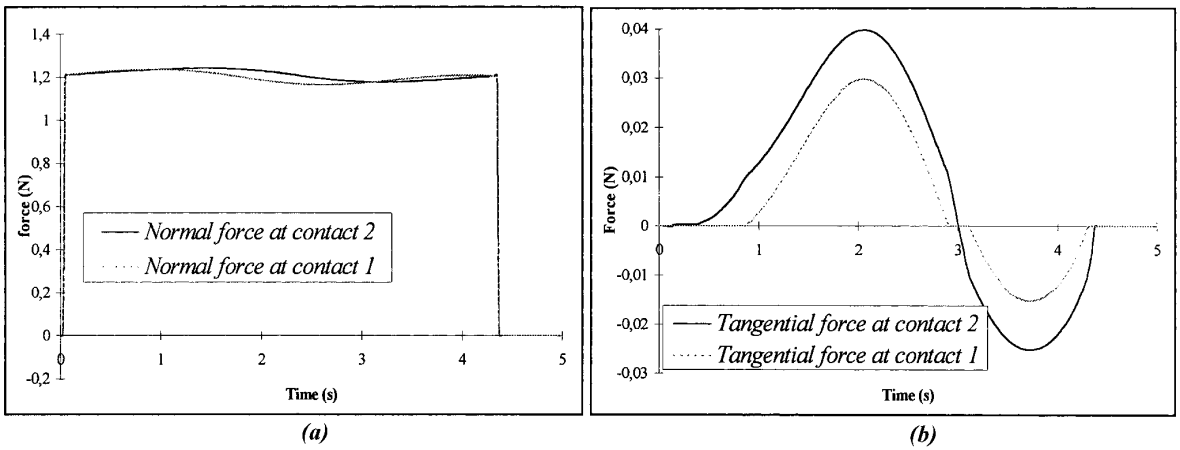


Fig. 6. Computed forces for the pushing operation, (a) Tangential force at finger 1 and 2, (b) normal force at finger 1 and 2.

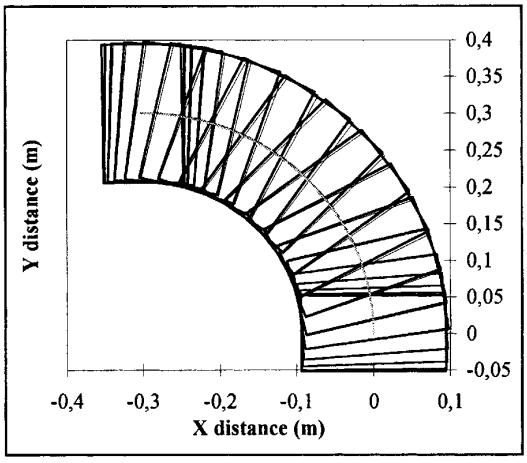


Fig. 7. Comparison between desired and measured object's trajectories during the first pushing operation.

object loss. The desired trajectory is given in the following form:

$$f(t)=\frac{f_d^{end}}{2\pi}\left(\frac{2\pi\cdot t}{t_{end}}-\sin\left(\frac{2\pi\cdot \mathrm{t}}{\mathrm{t_{end}}}\right)\right) \qquad (17)$$

5.2 Simulation results

In this section, we present the simulation results obtaining during a pushing operation of a rectangular block of mass = 0.5 kg with two fingers. The friction coefficients μ_s (between object and support) and μ_{ci} (at each contact) are taken equal to 0.5. The gain matrices were adjusted empirically, and we have found that $Kp_i=10$, $K\nu_i=10$, $\boldsymbol{Kp}=diag(Kp_i)$, $\boldsymbol{K\nu}=diag(K\omega_i)$ for $\mathrm{i}=1\ \ldots\ 6$, gave good results. The tasks's duration was $t=5$ seconds. We have considered two tasks, the first with a rotational motion (Figures 6 and 7) and a translational motion (Figure 8). In Figure 6, we display the sliding forces at the support (a), the tangential and normal forces at each contact (b, c) for the first task. In Figure 7, we present the object's measured trajectory. In Figure 8, we display the finger forces (Figure

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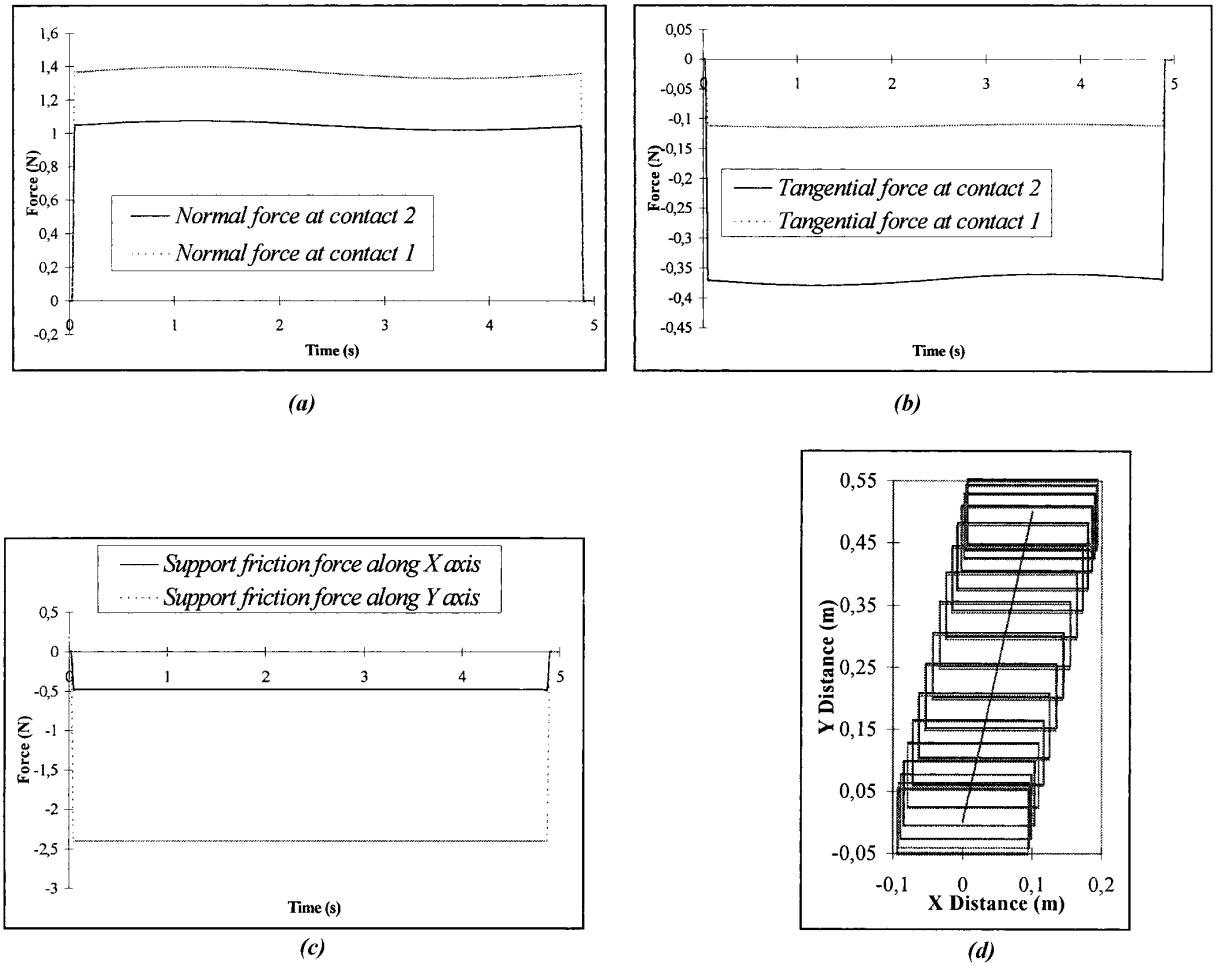


Fig. 8. Computed forces for the second pushing operation, (a) Tangential force at finger 1 and 2, (b) normal force at finger 1 and 2, (c) friction forces at the support, (d) measured and desired object's trajectories.

8a, b, c) and measured object's trajectory (Figure 8d) for the second task.

During the first trial, the maximum error is 3 mm in the X and Y direction, which corresponds to 1% of the total distance traveled. The final orientation error is about 2 degrees and represents approximately 2,2% of the whole object's rotation.

During the second trial the maximum error is 1 mm in the X direction and 4,5 mm in the Y direction corresponding to approximately 1% of the traveled distance in each direction.

6. CONCLUSION

In this paper, we presented a general scheme for object pushing taking into account the object's dynamics. Using a three levels hierarchic architecture, we have shown how using a linear programming method we could compute manipulation forces for the graspless manipulation of object pushing. To solve the force distribution problem, we introduce linear constraints on the action of the environment on the object. We illustrate the trajectory tracking and the force distribution problem with simulation results. This formulation is interesting because we take into account the acceleration phase of the object and if the desired velocity violate the classical quasi-static assumption, dynamical effects which can no longer be neglected are taken into account. Nevertheless, if the desired velocity is too large, dynamical effects become preponderant relative to the frictional forces and the object's movement is no longer controllable by the fingers and depends only on the initial impulsion and support frictional constraints.[44,45]

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