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Formulation of a control and path planning approach for a cab front cleaning robot

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Abstract

This paper formulates a control and path planning approach for a Cab Front Cleaning Robot. Currently, the operation of cleaning the front part of a train cab is performed manually under challenging conditions. The aim of this work is to formulate a control and path planning solution for the employment of a robot manipulator for such cleaning activity. The proposed solution comprises the study of the interaction between the robotic manipulator and an unknown surface, and consists in using an Operational Space Formulation implementation of simultaneous force and position control. The end-effector trajectory results from projecting a raster scan onto the surface to be cleaned, in real-time, with path adaptation to local surface geometry nuances. This paper also presents a list of criteria to validate future results.

Keywords: Cleaning robot; simultaneous force and position control; operational space formulation.

1. Introduction

Interacting with constrained environments, such as rigid surfaces, using only the touch sense is a skill that humans easily use in common everyday tasks as, for instance, in cleaning a surface. This is considered a constrained operation because when interacting with any rigid object our hand can not freely move by simply surpassing the physical boundaries of the respective surface. Therefore, the movement of the hand is constrained to the object surface while keeping contact with it during the task [1]. We easily handle this kind of interaction with a variety of rigid objects without breaking them or hurting our arms, by properly adjusting its position and stiffness [2]. Even without using our vision sensing - with our eyes closed - we can still trace an unknown surface using only tactile information.

A robotic system endowed with similar capabilities would be able to automate a significant number of operations that currently are only manually performed. One such operation is the cleaning process of the train cab fronts. The current process includes mechanised train washers that are unable to clean the train cab front ends due to complicated shapes. As a result, these surfaces keep being manually cleaned which could cause some health and safety issues, including working in non ergonomic postures and subject to bad weather conditions. Moreover, workers are exposed to a highly humid environment close to 25kV overhead lines and 750V rails, although the train is not manually washed above an orange “wash line” on the train as a safety procedure. Fig. 1 shows an example of a train being manually cleaned.

The working conditions described above have supported the study of the application of a robotic and autonomous system (RAS) to this particular task. In this paper we present an approach for the control and path planning of an automated cleaning manipulator.

Fig. 1. Manual cleaning operation of a train cab front.
Despite being a task easily achieved by humans, few works address the challenge of using a robot to clean a 3-dimensional (3D) surface. Hess et al. [3] states that at that time they could not find any manipulator robot that could clean arbitrary 3D surfaces. Hess et al. [3] propose an algorithm to cover a 3D surface using a redundant manipulator, by making use of an explicit surface model generated from a point cloud obtained using a Kinect sensor. However, given that the Kinect sensors are known to perform poorly in a outdoor environment under ambient infra-red radiation, this sensor would not be suited for a train cleaning application. Moreover, guaranteeing a constant pressure between the end-effector and the train surface would require precise measurements, and the incorporation of more precise sensors to measure the global position of the components could result in much more complex and expensive system.

The cleaning manipulator has to be able to sweep the train surface without damaging it and at the same time apply enough pressure to guarantee a contact between the cleaning tool and the train surface. Hence, the relevance in studying and applying force control techniques. In the works [4–6] a mobile manipulator was successfully employed in the operation of aircraft canopy polishing using simultaneous force and position control and the Operational Space Formulation proposed by Khatib [7,8]. The aircraft polishing manipulator does not make use of any explicit model of the surface being polished, but the end-effector only moves along a line in the surface.

For the process of cleaning the train cab front we propose a similar control approach used in the polishing manipulator, but that incorporates the global information and location to guarantee that all the surface is covered. Values such as the deviation of the measured force to the cleaning force set point, trajectory error, and area covered present a potential set of criteria to validate the proposed approach in future results.

2. Operational Space Force and Motion Control

In general the dynamic model of a robotic manipulator with rigid links is written in the form [8]

\[ M(q) \dot{\dot{q}} + \mathbf{C}(q, \dot{q}) + \mathbf{g}(q) = \tau, \]  

(1)

where \( q \) is the vector of \( n \) joint coordinates, and \( \dot{q} \) and \( \ddot{q} \) are the first and second time derivatives of \( q \), corresponding respectively to the joint velocities and accelerations. The matrix \( M(q) \) is the inertia matrix and the matrix \( \mathbf{C}(q, \dot{q}) \) is due to Coriolis and centrifugal effects of motion. The term \( \mathbf{g}(q) \) is due to the gravitational forces acting on the manipulator links, and \( \tau \) is the vector of \( n \) generalized forces acting on the joints (torques in the case of revolution joints).

The equivalent dynamic model in the operational space (end-effector frame) is given by

\[ M_{e}(q) \dot{\dot{x}} + \mathbf{C}_{e}(q, \dot{q}) + \mathbf{g}_{e}(q) = \mathbf{f}_{e}, \]  

(2)

where vector \( \dot{x} \) is manipulator’s end-effector acceleration, and the vector \( \mathbf{f}_{e} \) is the force resulting from the manipulator movement. The vectors \( \dot{x} \) and \( \mathbf{f}_{e} \) have 6 components each. The first 3 correspond respectively to the 3 linear accelerations and forces, and the last 3 correspond respectively to the angular accelerations and torques. The matrices \( M_{e}, \mathbf{C}_{e}, \) and the vector \( \mathbf{g}_{e} \) are analogous to the ones used in Equation 1 and can be computed using the matrices from the configuration space dynamic model, as follows

\[ \mathbf{g}_{e}(q) = J^{-T}(q) \cdot \dot{\mathbf{g}}(q) \]  

\[ \mathbf{C}_{e}(q, \dot{q}) = J^{-T}(q) \cdot \mathbf{C}(q, \dot{q}) - M(q) \cdot \dot{\mathbf{J}}(q) \cdot \dot{q} \]  

\[ M_{e}(q) = \left[ \mathbf{J}(q) \cdot \mathbf{M}^{-1}(q) \cdot \mathbf{J}^{T}(q) \right]^{-1}, \]  

(3)

where the matrix \( \mathbf{J} \) is the Jacobian of the manipulator. The generalized joint forces \( \tau \) that produce the total force applied in the end-effector \( \mathbf{f}_{e} \) can be computed using the transpose of the Jacobian matrix \( \mathbf{J}^{T} \)

\[ \tau = \mathbf{J}^{T}(q) \cdot \mathbf{f}_{e}. \]  

(4)

Khatib [8] proposed an approach for simultaneous motion and force control of a robot manipulator in the operational space, where the end-effector acceleration \( \dot{x} \) encompasses 2 contributions

\[ \ddot{x} = \Omega \cdot \ddot{x}_{m} + \ddot{x}_{f}. \]  

(5)

The vectors \( \ddot{x}_{m} \) and \( \ddot{x}_{f} \) are, respectively, the accelerations that result from the desired motion and force responses. Matrices \( \Omega \) and \( \ddot{x}_{f} \) respectively define the direction of motion and force control. Therefore for each end-effector direction only one position or force can be controlled and not both at the same time.

In a constrained task where the end-effector applies a desired force \( \mathbf{f}_{d} \) on a surface, the total force applied is

\[ \mathbf{f}_{e} = \mathbf{f}_{d} + \Omega \cdot \ddot{x}_{f}. \]  

(6)

By combining Expression 5 in 2, 2 in 6, and 6 in 4, we obtain

\[ \tau = \mathbf{J}^{T}(q) \left[ M(q) \cdot \left( \Omega \cdot \ddot{x}_{m} + \ddot{x}_{f} \right) + \dddot{x}_{f} \right] + \mathbf{J}^{T}(q) \cdot \mathbf{C}(q, \dot{q}) + \mathbf{g}(q), \]  

(7)

which computes the manipulator joint torques for a task with simultaneous force and position control.

The diagram shown in Fig. 2 illustrates the operational space force and motion control. The Manipulator block corresponds to the real physical robot manipulator where we can directly control the joint torques \( \tau \) and measure the joint positions \( q \) and velocities \( \dot{q} \), and the force and torques applied at the end-effector \( f \). The end-effector position is obtained using the forward kinematics model \( x = \mathbf{G}(q) \) and the end-effector velocity is computed using the manipulator Jacobian \( \dot{x} = \mathbf{J}(q) \cdot \dot{q} \). The end-effector position \( x \) and force \( f \) are then controlled using 2 PID (Proportional-Integral-Derivative) controllers so to achieve the respective desired values \( \mathbf{x}_{d} \) and \( \mathbf{f}_{d} \). The control signal resulting from the PID controllers \( \dot{x} \) determines the joint torques \( \tau \) computed using the inverse dynamics - Expression 7. The matrix \( \Omega \) selects the position control directions.

3. Method

3.1. Local path planning

The local path planning refers to the control approach that allows one to simultaneously control the interaction force between the manipulator end-effector and the environment and the end-effector position.
Fig. 3. Illustration of the end-effector including the force sensor and a soft material such as sponge at the tip. The 3 coordinate systems shown correspond to: 0 - reference coordinate system; N - standard end-effector coordinate system; F - force sensor coordinate system; S - surface contact coordinate system.

Fig. 2. Simultaneous force and position control diagram.

coordinate system F. Therefore, the vector of generalized forces provided by the force sensor have to be transformed as follows

\[ \begin{align*}
\mathbf{f} & = \mathbf{f}_N \cdot \mathbf{N}_F \cdot \mathbf{f}_F, \\
\mathbf{N}_F & = \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}, \\
\mathbf{f}_F & = \begin{bmatrix}
F_x \\
F_y \\
F_z
\end{bmatrix},
\end{align*} \]

(8)

where

\[ \begin{align*}
\mathbf{f}_N & = \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}, \\
\mathbf{N}_F & = \begin{bmatrix}
I \\
0 \\
0
\end{bmatrix}, \\
\mathbf{f}_F & = \begin{bmatrix}
F_x \\
F_y \\
F_z
\end{bmatrix},
\end{align*} \]

(9)

\[ \begin{align*}
\mathbf{N}_F & = \begin{bmatrix}
0 & -a_z & a_y \\
a_z & 0 & -a_x \\
-a_y & a_x & 0
\end{bmatrix},
\end{align*} \]

(10)

Even though, the generalized forces are measured relative to the coordinate system F, thinking in terms of the coordinate system S provides better insight on the forces we intend to control when sweeping a surface in a cleaning operation. The force diagram shown in Fig. 4 illustrates the resulting forces from the end-effector movement. In a movement where the end-effector contacts with the surface the expected forces and torques are: the normal force \( F_n \), which we wish to control so to be roughly constant along the path; the friction force \( F_f \), which is not going to be controlled and depends on the normal force, the end-effector velocity, and properties of the surfaces in contact; the torque \( M_f \) due to changes in the surface.

If the end-effector were to sweep a planar surface with perfect contact, then the torque \( M_f \) would be zero. When the end-effector sweeps through a non flat surface and the contact between the end-effector tip and the surface is not planar then there will be a resulting non zero torque \( M_f \). Therefore, one
4. Illustration of the forces and torques acting on the end-effector during a cleaning movement. The expected resulting forces and torques are the desired force normal to the surface $F_d$, the friction force $F_a$, and the torque resulting from the surface geometry changes $M_q$.

A way to guarantee that the end-effector keeps the most normal to the surface at all times is to minimize the absolute value of the moment $M_q$ around the axis $\hat{y}$, i.e., control it to be 0.

Because minimizing the torque around the axis $\hat{y}$ ($-M_q$) is not the same as minimizing the torque around the $\hat{y}$ axis ($-M_q + l_s \cdot F_d$), we define the vector of desired forces relative to the frame $S$ as

$$^Sf_d = \begin{bmatrix} 0 & 0 & F_d & 0 & 0 \end{bmatrix}^T.$$  \hspace{1cm} (12)

and then transform it to the reference frame as follows

$$^0f_d = ^0TN \cdot ^NP_s \cdot ^Sf_d.$$  \hspace{1cm} (13)

The selection matrix $\Omega$ and $\Omega$ are given by

$$\Omega = \begin{bmatrix} ^6R_N^0 \cdot ^6R_F \cdot 0 & 0 \\ 0 & ^6R_N^0 \cdot ^6R_M \cdot 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix},$$  \hspace{1cm} (14)

where the matrices $\Sigma_F$ and $\Sigma_M$ can be seen as the selection matrices in the end-effector frame. For the case of the cleaning operation, they can be defined as

$$\Sigma_F = \text{diag}(1, 1, 0)$$

and $\Sigma_M = I - \Sigma$. These selection matrices correspond to controlling the force in the end-effector $z$ direction (perpendicular to the surface) and the torques in the end-effector $x$ and $y$ directions (ensure normal normal contact between the tool and the surface).

3.2. Global path planning

Concerning the execution of a trajectory that effectively covers all the surface, the planning approach has to consider that the surface is unknown. Therefore, the trajectory should not include a rigid set of positions but should rather encompass a more flexible plan that can be adapted according to the local geometry of the surface, in order for the tool to apply a roughly constant pressure.

To achieve such flexibility, the end-effector motion (position, velocity, and acceleration) cannot be planned in all directions, given that the surface geometry is unknown. One hypothesis is to use a planar trajectory, as shown in Fig. 5, and leave the other direction with no position control, such that the end-effector can move perpendicularly to this plane in order to accommodate the surface geometry. This hypothesis corresponds to project the planar raster scan onto the surface instead of planning the 3D trajectory (Fig. 6), which could not be done because the surface is unknown.

In conclusion, when executing a trajectory such as raster scan constrained to a surface, part of the motion is planned in the end-effector frame and in real time, subject to the unknown surface geometries and adjusting the arm configuration, whereas the motion boundaries and global motion directions are provided by a global plan (directions of motion specified in the reference frame). A prior knowledge of the global surface geometry, such as surface height and width, is useful for guaranteeing that the end-effector covers all the surface to be cleaned.

3.3. Motion Transition

The dynamics for an unconstrained motion is different from the dynamics of a constrained motion, and switching between these different dynamic modes should be carefully addressed in order to avoid an unstable transition. The first impact between the tool and the surface is in itself a complex research problem often referred to as switching dynamics. However, a naive approach can be tested. This approach will consist in initializing the end-effector in such position and orientation relative to the surface that when approaching the surface it performs a stable contact. The incorporation of a smooth material attached to the end-effector will also allow to obtain a smoother impact. Once the transition between the unconstrained and constrained motions is detected through the end-effector force sensor measurement...
ments, the control policy applied to the robotic manipulator is switched from a simple position controller to the simultaneous force and position controller.

4. Validation Criteria

The validation of the automatic cleaning operation - control and path planning algorithm - will consist in automatically cleaning a non-flat unknown surface and evaluating the following criteria:

- Force applied by the end-effector in the surface - the mean value of force should be equal to the desired contact force and it should remain roughly constant during all sweep path. Therefore, the evaluation of the measured force standard deviation gives an indication of how smooth is the interaction with the surface;
- Mean projected trajectory error - given that the surface geometry is unknown we can not measure the trajectory error. Nevertheless, we can compare the projection of the real trajectory with the reference two dimensional trajectory, and compute the mean error for a sweeping trial;
- Area of surface covered - this criteria consists in marking a region of the surface with ink and executing the automatic cleaning process. By analysing an image before and after the cleaning process, it is possible to verify how much of the region was covered;
- Surface cleanliness - evaluating by inspecting how clean is the surface after performing the automatic cleaning process.

The described criteria are useful not only to validate this work control and path planning approach, but as well for tuning the controller parameters and selecting parameters such as cleaning velocity (velocity of the end-effective while cleaning) and the cleaning force (normal force set point).

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