Hybrid Control on a Domestic Service Robot Designed for Cleaning Tasks

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Abstract: - In this paper, the problem of the compliant interaction of a mobile manipulator for home assistance with the environment is addressed. Robot systems will work directly with people in domestic areas, thus placing a central importance on making interactions between people and machines as natural as possible. A new kind of hybrid force/position control algorithm is devised, to provide the manipulator with a flexible controller which can deal with different interaction tasks. This approach is very simple since it does not require joint torque / motor current interface but only a positional interface. A new household mobile robot was used to test this method. The compliant motion performed by this controller allows the robot to execute interaction tasks both with the environment and with the user and this make it easy to be used by non-experts. A table cleaning and a path teaching are two example of such a kind of tasks that will be performed from the robot in order to validate experimentally the results of the paper.

Key Words: - Hybrid force/position control, household mobile robot, compliant behavior.

1 Introduction

Force and motion control design has been widely discussed in robotics. Operational space force and position control [3], impedance control [2], parallel force/position control [1], active stiffness control [9], hybrid position/force control [8], [5] are among the various methods that have been proposed in order to ensure regulation of contact force to a desired value during the interaction of a robot manipulator with the environment. In these schemes, however, the measured force error is directly converted to actuator forces or torques thus they require a joint torque / motor current interface. In [4], a force/position controller implemented on a industrial robot with positional interface is presented. This is a specific way of hybrid control which decouples rigidly force control actions from motion control actions losing a part of the sensor information.

In this paper, a new hybrid controller is proposed. According to [4], our approach requires only a positional interface, but it improves the classical hybrid controller using the sensor information ignored in the classical approach to handle critical situations due to imperfect task planning, e.g. an unplanned impact during a cleaning trajectory exploiting. In this case the controller modifies its task geometry models to fit the actual ones. The designed controller has been experimentally tested on a new service robot designed for cleaning tasks in home environments, the *CleaningAssistant*. In Section 2 of this article, design and sensor setup of the CleaningAssistant is introduced. This household robot system will work directly with people in domestic area to perform simple housework such as setting the table or performing cleaning tasks. Thus placing a central importance the manipulator compliant behavior achieved by the hybrid controller presented in Section 4. Another advantage of this controller is its flexibility. In fact, as explained in Section 4.2, it is structured in a modular way in order to deal with other very different interaction tasks. The path teaching is taken as an example. In such a situation the new hybrid controller requires only a simple task description to perform the given task (see Section 5).

Fig. 1: CleaningAssistant: a mobile manipulator for home environments.

The experimental results presented in Section 5 were very satisfying also in consideration of the low computational weight of the algorithm which is very important in a real time application.

2 Design of The *CleaningAssistant*

The *CleaningAssistant* shown in Fig. 1 consists of a mobile base and a manipulator on top of it. The manipulator joints as well as the differential drive system for the mobile base are built from modular drive components.

The 7 DOF manipulator is based on a vertical linear axis used to enhance the vertical workspace of the system. Next a SCARA-like chain of revolute joints are mounted on the linear axis. An additional degree of freedom is used to switch between the horizontal and vertical arrangement of the SCARA-like chain. Intermediate configurations are also allowed. A discussion of the kinematics together with a solution for the inverse kinematics problem can be found in Marrone and Strobel [6].

Sensory feedback is provided by: (a) a new kind of compliant force-torque-sensor, developed at the German Aerospace Center (DLR) (see Meusel and Hirzinger [7]) mounted between the wrist and the end-effector of the manipulator, (b) a 2D range laser-scanner used for position estimation as well as for obstacle detection and avoidance while navigating the mobile base, (c) a trinocular stereo-vision system for gesture and object recognition and localization, (d) a touchscreen for additional gesture input, e.g. for the qualitative path specification or object selection in a displayed scene representation. This kind of sensors allows the user to communicate with the robot in a natural way using speech and gesture (see Strobel [10]).

3 The Task Geometry

A kineto-statics analysis of a situation of interaction between the manipulator and the environment leads the consideration that along each degree of freedom of the task space, the environments imposes either a position or a force constraint to the end-effector (named *natural constraint*) and the manipulator can control only the remaining one, the so-called *artificial constraint*. Thus, in order to simplify the task geometry description, a new coordinate frame is introduced. This *constraint frame* defined as $\mathcal{R}_c(O_c, x_c, y_c, z_c)$ and obtained from the base frame by a rotation transformation described by the rotation matrix $\mathbf{R}_c$, is chosen so as to allow an easier representation of the natural and artificial constraint.

Using these considerations, the constraint frame for the cleaning task was defined as follows: the $\mathbf{z}_c$ axis lies along the normal to the surface whereas the $\mathbf{x}_c$ axis lies along the trajectory tangent, the $\mathbf{y}_c$ axis is consequently derived as $\mathbf{z}_c \times \mathbf{x}_c$.

By this frame definition the task geometry is noticeably simplified in fact during the whole task execution, the tool force is exerted along the $\mathbf{z}_c$ axis and its motion direction lies along the $\mathbf{x}_c$ axis. Therefore in case of task geometry changing only the constraint frame $\mathcal{R}_c$ and then the rotation matrix $\mathbf{R}_c$ will be changed.

Thus on the one hand the task planning is simplified, but on the other hand the control strategy will obviously have to account the rotation matrix $\mathbf{R}_c$.

4 Hybrid Force/Position Control

In order to control simultaneously both the end-effector motion and contact forces, a hybrid force/position controller (see Craig [8]) is developed. Nevertheless this approach has the drawback that it is rigidly founded on the assumption of perfect task planning. In fact it structurally decouples force control actions from motion control actions in terms of the components of the task space, avoiding in this way undesirable interfer-

ence between motion and force controllers. But on the other it cancel part of the sensor measurements on the assumption that this information is not useful. Thus when hybrid control has to operate under imperfect task planning e.g. unplanned impact the system behavior may become quite critical. The hybrid controller shown in Fig. 3 handles these critical situations using the sensor information ignored in the classical approach.
In Section 4.1 the control system is introduced then in Section 4.2, 4.3 and 4.4 each controller components will be explained.

4.1 Control Scheme

A classical feedback control is designed for the robotic manipulator in order to take advantage of the stability property of this kind of control scheme.
As shown in Fig. 2, only a positional interface is used

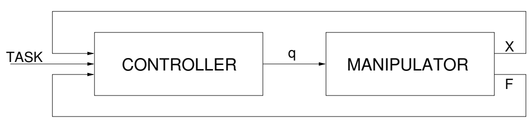

Fig. 2: Manipulator control scheme.

in this approach (see also Lange and Hirzinger [4]), in fact the command variable is the joint vector

$$\mathbf{q} = \begin{pmatrix} q_1 \\ q_2 \\ \vdots \\ q_7 \end{pmatrix} \tag{1}$$

where q_i, for i=1,$\cdots$,7, is the i'th joint variable. The feedback data is the end-effector position

$$\mathbf{x} = \begin{pmatrix} x_b \\ y_b \\ z_b \end{pmatrix} \tag{2}$$

evaluated by forward kinematics from the joint angle sensor data and the force vector

$$\mathbf{f} = \begin{pmatrix} fx_b \\ fy_b \\ fz_b \end{pmatrix} \tag{3}$$

defined by measured force expressed with respect to the tool center point and with compensated weight. The controller inputs are the feedback data and the *task object* that describes the kind of task but which will be explained in following Section 4.2.

4.2 Task Manager

As shown in Fig. 3 the control law requires the desired value of the force ($\mathbf{f}_d$) and velocity ($\mathbf{v}_d$). These reference values and the selection matrix $\mathbf{S}$ (see Section 4.3) describe the desired end-effector behavior and then they will be defined *behavior parameters* whereas the rotation matrix $\mathbf{R}_c$ (see Section 3) which describes the task geometry is named *task geometry parameter*. Thus geometry task and system behavior changes don't require to change the control law but only those parameters. Therefore the controller needs a subsystem which evaluates these parameters according to the task target. This subsystem is named *task manager* and, as shown in Fig. 3, its input values are the feedback variables and the task object. Using these inputs it evaluates the desired force and velocity, the selection matrix and the rotation matrix.
Now the question is how these parameters are evaluated. The task object is the answer. In fact it is a complete description of the task which includes also the algorithms for evaluating both the behavior and the task geometry parameters from the feedback variables. Thus the task manager outputs are calculates from the input values by the task object algorithms.
In order to achieve a high level of flexibility, an object oriented language (C++) is used for the implementation. Thus the definition of a generic parent class (task) allows to define a variety of children class(cleaning task, path teaching task, etc.) very different from each other but the task manager can deals with them always in the same way.
Another improvement achieved by the task manager is the ability to overcome critical situations. In fact it receives the entire sensor data ($\mathbf{f}$ and $\mathbf{x}$) and, before to lose part of them in the control law, it can check if there is a critical situation due, for example, to imperfect task planning. In this case the controller modifies its task geometry models to fit the actual ones and consequently also the strategy for executing the given task. Thus the task specification is actively upgraded by autonomous learning.

4.3 Selection Matrix

Our approach follows the idea of Khatib [3] who introduced the *generalized task specification matrix* to divide the force control from the motion control. In fact along each axis of the constraint frame only either a position or a motion control action is exerted. Thus it is

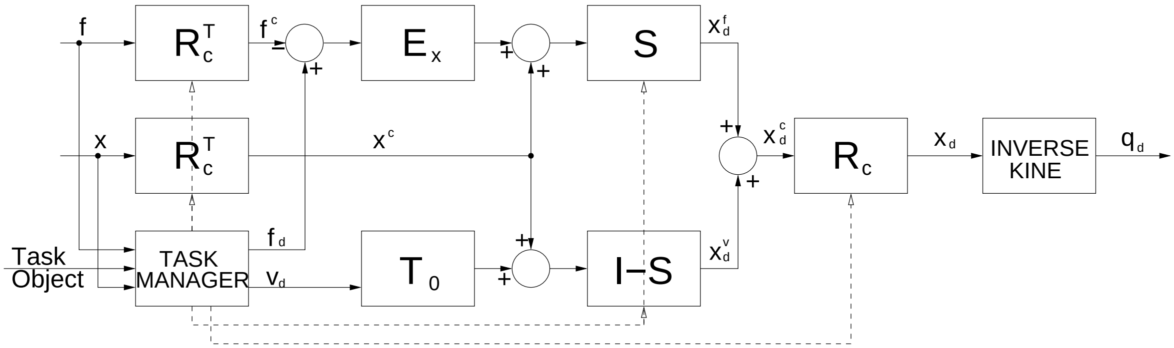

Fig. 3: Controller scheme.

worth to define the selection matrix as a 3 x 3 matrix

$$\mathbf{S} = \begin{pmatrix} \sigma_x & 0 & 0 \\ 0 & \sigma_y & 0 \\ 0 & 0 & \sigma_z \end{pmatrix} \tag{4}$$

where σ_i are binary numbers assigned the value 0 when a free motion is specified along the i-axis, for $i = x, y, z$, of the constraint frame. This matrix selects the directions of force control with respect to the constraint frame $\mathcal{R}_c$ whereas the directions of motion control are described by the matrix $\mathbf{I} - \mathbf{S}$ where $\mathbf{I}$ designates the 3 x 3 identity matrix. Thus the input values must be translated in $\mathcal{R}_c$ and similarly the outputs must be translated from $\mathcal{R}_c$ into base frame, this means that the controller scheme must take into consideration the rotation matrix $\mathbf{R}_c$.

4.4 Force and Motion Control

The high stiffness of the robot could be problematic for the stability of the whole system. Nevertheless the force/torque sensor inserts an artificial compliance between the last link of the robot and the end-effector which avoids stability problems furthermore the cleaning tool used during the cleaning task introduces an additional compliance. Those compliance can be described by coefficients of elasticity expressed by the estimated diagonal matrix $\mathbf{E}_x$. The robot as well as the environment can be regarded to be stiff. Thus, if there is no movement in the motion controlled direction, the desired value of the position is

$$\mathbf{x}_d^f = \mathbf{x}^c + \mathbf{E}_x \cdot (\mathbf{f}_d - \mathbf{f}^c) \tag{5}$$

where $\mathbf{f}_d$ is the desired force vector and it is evaluated by the Task Manager as will be explained in Section 4.2.

Similarly along the motion controlled direction it is desired to have a given velocity $\mathbf{v}_d$ and thus the desired position is

$$\mathbf{x}_d^v = \mathbf{x}^c + \mathbf{v}_d \cdot T \tag{6}$$

where also $\mathbf{v}_d$ is an output of the Task Manager.
Considering now both motion and force control and separating their effects with the selection matrix yields

$$\mathbf{x}_d^c = \mathbf{S} \cdot \mathbf{x}_d^f + (\mathbf{I} - \mathbf{S}) \cdot \mathbf{x}_d^v \tag{7}$$

where $\mathbf{x}_d^c$ is expressed in the constraint frame as well as the other variables in the equation.
Using (5) and (6) the desired end-effector position (7) can be rewritten as

$$\mathbf{x}_d^c = \mathbf{x}^c + \mathbf{S} \cdot (\mathbf{f}_d - \mathbf{f}) + (\mathbf{I} - \mathbf{S}) \cdot \mathbf{v}_d \cdot T \tag{8}$$

Finally the desired joint vector $\mathbf{q}_d$ will be calculated from the desired position translated in the base frame, by the manipulator inverse kinematics (see Marrone and Strobel [6]).

5 Interaction Tasks

The mobile manipulator presented in this paper was designed to perform housekeeping cleaning tasks in collaboration with the user. A typical housework in everyday domestic setting is the cleaning of a surface. It is the aim of this task that a special tool (e.g. a sponge) attached to the end-effector follows a path on the surface while along the surface normal it exerts a force of given value (see Fig. 4). To perform this surface cleaning the system need an appropriate task description: the task object. This one will be defined by targets for the absolute value of the force vector $|\mathbf{f}_d|$ and for the absolute value of speed $|\mathbf{v}_d|$, by the plane to be cleaned

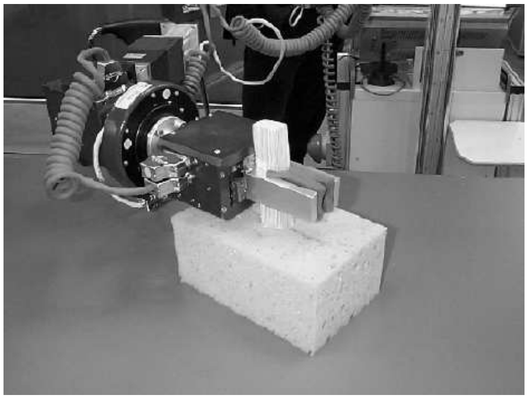

Fig. 4: Cleaning task.

expressed by the normal unit vector $\mathbf{n}$ and by the cleaning path vertices.
Using these setting and the sensor data the task object evaluates behavior and task geometry parameter as follows.

1. Set the rotation matrix $\mathbf{R}_c$ as outlined in Section 3 i.e. the $\mathbf{z}_c$ axis lies along the normal $\mathbf{n}$ to the surface whereas the $\mathbf{x}_c$ axis lies along the line between the actual position and next path vertex, the $\mathbf{y}_c$ axis is consequently derived as $\mathbf{z}_c \times \mathbf{x}_c$.

2. Set the desired velocity $\mathbf{v}_d$ as a vector in $\mathcal{R}_c$ with direction $\mathbf{x}_c$ and norm $|\mathbf{v}_d|$, thus

$$\mathbf{v}_d = \begin{pmatrix} |\mathbf{v}_d| \\ 0 \\ 0 \end{pmatrix} \tag{9}$$

3. Set the desired force $\mathbf{f}_d$ as a vector in $\mathcal{R}_c$ with direction $-\mathbf{z}_c$ and module $|\mathbf{f}_d|$, thus

$$\mathbf{f}_d = \begin{pmatrix} 0 \\ 0 \\ -|\mathbf{f}_d| \end{pmatrix} \tag{10}$$

4. Set the selection matrix to

$$\mathbf{S} = \mathbf{k} \cdot \mathbf{k}^t \tag{11}$$

where $\mathbf{k} = (0\,0\,1)$, in order to yield a force control along $\mathbf{z}_c$ and a position control on $\mathbf{x}_c$–$\mathbf{y}_c$ plane.

5. Check critical situation. Let

$$\mathbf{f}^c = \begin{pmatrix} fx_c \\ fy_c \\ fz_c \end{pmatrix} \tag{12}$$

be the data force in constraint frame with friction compensation. If

$$fx_c > f_{lim} \tag{13}$$

where f_{lim} is a constant value,then a probable collision was detected. In this case an error massage is sent to an higher control level (see Section 7) and in order to avoid the obstacle, a complete reconfiguration procedure is started:

- Set the desired velocity direction to $\mathbf{y}_c$ that yields

$$\mathbf{v}_d = \begin{pmatrix} 0 \\ |\mathbf{v}_d| \\ 0 \end{pmatrix} \tag{14}$$

- Add the $\mathbf{x}_c$ direction to the force control. Therefore $\mathbf{f}_d$ and $\mathbf{S}$ are changed:

$$\mathbf{f}_d = \begin{pmatrix} 1,5 f_{lim} \\ 0 \\ -|\mathbf{f}_d| \end{pmatrix} \tag{15}$$

and

$$\mathbf{S} = \mathbf{I} - \mathbf{j} \cdot \mathbf{j}^t \tag{16}$$

where $\mathbf{j} = (0\;1\;0)$.

This reconfiguration try to avoid the obstacle moving the cleaning tool around it.

Another interaction task which is taken as an example is the path teaching (see Fig. 5). In every day setting,

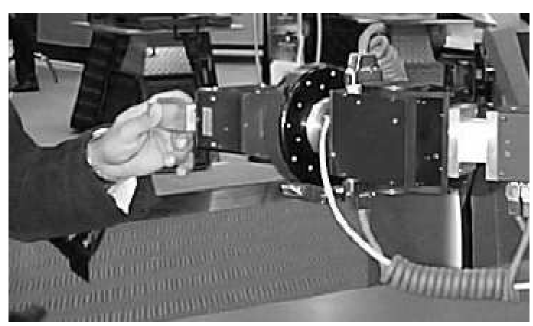

Fig. 5: Path teaching task.

in fact, it is possible that the robot user wants to show the robot a path e.g. a cleaning path, then a compliance behavior of the manipulator is required. In this case the force applied by the user is translated in a displacement. This means that only a force control is required. The system flexibility allows to achieve this aim. In fact the object task set the rotation matrix to the identity matrix $\mathbf{R}_c = \mathbf{I}$, the selection matrix to the null matrix $\mathbf{S} = \mathbf{0}$, the desired force to the null vector $\mathbf{f}_d = \mathbf{0}$ and the desired velocity to a linear combination of the force feedback vector

$$\mathbf{v}_d = -k\mathbf{f} \tag{17}$$

where k is a transduction coefficient between force and velocity.

6 Experiments

The experiments are executed with the mobile manipulator presented in Section 1. The sampling time of the controller is chosen to $T_0 = 0.5s$. Elasticity is measured to be about $1mm/N$. It is desired that the cleaning path shown in Fig. 6 will be followed at $0.3m/s$ and exerting a vertical force of $10N$ then the absolute value of the desired velocity is $|\mathbf{v}_d| = 0.3m/s$ and the absolute value of the force vector is $|\mathbf{f}_d| = 10N$. The results of this experiment are shown in Fig. 6. The end-effector follows the planar path with a good precision the maximal error is $1cm$. The vertical force exerted by the cleaning tool is not smooth but the maximal error is never greater than $2N$ this is due to a force threshold used to avoid frequent vertical movement and in fact the vertical position is very smooth. These performances are interesting because a housework as e.g. a cleaning task doesn't require a high precision on the contrary it is necessary a real time behavior in order to make interactions between man and robot more as natural as possible.
The path teaching task was tested in several situation without problem.

7 Conclusion

The paper presents a new flexible hybrid force/position controller. The testing system is a prototype of service robot for home cleaning. The hybrid controller performance are interesting not only for the 3D path following accuracy and the limited vertical force error (shown in Section 6), but also for the low computational time and for the simple application that require only a positional interface. In fact it is to take into account that the typical application of this kind of robot is a domestic cleaning assistant. Thus it has to perform simple housework such as cleaning tasks where it is very important the real time behavior in order to make interactions between man and robot more as natural as possible.
Further improvements of the system will consider how to deal with a collision at a higher level (supervisor). In fact it is not difficult to imagine the improvements could be achieved in future developments of this approach which take into consideration also other kind of sensor input e.g. visual information.

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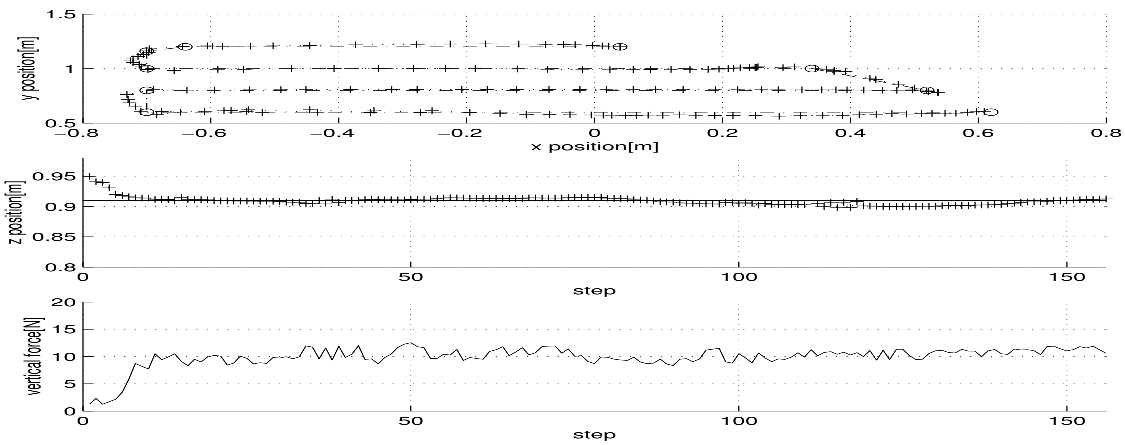

Fig. 6: Planar path, vertical position and vertical force during the cleaning task execution.

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