

# Compliant Interaction of a Domestic Service Robot with a Human and the Environment.

**F. Marrone and F.M. Raimondi**

Dept. of Automation and Comp. Engineering  
University of Palermo viale delle scienze, 90128 Palermo, Italy  
{marrone,raimondi}@ias.unipa.it

**M. Strobel**

Research Institute for Applied Knowledge Processing  
Helmholtzstr. 16, 89081 Ulm, Germany  
Matthias.Strobel@faw.uni-ulm.de

## ABSTRACT

A new service robot designed for cleaning tasks in home environments is introduced. Robot systems will work directly with people in these areas, thus placing a central importance on making interactions between people and machines as natural as possible. The main focus of this paper is to introduce to the system's design and control. In this context a new kind of hybrid force/position controller for the mobile manipulator will be presented. The compliant motion performed by this controller allows the robot to execute interaction tasks both with the environment and with the user and this makes it easy to be used by non-experts. A table cleaning and a path teaching are two examples of such a kind of tasks that will be performed from the robot in order to validate experimentally the results of the paper.

**Keywords:** household mobile robot, cleaning task, hybrid force/position control, compliant behavior, positional interface.

## 1 INTRODUCTION

Housekeeping robot assistants focus on the employment of assistive robot systems in everyday domestic settings. There are different motivating factors for the employment of robots at home: on one side, comfort factors and on the other side, an increasing number of households include inhabitants that require physical support in day-to-day life due to sickness or age. Robot systems will work directly with people in this area to perform simple housework such as setting the table or performing cleaning tasks. Thus placing a central importance on making interactions between people and machines as natural as possible.

The mobile manipulator presented in this paper (see Fig. 1) consists of a mobile base, built of two independently controlled drive components, and a 7 DOF manipulator on top of it. It was designed to perform



Figure 1: Mobile Manipulator for home environments.

housekeeping cleaning tasks in collaboration with the user. Therefore the sensory feedback has been carefully studied and designed for this purpose. The most important device in our application is a new kind of compliant force/torque sensor, developed at the German Aerospace Center DLR and mounted at the end of the cinematic chain just before the end-effector of the manipulator. Beyond its accuracy, one of the most important improvements introduced from this sensor is its compliance. In fact the sensor inserts an artificial compliance between the last link of the robot and the end-effector which avoids stability problems. In the following the compliance behavior performed using these data sensor will be explained. The sensory equipment is completed with a 2D range laser-scanner for mobile

base navigation, a trinocular stereo-vision system for gesture and object recognition and localization, a touch-screen for additional gesture input. This kind of sensors allows the user to communicate with the robot in a natural way using speech and gesture (see Strobel [3]). A first example of task to be executed by the robot is the cleaning of a surface. In this case the end-effector must follow a path on the surface while along its normal it is desired to exert a force of given value. It is worth that in this task both end-effector position and contact force must be controlled and consequently it is reasonable choosing a hybrid force/position control scheme. Nevertheless the classical hybrid force/position controller has the drawback that it is rigidly founded on the assumption of perfect task planning. The new hybrid controller presented in Section 3 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.

Another advantage of this controller is its flexibility. In fact, as explained in Section 3.2, 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.

Finally it is to take into account the simple application of this controller that doesn't require any joint torque / motor current interface but only a positional interface.

The experimental results presented in Section 4 were very satisfying also in consideration of the low computational weight of the algorithm which is very important in a real time application.

## 2 THE TASK GEOMETRY

A real manipulation task is characterized by complex contact situations where some directions are subject to end-effector position constraints and others are subject to interaction force constraints. During task execution, the nature of constraints may vary substantially. The need to handle complex contact situation requires the capability to specify and perform control of both end-effector position and contact force. An example is that of a surface cleaning task where the tool motion is specified in the direction tangent to the surface, while along the normal direction is desired to exert a force of given value. A fundamental aspect to be considered is that it is not possible to simultaneously impose arbitrary values of position and force along each direction. 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 re-

maining 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  $z_c$  axis lies along the normal to the surface whereas the  $x_c$  axis lies along the trajectory tangent, the  $y_c$  axis is consequently derived as  $z_c \times x_c$ .

By this frame definition the task geometry is noticeably simplified in fact during the whole task execution, the tool force is exerted along the  $z_c$  axis and its motion direction lies along the  $x_c$  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  $\mathbf{R}_c$ .

## 3 HYBRID FORCE/POSITION CONTROL

In order to control simultaneously both the end-effector motion and contact forces, a hybrid force/position controller (see Craig [2]) 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 interference 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 3.1 the control system is introduced then in Section 3.2, 3.3 and 3.4 each controller components will be explained.

### 3.1 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.

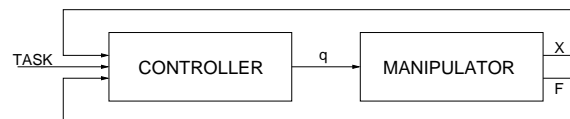


Figure 2: Manipulator control scheme.

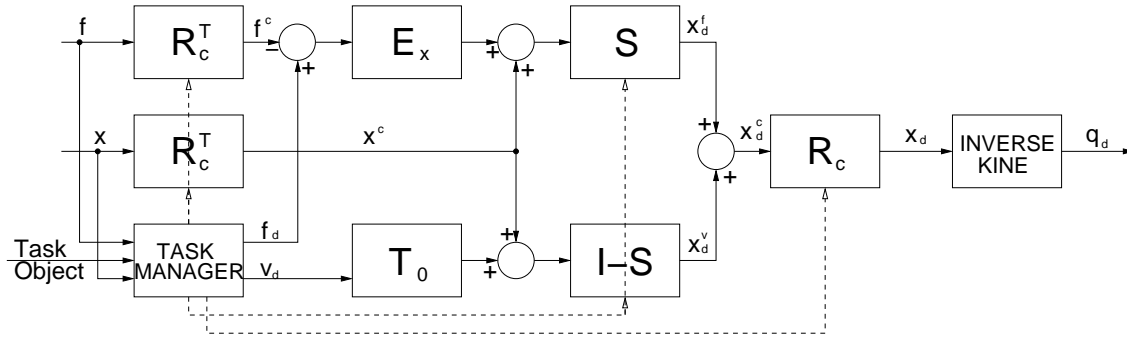


Figure 3: Controller scheme.

As shown in Fig. 2, only a positional interface is used in this approach (see also Lange and Hirzinger [5]), in fact the command variable is the joint vector

$$\mathbf{q} = \begin{pmatrix} q_1 \\ q_2 \\ \vdots \\ q_7 \end{pmatrix} \quad (1)$$

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

$$\mathbf{x} = \begin{pmatrix} x_b \\ y_b \\ z_b \end{pmatrix} \quad (2)$$

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

$$\mathbf{f} = \begin{pmatrix} f x_b \\ f y_b \\ f z_b \end{pmatrix} \quad (3)$$

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 3.2.

### 3.2 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 3.3) describe the desired end-effector behavior and then they will be defined *behavior parameters* whereas the rotation matrix  $\mathbf{R}_c$  (see Section 2) 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 calculated 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 deal 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.

### 3.3 Selection matrix

Our approach follows the idea of Khatib [1] 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 worth to define the selection matrix as a 3 x 3 matrix

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

where  $\sigma_i$  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  $3 \times 3$  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  $\mathbf{R}_c$ .

### 3.4 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

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

where  $\mathbf{f}_d$  is the desired force vector and it is evaluated by the Task Manager as will be explained in Section 3.2. Similarly along the motion controlled direction it is desired to have a given velocity  $\mathbf{v}_d$  and thus the desired position is

$$\mathbf{x}_d^v = \mathbf{x}^c + \mathbf{v}_d \cdot T \quad (6)$$

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

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

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

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

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 [4]).

## 4 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

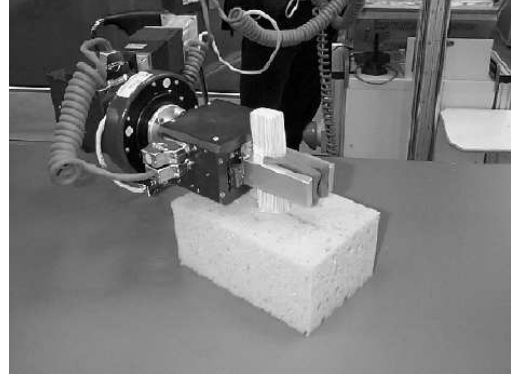


Figure 4: Cleaning task.

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 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 2 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

$$\mathbf{v}_d = \begin{pmatrix} |\mathbf{v}_d| \\ 0 \\ 0 \end{pmatrix} \quad (9)$$

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

$$\mathbf{f}_d = \begin{pmatrix} 0 \\ 0 \\ -|\mathbf{f}_d| \end{pmatrix} \quad (10)$$

4. Set the selection matrix to

$$\mathbf{S} = \mathbf{k} \cdot \mathbf{k}^t \quad (11)$$

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

$$\mathbf{f}^c = \begin{pmatrix} f_{x_c} \\ f_{y_c} \\ f_{z_c} \end{pmatrix} \quad (12)$$

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

$$f_{x_c} > f_{lim} \quad (13)$$

where  $f_{lim}$  is a constant value, then a probable collision was detected. In this case an error message is sent to a higher control level (see Section 6) and in order to avoid the obstacle, a complete re-configuration procedure is started:

- Set the desired velocity direction to  $y_c$  that yields

$$\mathbf{v}_d = \begin{pmatrix} 0 \\ |\mathbf{v}_d| \\ 0 \end{pmatrix} \quad (14)$$

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

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

and

$$\mathbf{S} = \mathbf{I} - \mathbf{j} \cdot \mathbf{j}^t \quad (16)$$

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).

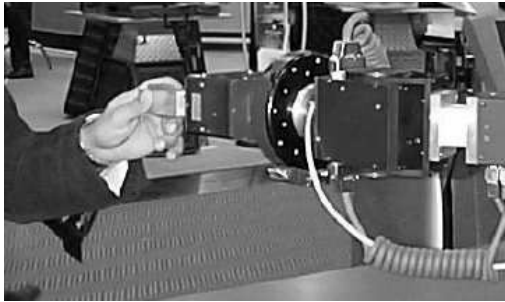


Figure 5: Path teaching task.

In every day setting, 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

$$\mathbf{v}_d = -k\mathbf{f} \quad (17)$$

where  $k$  is a transduction coefficient between force and velocity.

## 5 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  $|\mathbf{f}_d| = 10N$ .

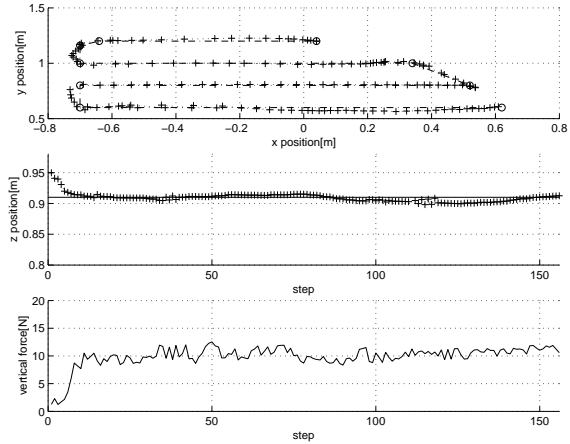


Figure 6: Planar path, vertical position and vertical force during the cleaning task execution.

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 different situation without problem.

## 6 CONCLUSION

The paper presents a new mobile manipulator designed for cleaning task and its hybrid force/position control. The system has very large potentiality and it is still in a developing phase. The hybrid controller performance are interesting not only for the 3D path following accuracy and the limited vertical force error (shown in Section 5), 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.

#### ACKNOWLEDGEMENT

This work was supported by the German Department for Education and Research (BMB+F) under grant no. 01 IL 902 F6 as part of the project MORPHA and by the German Academic Exchange Service (DAAD) under grant no. A/01/22339.

#### REFERENCES

- [1] Khatib, O., "A unified approach for motion and force control of robot manipulators: The operational space formulation," *IEEE Journal of Robotics and Automation*, pp. 43–53, February 1987.
- [2] Raibert, M. and Craig, J., "Hybrid position/force control of manipulators," *ASME J. Dynamic Syst., Meas., Contr.*, June 1981.
- [3] Strobel, M. and Illmann, J. and Kluge, B. and Marrone, F., "Gesture recognition in a spatial context for commanding a domestic service robot," in *submitted to 33rd Int. Symposium on Robotics, Stockholm, October 7-11, (ISR 2002)*, October 2002.
- [4] Marrone, F. and Strobel, M., "CleaningAssistant - a service robot designed for cleaning tasks," in *Proc. Advanced Mechatronic Systems (AIM 2001)*, 2001.
- [5] Lange, F. and Hirzinger, G., "Learning force control with position controlled robots," in *Proc. Int. Conf. on Robotics and Automation*, April 1996.
- [6] Hogan, N., "Stable execution of contact tasks using impedance control," in *Proc. IEEE Int. Conf. on Robotics and Automation*, 1987.
- [7] Pelletier, M. and Doyon, M., "On the implementation and performance of impedance control on position controlled robots," in *Proc. IEEE Int. Conf. on Robotics and Automation*, 1994.
- [8] Khatib, O. and Burdick, J., "Motion and force control of robot manipulators," in *Proc. IEEE Int. Conf. on Robotics and Automation*, pp. 1381–1386, 1986.
- [9] Luh, J., Y., S. and Gu, Y., L., "Industrial robots with seven joints," in *Proc. IEEE Int. Conf. on Robotics and Automation*, pp. 1010–1015, 1985.
- [10] Mason, M., T., "Compliance and force control for computer controlled manipulators," in *IEEE Trans. Syst., Man, Cybern.*, pp. 418–432, 1981.
- [11] Yoshikawa, T., "Analysis and control of robot manipulators with redundancy," in *Preprints 1<sup>st</sup> Int. Symp. Robotics Res.*, August 1983.
- [12] Sciavicco, L. and Siciliano, B., *Modelling and Control of Robot Manipulators*. Springer, 2000. ISBN 1-852-33221-2.
- [13] Murray, R. and Li, Z. and Sastry, S., *A mathematical introduction to robotic manipulation*. CRC press, Inc., 1994.
- [14] J. Craig, *Introduction to Robotics*. Addison-Wesley Publishing Company, Inc., 2nd ed., 1989.
- [15] Schraft, R.D. and Schmierer, G., *Serviceroboter - Produkte, Szenarien, Visionen*. Springer Verlag, 1998. ISBN 3-540-64330-3.
- [16] Meusel, P. and Hirzinger, G., "Compliant force-torque-sensor for sensory-based assembly." <http://www.robotic.dlr.de/COMPLIANCE/>, 1999. Information Sheet.
- [17] Marrone, F., "Modelling, forward and inverse kinematics of a mobile redundant robotic manipulator for home assistance," Master's thesis, University of Palermo, Italy / FAW Ulm, April 2001.