Intrinsically Passive Grasping and Manipulation

S.Stramigioli, *Member* IEEE, C.Melchiorri, *Member* IEEE , S.Andreotti.

Abstract— **This article presents and discusses the application of an Intrinsically Passive Control (IPC) strategy to robotic grasping and manipulation tasks. Major advantages of the presented control strategy are the physical intuition on which it is based, its passive nature, and the ensured stability for the overall system in all the situations, including in particular the transition from no-contact to contact and** *vice-versa*. **One of the main features of the proposed control is that only joint position measurements are needed. This means that no velocity or force measurements are required in the control loop, simplifying the sensorial complexity and enlarging the possibilities of application of the scheme. Experimental results are reported, showing the effectiveness of the proposed control strategy.**

Keywords— **Passivity, Interaction, Physical Control, Robotic Manipulation.**

I. Introduction

In general, the environment a robot interacts with must be characterized from a geometrical point of view, i.e. the dimensions and location of the object to be handled must be known in advance. This knowledge is used for planning the grasp or manipulation phases, e.g. approach, contact, force application and so on. On the other hand, from a mechanical point of view the information on the object/environment, if available, are often poor or not precise, e.g. mass and friction properties are in general not exactly known *a priori* and therefore cannot be used for the task planning. For this reason, additional sensors (force, tactile, ...) must be introduced and used in real time, and the planned grasp should be robust enough to ensure a proper behavior, i.e. the safe achievement of the grasp/manipulation, for different materials and grasping configurations.

From the control point of view, several control and task planning strategies have been proposed in the literature in order to execute grasps and manipulations with a robotic system, see e.g. [1] among many others. Concerning these control schemes, it may be noticed that very few among them consider explicitly the problem of controlling, or even defining, the dynamics of *interaction*. In addition, one of the most problematic phenomena in force control strategies is that stability cannot be ensured if not assuming as known important features of the object to be grasped, like its stiffness and friction. Furthermore, a force control strategy alone is not suitable to properly control the transition between no-contact and contact. This is due to the obvious fact that force control is meaningful only in contact, since no force can be exerted in free space. For these reasons, a control strategy for grasp and manipulation based on physically-based observations and on passivity concepts seems worth to be pursued.

This paper presents a control scheme that can be framed in the general and well known context of impedance control, [2], [3], [4], although it presents some further developments in the Hamiltonian setting, as discussed in [5]. This impedance strategy does not have the shortcomings of other grasping control techniques. In particular, it is strictly passive in steady-state while during manipulation the supplied energy is directly controllable. Moreover, the related compliance control of each finger allows for rolling, slipping, and whole-hand grasps in a natural way.

In other terms, the technique illustrated in this paper allows to shape the potential energy of the robot/object system in order to achieve a desired compliance, and injects damping to ensure both asymptotic stability and proper transient behavior. The main point here is to study the interaction between the robot and an object (the environment) in such a way that the overall system is stable independently on partially unknown geometrical or mechanical properties, and also achieves desired performances during task executions.

The underlying design method is based on physical intuition, and on the connection of 'physical' elements in order to obtain a desired dynamic behavior. With this respect, from a mathematical point of view the interaction among physical 'bodies' can be easily and rigorously described using the concept of *power port*, [6]. Furthermore, as shown in [5], to ensure a stable behavior during interaction, the underling control strategy should be such that the controlled system, as seen from the interaction energetic port, can be characterized by passive properties. A way to obtain this feature is to develop a controller which is passive by itself, and whose action on the robot can be described as a physical interconnection with the system to be controlled. In this manner, suitable passive properties for the overall system can be defined and imposed. On the other hand, a problem with this approach is that, in order to perform some useful tasks, the robot should supply energy to the environment, e.g. to move an object in space or to apply forces/torques to it. A possibility for combining these two apparently conflicting goals can be found in the so-called *Physical Control* and in the *IPC-Supervisor architecture*, as discussed also in [5], [7].

This paper is organized as follows. In Sect. II the control architecture will be illustrated in general terms, in Sect. III and Sect. IV some basic definitions and concept of the Hamiltonian formulation in terms of Poisson structures are recalled and the basic elements of the control presented, while in Sect. V the proposed control scheme is illustrated.

Stefano Stramigioli is with the Faculty of Information Technology and Systems, Department of Electrical Engineering, Systems- and Control Laboratory of the Delft University of Technology. E-mail: S.Stramigioli@its.tudelft.nl.

Claudio Melchiorri and Stefano Andreotti are with the "Dipartimento di Elettronica Informatica e Sistemistica" of the University of Bologna. E-mail: {cmelchiorri, sandreotti}@deis.unibo.it.

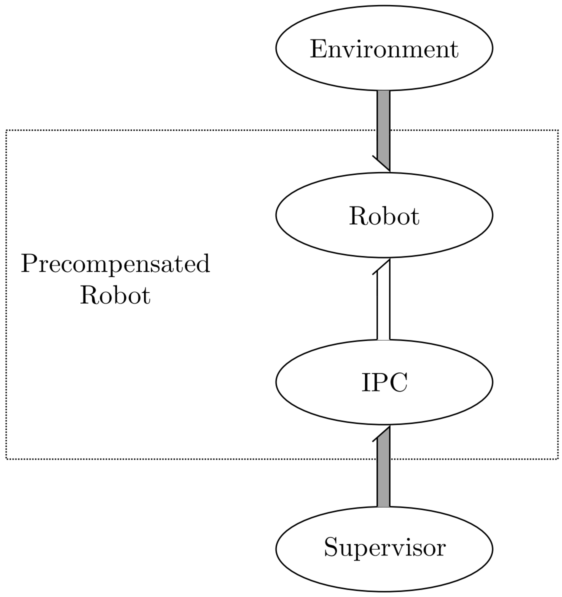

Fig. 1. The general form of an intrinsically passive control scheme.

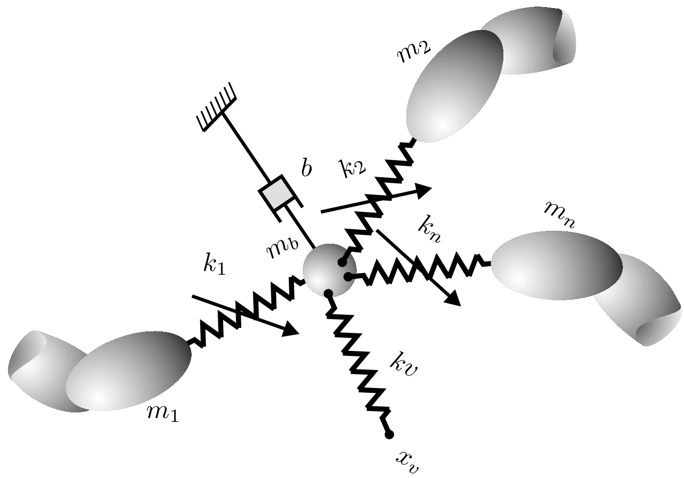

Fig. 2. Basic idea of the proposed IPC.

Sect. VI presents some experimental results and Sect. VII concludes with comments and final remarks.

II. The IPC-Supervisor architecture

The control architecture proposed in this paper is composed of two energetically coupled parts: the *Intrinsically Passive Controller (IPC)* and the *Supervisor*, as shown in Fig. 1.

The Supervisor, that can be considered hierarchically as a higher control level, takes care in general of all the deliberative and planning actions, and can also use *a priori* knowledge about the shape of the object to implement either tips of full hand grasps. The Supervisor can directly control the energy injected to the pre-compensated robot (i.e. the robot with the IPC), as shown in Fig. 1: tasks like 'open the hand', 'close the hand' or 'move the object' are achieved by the Supervisor by effectively suppling energy to the IPC.

Real-time control of interactive behaviors and the achievement of suitable features like damping, compliance and so on, are implemented by the IPC, independently of the Supervisor. In particular, the IPC has a physical Hamiltonian structure, as described in the following Sections, can only exchange energy with the robot or with the Supervisor, and is the responsible for the real time interactive behavior. In some sense, it may be compared to the local muscle control performed by the muscle spindles in biological systems.

This paper is concerned with the design of the IPC part of the controller. Since the IPC has been conceived in order to have a physically interpretable behavior, it will be described here in terms of spatial interconnection of physical elements like springs, dampers and inertias. As a matter of fact, the basic idea of the IPC is shown in Fig. 2, where bodies $m_1, m_2 \ldots, m_n$ represent the last links of some kinematic chains, e.g. the fingertips of a robotic hand or the distal links of robot arms. Both the body with mass m_b (assumed to be rigid) and the springs (with stiffnesses $k_1, k_2, \ldots, k_n$ and k_v) are implemented directly by means of control and are exploited, along with the damping b, in order to define the dynamic behavior of the IPC and consequently of the overall system.

In the control algorithm, the dynamics of mass m_b (called here the *virtual object*) is simulated in real-time. In particular, since it is subject to the forces generated by springs $k_1, k_2, \ldots, k_n$ and by the damper b, its motion in 3D is computed in real time. Although this mass does not physically exist, it is of major importance for the control, since its "kinetic energy" can be dissipated by the damper b, achieving in this manner a passive behavior for the control. Note that the computation of the damping force due to b needs only the knowledge of the velocity of the virtual mass m_b, that is known since it is computed in the controller. If dampers had been attached to masses $m_1, \ldots, m_n$, their velocities would have been necessary to simulate their behavior, with the necessity of joint velocity measurements for the robot.

The stiffnesses $k_1, \ldots, k_n$ and k_v of the springs, their rest lengths, the mass m_b of the virtual object and the position x_v are parameters to be used in real-time to achieve the desired behavior from the system. Obviously, it should be taken into account that careless changes of these parameters can result in a non passive behavior due to an apparent energy change of the system.

In the following Section, a formal model of these physical entities and of their interconnection is discussed. This model is the basis of the proposed control strategy.

III. Background on the Generalized Hamiltonian Theory

In this paper, the generalized Hamiltonian theory plays a fundamental role since it can nicely express the interconnection of physical parts. Basic features of this framework used in the following are the concepts of interconnection and ports, and of a Generalized Port Controlled Hamiltonian System (GPCHS) [8].

A. Interconnection and Ports

A basic concept used in this paper is the power port [6]. A power port is the entity which describes the media by means of which subsystems can mutually exchange physical energy. Analytically, a power port can be defined by the Cartesian product of a vector space V and its dual space V^*:

$$P := V \times V^*$$

Therefore, power ports are pairs $(e, f) \in P$. The values of both e and f (*effort* and *flow* variables) change in time and these values are shared by the two subsystems which are exchanging power through the considered port. The power exchanged at a certain time is equal to the intrinsic dual product:

$$\text{Power} = \langle e, f \rangle$$

This dual product is intrinsic in the sense that elements of V^* are linear operators from V to $\mathbb{R}$, and therefore, to express the operation, we do not need any additional structure than the vector space structure of V.

In this work, the space V will be the space of twists (flows) $se(3)$ or a Cartesian multiple: $se(3) \times \ldots \times se(3)$.

B. Generalized Poisson Hamiltonian Systems

In the standard symplectic Hamiltonian theory, the starting point is the existence of a generalized configuration manifold $\mathcal{Q}$. Based on $\mathcal{Q}$, its co-tangent bundle $T^*\mathcal{Q}$ is introduced which represents the state space to which the configuration-momenta pair (q, p) belongs. It is possible to show that $T^*\mathcal{Q}$ can be naturally given a symplectic structure on the base of which the Hamiltonian dynamics can be expressed [9].

A limitation of this approach is that, by construction, the dimension of the state space $T^*\mathcal{Q}$ is always even. Moreover, it can be shown that in general the interconnection of Hamiltonian systems in this form does not originate a system of the same form.

These problems can be easily solved with the more general approach in the Poisson framework, [10]. In general a GPCHS in the Poisson formulation is characterized by 4 elements: (a) a state manifold $\mathcal{X}$ which can be of any dimension, even or odd; (b) an interaction vector space V on which a power port is described as presented in Sect. III-A; (c) a Poisson structure on $\mathcal{X}$; (4) a local vector bundle isomorphism [11] between $\mathcal{X} \times V$ and $T\mathcal{X}$. For the purposes of this paper, it is sufficient to consider that a Poisson structure is characterized by a contravariant skew-symmetric tensor-field $J(x)$ defined on $\mathcal{X}$.

If we consider a chart ψ and the corresponding set of coordinates x for $\mathcal{X}$, and a base $B := \{b_1, \ldots, b_n\}$ for V, we can express a GPCHS with a set of equations of the following form:

$$\dot{x} = J(x)\frac{\partial H(x)}{\partial x} + g(x)u \tag{1}$$

$$y = g^T(x)\frac{\partial H(x)}{\partial x} \tag{2}$$

where u is a representation of an element of V in the base B, $J(x) = -J^T(x)$ is the skew-symmetric Poisson tensor, $g(x)$ is the representation of the fiber bundle isomorphism and y is the representation of an element belonging to the dual vector space V^* in the dual base of B.

Any explicit physical conservative element can be given the previous representation. To account for dissipating elements, we can generalize the previous form considering a symmetric, semi-positive definite, two covariant tensor $R(x)$ which can be subtracted from $J(x)$:

$$\begin{aligned} \dot{x} &= (J(x) - R(x))\frac{\partial H(x)}{\partial x} + g(x)u \\ y &= g^T(x)\frac{\partial H(x)}{\partial x} \end{aligned} \tag{3}$$

With this new term, it can be seen that the change in internal energy is:

$$\dot{H} = \underbrace{y^T u}_{\text{supplied power}} - \underbrace{\left(\frac{\partial H}{\partial x}\right)^T R(x)\frac{\partial H}{\partial x}}_{\text{dissipated power}}$$

Since $R(x)$ is positive semi-definite, this implies that the internal energy can only increase if power is supplied through the ports.

IV. Dynamic model of the 'physical' parts

The basic elements of the IPC control scheme, shown in Fig. 2, are now modeled as GPCHS. Obviously, only those physical parts that can store energy will have a state. Elements like dampers, if considered as isolated, do not have any physical state. Using their port structures, it is then possible to connect these elements in a power consistent way.

A. The Springs - Spatial Compliance

A spatial (3D) compliance is a geometric spring connecting two rigid bodies B_i and B_j. Lončarić [12], [13] studied geometric springs represented by potential energy functions of the relative position of the rigid bodies to which they are attached. Successively, Fasse and Breedveld [14], [15], [16] extended this work giving some useful geometrical parameterizations. More recently, Stramigioli [5] extended the formulation to a completely coordinate-free setting and also in order to consider elastic elements with more than two ports and variable lengths.

A spring between two rigid bodies B_i and B_j is characterized by a positive definite function representing the stored potential energy[1] with the following form:

$$V_{i,j} : SE(3) \to \mathbb{R}; H_i^j \mapsto V_{i,j}(H_i^j)$$

[1] This function defines implicitly the unit of energy.

where $H_i^j \in SE(3)$ is the matrix representing the isometry which brings a chosen reference frame Ψ_j (fixed to body B_j) to another reference frame Ψ_i (fixed to body B_i)[2]. Once a potential energy has been defined, the corresponding "force" generated by the elastic potential can be computed by considering the differential of $V_{i,j}$:

$$dV_{i,j} : SE(3) \rightarrow T^*SE(3)$$

which is the local force that body B_i applies on the spring $V_{i,j}$ in the relative position H_i^j: $dV_{i,j}(H_i^j) \in T^*_{H_i^j}SE(3)$. This local force can be seen as the generalized force corresponding to a parameterization of $SE(3)$ like Euler angles and translation positions.

The wrench applied on the spring connecting B_i to B_j by body B_i and expressed in frame Ψ_j, with a relative position H_i^j is (see Notation):

$$\tilde{W}_{i,j}^j(H_i^j) = \begin{pmatrix} \tilde{f}_{i,j}^j & n_{i,j}^j \\ 0 & 0 \end{pmatrix} = R^*_{H_i^j} dV_{i,j}(H_i^j)$$

where $\tilde{f}_{i,j}^j \in \mathbb{R}^{3\times 3}$ is a skew-symmetric matrix corresponding to the force $f_{i,j}^j \in \mathbb{R}^3$ and such that:

$$x = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} \Rightarrow \tilde{x} = \begin{pmatrix} 0 & -x_3 & x_2 \\ x_3 & 0 & -x_1 \\ -x_2 & x_1 & 0 \end{pmatrix} \tag{4}$$

We can also associate to the wrench matrix $\tilde{W}_{i,j}^j \in \mathbb{R}^{4\times 4}$ the corresponding vector representation which we indicate with $W_{i,j}^j := ((n_{i,j}^j)^T \quad (f_{i,j}^j)^T)^T \in \mathbb{R}^6$. It can be seen that[3] $W_i^i = -W_{i,j}^i = -Ad^*_{H_i^j} W_{i,j}^j$ is the wrench that the spring applies to body B_i expressed in the frame Ψ_i and that $W_j^j = -W_{j,i}^j = -Ad^*_{H_j^i} W_{j,i}^i$ is nothing else than the wrench that the spring applies to body B_j expressed in frame Ψ_j and furthermore $W_{i,j} = -W_{j,i}$ due to the nodicity of a spring.

A desired energy function can be defined (and implemented using control) such that the relative configuration $H_i^j = I_4$ corresponds to a minimum of the potential energy $V_{i,j}(\cdot)$ [14]. In this configuration, the frames Ψ_j and Ψ_i will coincide. The energy function can be chosen such that the common origins of Ψ_i and Ψ_j in the equilibrium position represent the *center of stiffness* [5]. Expressed in the equilibrium frame ($\Psi_i = \Psi_j$), we can then choose three 3×3 desired stiffness matrices K_o, K_t and K_c, corresponding respectively to the orientational, translational and coupling stiffnesses. From these stiffness matrices, we can calculate the so-called co-stiffness matrices [14] G_o, G_t and G_c related to the stiffnesses matrices by:

$$G_\alpha = \frac{1}{2}\,\mathrm{tr}(K_\alpha)I - K_\alpha$$

where $\alpha = o, t, c$ and where tr() is the tensor trace operator. It is then possible to give an expression of the wrench W_i^i as a function of the relative configuration $H_i^j = \begin{pmatrix} R_i^j & p_i^j \\ 0 & 1 \end{pmatrix}$ (see [14]):

$$W_i^i(H_i^j) = \begin{pmatrix} \tilde{f}_i^i & n_i^i \\ 0 & 0 \end{pmatrix} \text{ where}$$

$$\begin{aligned} n_i^i &= -2\,\mathrm{as}(G_o R_i^j) - \mathrm{as}(G_t R_j^i \tilde{p}_i^j \tilde{p}_i^j R_i^j) - 2\,\mathrm{as}(G_c \tilde{p}_i^j R_i^j) \\ \tilde{f}_i^i &= -R_j^i\,\mathrm{as}(G_t \tilde{p}_i^j) R_i^j - \mathrm{as}(G_t R_j^i \tilde{p}_i^j R_i^j) - 2\,\mathrm{as}(G_c R_i^j) \end{aligned} \tag{5}$$

and where as($\cdot$) is an operator which takes the skew-symmetric part of a square matrix and the 'tilde operator' is defined in Eq. (4).

Eq. (5) is an expression that can be directly used for the implementation, but as previously remarked, it is possible to give a GPCHS form of a spring [17]:

$$h_i^j = R_{h_i^j} T_i^{j,j} \tag{6}$$

$$W_{i,j}^j = R^T_{h_i^j} \frac{\partial V_{i,j}}{\partial h_i^j}. \tag{7}$$

where h_i^j is a six dimensional local coordinate of $SE(3)$, $J(h_i^j) = 0$, and $R_h(\cdot)$ represents the Lie group right translation in the chosen coordinates h. It is also possible to consider an additional power port which can be used to vary the effective rest length of a spring as shown schematically in Fig. 3. By using an additional port, the relative position of b and i can be modified. The obtained effect is to change the rest length of the spring between b and j. Applying in the general 3D case the concept of Fig. 3, the twist relation becomes:

$$T_i^{j,j} = T_b^{j,j} + Ad_{H_b^j} T_i^{b,b} \tag{8}$$

In this case, its GPCHS representation is:

$$h_i^j = \begin{pmatrix} R_{h_i^j} & R_{h_i^j} Ad_{h_b^j} \end{pmatrix} \begin{pmatrix} T_b^{j,j} \\ T_i^{b,b} \end{pmatrix} \tag{9}$$

$$\begin{pmatrix} W_{b,j}^j \\ W_{i,b}^b \end{pmatrix} = \begin{pmatrix} R^T_{h_i^j} \\ Ad^T_{h_b^j} R^T_{h_i^j} \end{pmatrix} \frac{\partial V_{i,j}}{\partial h_i^j}.$$

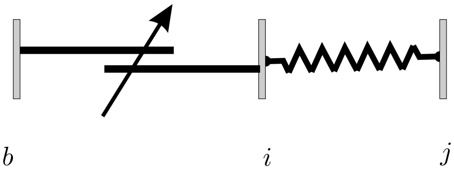

Fig. 3. Schematic drawing of a power consistent variable spring.

[2]Note that H_i^j is also the matrix expressing the change of coordinates from Ψ_i to Ψ_j, but the corresponding motion is given by its inverse $(H_i^j)^{-1}$.

[3]Note that $Ad_{H_i^j}$ is the Lie group adjoint map and $Ad^*_{H_i^j}$ its dual adjoint. They are linear operators that represent a change of coordinates and are of the form $Ad_{H_i^j} = \begin{pmatrix} R_i^j & 0 \\ \tilde{p}_i^j R_i^j & R_i^j \end{pmatrix}$ for $H_i^j = \begin{pmatrix} R_i^j & p_i^j \\ 0 & 1 \end{pmatrix}$ and $Ad^*_{H_i^j}$ is represented by the transpose of $Ad_{H_i^j}$.

where the port $(T_i^{b,b}, W_{i,b}^b)$ can be effectively used to change the rest length of the spring. More details on the above concepts and mathematical derivations can be found in [5] and [14].

B. Masses

The dynamic properties of a rigid body are uniquely described by its inertia tensor $\mathcal{I}_b$. Let us consider a uniform sphere B_b, and a reference system Ψ_b fixed to it with origin coincident to the center of the sphere. The dynamics of a general rigid body is expressed by:

$$P_b^b = P_b^b \wedge T_b^{b,0} + W_{b\,\mathrm{tot}}^b \tag{10}$$

where $P_b^b = \mathcal{I}_b^b T_b^{b,0} \in \mathbb{R}^6$ is the generalized momentum[4], $T_b^{b,0} = ((\omega_b^{b,0})^T \quad (v_b^{b,0})^T)^T$ is the twist of the sphere respect to an inertial frame Ψ_0, $W_{b\,\mathrm{tot}}^b$ is the total wrench applied to the sphere and $P_b^b \wedge$ comes from the Lie-Poisson bracket and in the body coordinates Ψ_b is represented by a 6×6 matrix of the following form:

$$(P_b^b \wedge) := \begin{pmatrix} \tilde{P}_\omega^b & \tilde{P}_v^b \\ \tilde{P}_v^b & 0 \end{pmatrix}$$

where $P_b^b = (P_\omega^T \quad P_v^T)^T$. For the specific case of the sphere, $\mathcal{I}_b^b = \begin{pmatrix} jI_3 & 0 \\ 0 & mI_3 \end{pmatrix}$ where I_3 is the 3×3 identity matrix, j is the rotational inertia of the sphere and m its mass.

Also in this case, it is possible to give a GPCHS representation of the inertia's dynamics:

$$\begin{aligned} P_b^b &= (P_b^b \wedge) \frac{\partial E_k(P_b^b)}{\partial P_b^b} + I\, W_b^b \\ T_b^{b,0} &= I \frac{\partial E_k(P_b^b)}{\partial P_b^b} \end{aligned} \tag{11}$$

where $E_k(P_b^b) = \frac{1}{2}(P_b^b)^T (\mathcal{I}_b^b)^{-1} P_b^b$ is the kinetic energy which is a function of P_b^b instead that a function of $T_b^{b,0}$ as usually thought. The corresponding function $E_k^*(T_b^{b,o})$ is called co-energy.

C. Dampers - Energy Dissipation

The easiest manner to model a linear spatial damping effect is to use an element which generates a wrench directly proportional to the twist of the body whose free-energy has to be dissipated. In this paper we use:

$$W_{b\,\mathrm{diss}}^b = R T_b^{b,0} \tag{12}$$

where $R \in \mathbb{R}^{6\times 6}$ is a positive definite matrix representing a dissipation tensor in the frame Ψ_b.

Note that this element does not have a state and it will appear in the complete GPCHS of the interconnected part, as a part of the tensor $R(x)$ of Eq. (3).

[4]The notation $X_i^{j,k}$ represents the motion of frame H_i respect to H_k expressed in the frame H_j.

V. The IPC Control Scheme

Following the steps presented in [5], [18], it is possible to give a GPCHS description of the controller in the following form:

$$\begin{aligned} \begin{pmatrix} \dot{x}_B \\ \dot{x}_S \end{pmatrix} &= \begin{pmatrix} J_B - R_B & -\phi_B \phi_v^* \\ \phi_v \phi_B^* & 0 \end{pmatrix} \begin{pmatrix} \frac{\partial H_C}{\partial x_B} \\ \frac{\partial H_C}{\partial x_S} \end{pmatrix} + \\ &\quad \begin{pmatrix} 0 & 0 & 0 \\ \phi_\mathrm{r} & \phi_{v(b)} & \phi_\mathrm{var} \end{pmatrix} \begin{pmatrix} t_\mathrm{r}^0 \\ t_{v(b)}^0 \\ t_\mathrm{var}^b \end{pmatrix} \\ \begin{pmatrix} w_\mathrm{r}^0 \\ w_{v(b)}^0 \\ w_\mathrm{var}^b \end{pmatrix} &= \begin{pmatrix} 0 & \phi_\mathrm{r}^* \\ 0 & \phi_{v(b)}^* \\ 0 & \phi_\mathrm{var}^* \end{pmatrix} \begin{pmatrix} \frac{\partial H_C}{\partial x_B} \\ \frac{\partial H_C}{\partial x_S} \end{pmatrix}. \end{aligned} \tag{13}$$

where x_B, x_S are respectively the states of the virtual object and the springs as presented in Eq. (11) and Eq. (9), $H_C(x_B, x_S)$ is the the sum of the kinetic energy of the virtual object plus the potential energies of the springs, and ϕ_i, J_B and R_B are properly defined matrices [5]. The interaction ports are the pairs $(t_\mathrm{r}^0, w_\mathrm{r}^0)$,$(t_{v(b)}^0, w_{v(b)}^0)$ and $(t_\mathrm{var}^b, w_\mathrm{var}^b)$ where

$$t_\mathrm{r}^0 = \begin{pmatrix} T_1^{0,0} \\ \vdots \\ T_n^{0,0} \end{pmatrix}$$

is the vector of twists of the fingertips with respect to the inertial frame, $t_{v(b)}^0$ is the twist corresponding to the motion of the configuration x_v in Fig. 2 and it is used by the supervisor to change the virtual position of the hand and

$$t_\mathrm{var}^b = \begin{pmatrix} T_1^{b_1,b_1} \\ \vdots \\ T_n^{b_n,b_n} \end{pmatrix}$$

is the vector of twists that can be set by the supervisor to change the minimum potential configuration of the springs as shown schematically in Fig. 3 when changing the relative configuration of i and b. This last subsystem represents the IPC of Fig. 4. In the figure, bond graphs notation is used: each power port of Eq. (13) corresponds to a power bond in the figure.

In order to use the IPC for the real control of a robotic system, we need a way to map w_r^0 to the actuation of the robot. This is done by using the robot differential kinematics, expressed by the Jacobian matrix $J_\mathrm{r}(q)$, that maps a configuration velocity $\dot{q}$ to the twists t_r^0 of the tips of the hand:

$$t_\mathrm{r}^0 = J_\mathrm{r}(q)\dot{q}$$

which implies

$$\tau = J_\mathrm{r}^T(q) \begin{pmatrix} -W_1^0 \\ \vdots \\ -W_n^0 \end{pmatrix} = -J_\mathrm{r}^T(q) w_\mathrm{r}^0 \tag{14}$$

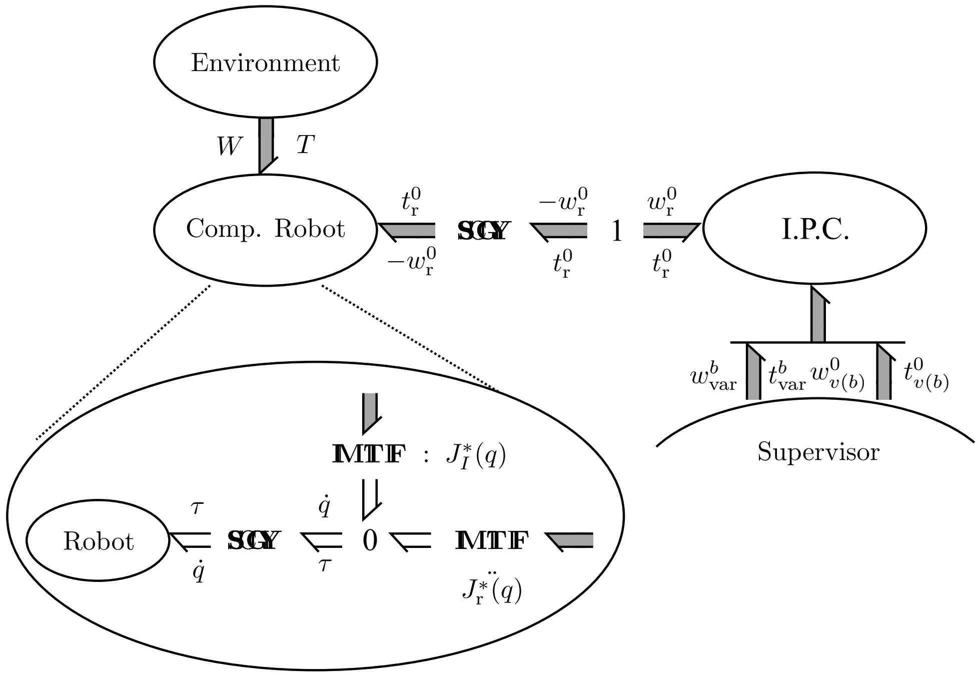

Fig. 4. The interconnection between the robot and the intrinsically passive controller.

where W_i^0 is the total wrench applied to tip i by the controller's spring i. From the above equations, it could be deduced at first that, for the given GPCHS representation of the controller, the velocities of the joints are needed for the proposed scheme. This is not the case, since the controller's actions (i.e. the torques) applied to the robot are a consequence of the springs attached to the fingertips, as shown in Fig. 2. These elastic forces are function only of the relative configuration of the tips with respect to the virtual object. In particular, this implies that only the pose of the tips are necessary to calculate these wrenches, and not their velocities. The configurations can be directly computed by using joints measurements and the forward kinematics.

Clearly, this has the advantage that only position measurements are necessary to implement the scheme: no velocity and not even force measurements are in fact required. On the other hand, note that this scheme can therefore be used if the robot is back-drivable, which means in particular that any external force applied to the robot will result in a motion of the robot itself, that can be therefore detected with position measurements alone.

This scheme does not change the driving point mass of the robot, but only its interactive compliance, differently than the well known impedance scheme presented in [3]. It should be noticed though that even if different from [2], [3], [4], the adopted philosophy is exactly the same as it has been commented in [19].

A. Energy dissipation

Even if only positions measurements are needed, overall dissipation is achieved because of the presence of the viscous term connected to the virtual object. The viscous force is applied to the virtual object as shown in Fig. 2. Any energy entering the control system which causes a motion of the virtual object is dissipated, and this has a nice physical interpretation. Again, note that this is achieved without the necessity to measure velocities of the robotic system.

A control design philosophy very similar to this one has been developed by Ortega and others, see for example [20]. However, it has to be pointed out that in this case the formulation is based on a Lagrangian framework. Here, the problem is considered in the more general Hamiltonian setting as the power consistent interconnection of GPCHSs.

VI. Experimental Results

A laboratory setup has been used for the evaluation of the control technique described in the previous Sections. The setup, schematically shown in Fig. 5, consists of two one-dof "fingers" equipped with position, force/torque and tactile sensors, [21], [22], [23].

The kinematics of the set-up is trivial, and the theory illustrated in the previous sections simplifies to the one-dimensional case. Anyhow, the goal is to demonstrate with a simple setup the idea of the virtual object concept during manipulation. Obviously, generalizations to more complex 3D systems can be made using the above theory.

The block-diagram of the control scheme used in the experiment is shown in Fig. 6. As discussed above, note that only position measurement is used in the control loop (x_1, x_2): force/torque and tactile information are acquired only in order to show the features and the performances of the overall control scheme.

In the following, two types of results are presented. The

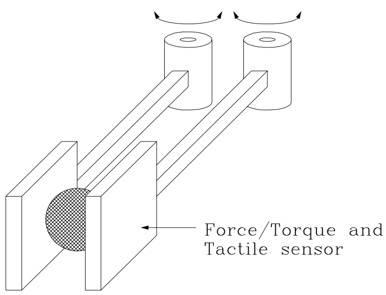

Fig. 5. Experimental setup.

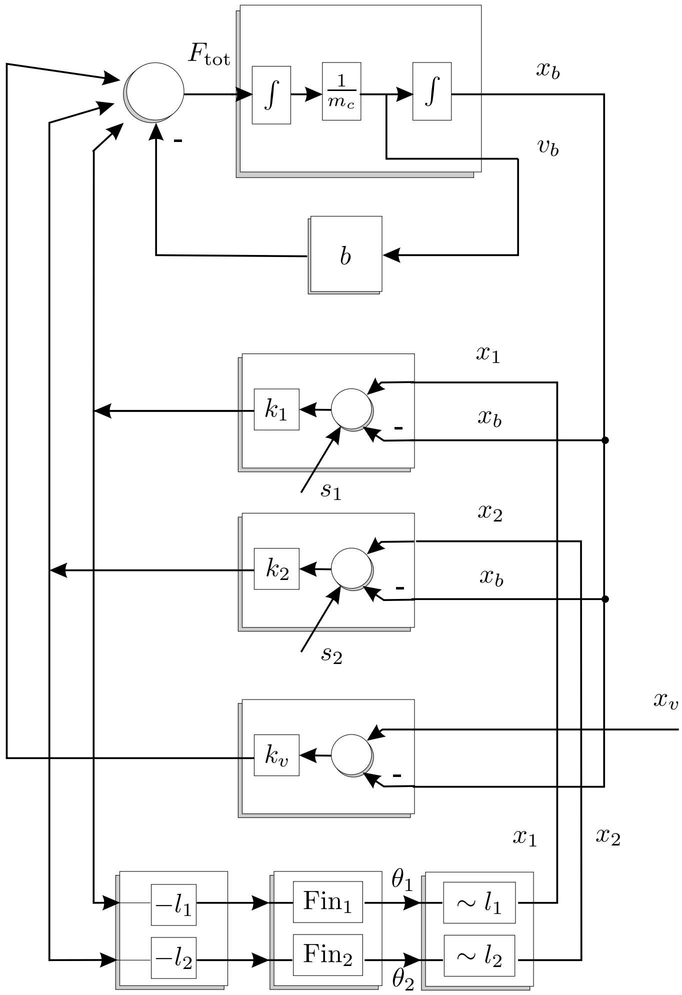

Fig. 6. The implemented control schema

first one refers to the damping injection and its stabilization features for the control loop, the second one illustrates the performances of the scheme in simple manipulation tasks.

A. The Damping Injection

Fig. 7, Fig. 8 and Fig. 9 show some experiments concerning the damping injection. In particular, Fig. 7 reports an experiment in which an external disturbance is applied to one of the two fingers. The time-history of the joint position without (plot a) and with (plot b) the damping action is shown when it is switched on. Note that in the first case there is practically no damping (some energy is anyhow dissipated by the friction present in the motor and in the joint), while in the second one, when damping is injected (at $t \approx 4.5$ s), oscillations are quickly stopped.

Fig. 8 reports an experiment still involving only one finger. In this case, the desired motion $\theta_v(t)$ of the virtual object follows a sinusoidal trajectory (dashed curve), causing an unplanned contact with an obstacle present in the workspace. From the plot of the real position (solid curve) it may be seen that the free-space/contact transition does not cause any problem. The forces applied to the obstacle are reported in Fig. 9, considering two different values for the stiffness coefficient k_c.

B. Grasp and Manipulation

The second type of experiment concerns the use of both the fingers for simple grasp and manipulation tasks of a spherical object.

Fig. 10 reports data concerning a grasp of an object. The joint positions of the two fingers are shown in Fig. 10.a, along with the equilibrium length and the deformations of the virtual spring, which allows the motion and the object's grasp. Fig. 10.b shows the time-history of the stored elastic energy and the force applied to the object, as measured by the force sensor.

An experiment concerning the manipulation of the grasped object is reported in Fig. 11, that shows the desired trajectory for the virtual object and the relative computed motion (plot a), along with the motion on the tactile pad (x-y directions) of the contact point (plot b).

A result concerning the robustness of the control scheme is shown in Fig. 12. An external disturbance is applied to the object, plot (a), and the energy dissipated by the control is shown in plot (b). Note that, as already mentioned, the force sensor is not used in the control, but only to measure and report the forces applied during the grasp.

Fig. 13 reports a similar experiment, showing the time-history of the energies (kinetic, elastic and dissipated) of the system when an external disturbance force is applied during a grasp. It can be seen that the energy is decreasing in the springs and the dissipated energy is increasing. This shows experimentally what illustrated in Sect. V-A: the energy supplied by a disturbing force flows from the springs to the virtual object where it is dissipated.

VII. Conclusions

This paper has illustrated a control strategy based on passivity concepts and on the damping injection principle. Basic features of the proposed control scheme are on one hand the physical intuition, that allows the designer to define suitable properties for the overall system, and on the other the implicit passivity, which is obtained without any need to measure velocities of the system. The control scheme, which may be adopted in principle for controlling any mechanical systems, has been applied here to robotic

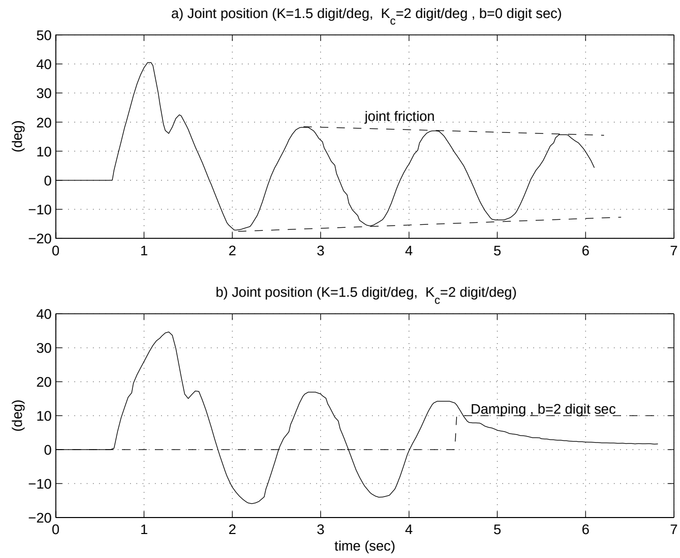

Fig. 7. Stability of the control loop without (a) and with (b) damping.

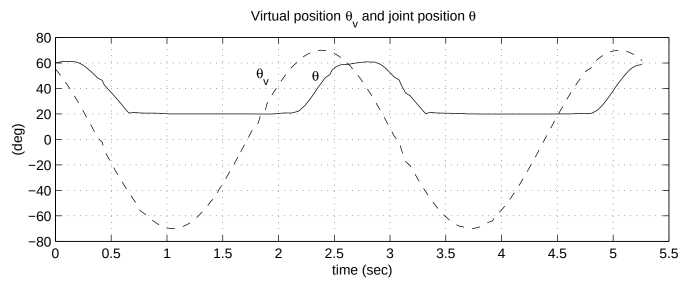

Fig. 8. Desired and real position of the finger.

grasping and manipulation tasks.

Experimental results obtained with a simple laboratory setup have been presented and discussed, showing that the scheme can be successfully adopted in this context, achieving robust properties for handling also partially unknown objects. With this respect, an aspect which deserves further research is the influence on the achievable performances of the contact model and of slip situations between the fingers and the grasped object. Part of future work will also address the implementation of this scheme on more general devices, such as advanced robotic hands. Moreover, it is planned to extend this control technique in order to take into account tele-manipulation systems with

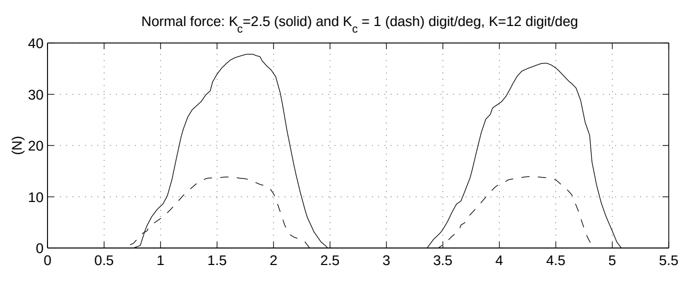

Fig. 9. Forces applied to the obstacle with two different values of k_c.

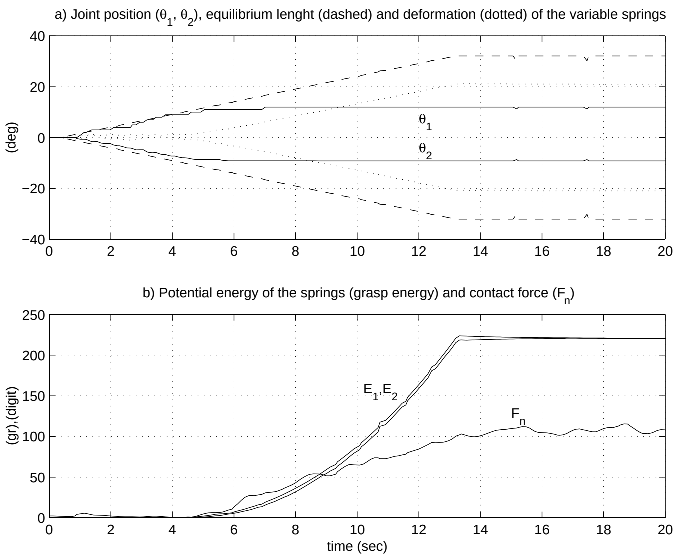

Fig. 10. Result of a grasp task: (a) Joint positions, springs' equilibrium length and deformations; (b) potential energies and contact force.

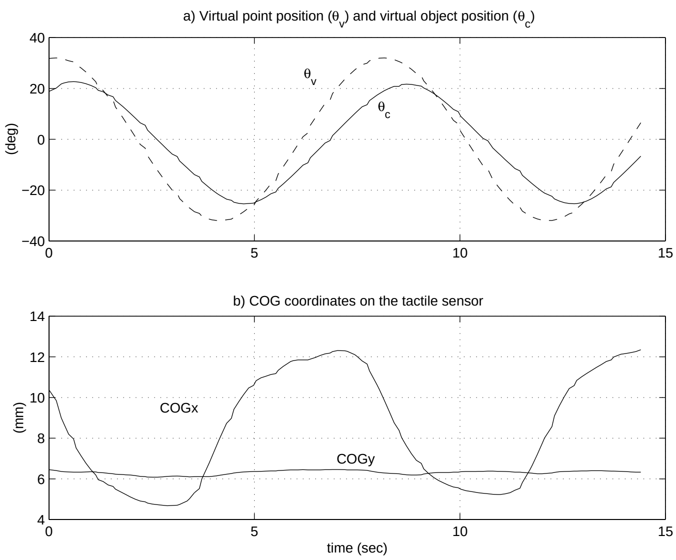

Fig. 11. Desired (dashed) and computed (solid) position of the virtual object (a); Contact point (COG: center of gravity) position on the tactile sensor (b).

time delays.

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Appendix

Notation

Ψ_i Right handed orthonormal coordinate frame i.

H_i^j Homogeneous coordinate transformation from Ψ_i to Ψ_j.

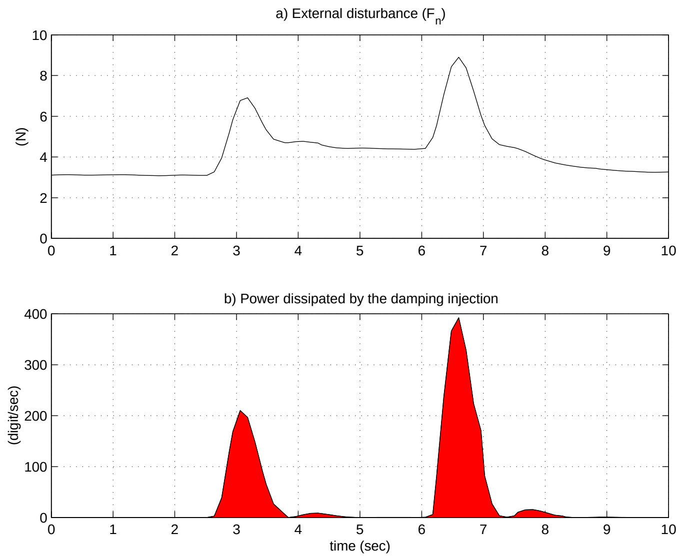

Fig. 12. External disturbance applied during the grasp (a) and relative dissipated energy for achieving stability (b).

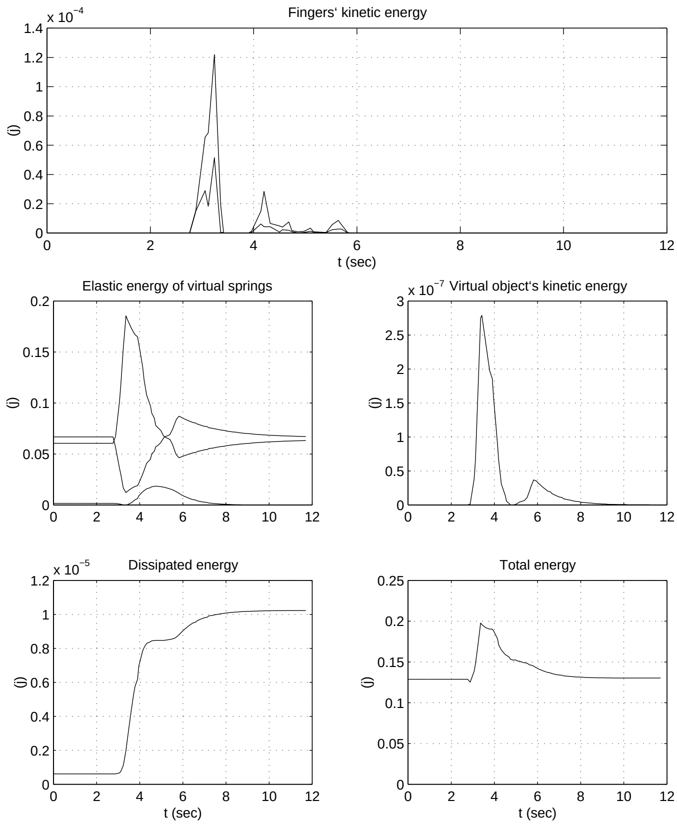

Fig. 13. An external disturbance is applied to the grasped object: behaviors of the energies stored in the system.

H_i^j Homogeneous coordinate transformation from Ψ_i to Ψ_j.

T_i^j Twist of Ψ_i with respect to Ψ_j.

$T_i^{k,j}$ Twist of Ψ_i with respect to Ψ_j as a numerical vector expressed in Ψ_k.

W_i Wrench applied to a mass attached to Ψ_i.

W_i^k Wrench applied to a mass attached to Ψ_i expressed as a numerical vector expressed in Ψ_k.

$W_{i,j}$ Wrench applied to a spring element connecting Ψ_i to Ψ_j on the side of Ψ_i.

$W_{i,j}^k$ Wrench applied to a spring element connecting Ψ_i to Ψ_j on the side of Ψ_i expressed as a numerical vector expressed in Ψ_k.

P_i Momenta of body B_i.

P_i^k Momenta of body B_i expressed as a numerical vector in Ψ_k.

$\mathcal{I}_i$ Inertia tensor of body B_i.

$\mathcal{I}_i^j$ Inertia tensor of body B_i expressed as a numerical vector in Ψ_j.

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Stefano Stramigioli was born in Bologna, Italy, on the 28th of March 1968. He got the Laurea degree *cum laude* in Electrical Engineering at the University in 1992. In 1992 he moved to the Netherlands where he has been working at the Control Laboratory of the Department of Electrical Engineering of the University of Twente. In 1994 he started working at the Control Laboratory of the former faculty of Electrical Engineering at the Delft University of Technology as a Ph.D student. In 1996 he was at the Massachussets Institute of Technology as a visiting scholar at the Newman Laboratory of Prof. Neville Hogan. In 1996 he received the D.I.S.C. certificate. In 1998 he received the Ph.D. with *(suma) cum laude* at the Delft University of Technology, where he is currently an Assistant Professor at the Department of Information Technology and System. His main interests lie in geometrical approach to physical systems and in particular robotics.

Claudio Melchiorri was born on October 23, 1959. He received the Laurea degree in Electrical Engineering in 1985, and the Ph.D. in 1990 both at the University of Bologna. He has been appointed as "Adjunct Associate in Engineering" at the Department of Electrical Engineering, University of Florida, Gainesville, FL, in 1988 and as "Visiting Scientist" at the Artificial Intelligence Laboratory, MIT, Cambridge, MA, USA, for periods in 1990 and 1991. Since 1985 he has been with DEIS, the Department of Electrical Engineering, Computer Science and Systems of the University of Bologna, working in researches in the field of robotics and automatic control. He currently holds the position of Associate Professor in Robotics at the University of Bologna. He is author or coauthor of about 90 scientific papers presented at conferences or published in journals, of 2 books on digital control, and is coeditor of 3 books on robotics. His research interests include dexterous robotic manipulation, haptic interfaces, tele-manipulation systems, advanced sensors, nonlinear control.

Stefano Andreotti was born in Modena, Italy, the 14th of May 1973. He got the Laurea degree *cum laude* in Electrical Engineering in March 1999. In the period October-December 1999 he has been a Visiting Scholar at the Delft University of Technology (DUT), working on the development of physical controllers applied to tele-manipulation systems. His main research interests are in the areas of nonlinear control, robotics and control of automatic machines.