Two-Stage Adaptive Impedance Control Applied to a Legged Robot.

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Abstract

In this paper we propose an adaptive impedance control scheme consisting of two stages. The first stage performs an on-line estimation of the robot parameters imposing the desired mechanical impedance. It constitutes the kernel of the control system and remains active during the complete, free or constrained, motion of the robot. A simple algorithm for the numerical computation of the defined impedance error is presented where only the available feedback information is used. The imprecision in the parameters of the environment (stiffness, positioning) is compensated by the second stage of adaptation. This one constitutes an external force control loop closed around the internal nonlinear impedance controller. Simulation results obtained for a single leg of a pneumatic driven, quadruped robot show the effectiveness of the proposed control scheme in case of considerable uncertainty both in the robot and ground parameters.

1. Introduction

Robots are general-purpose, programmable machines designed to perform various tasks in an environment such as an industrial plant. Many of these tasks, like grasping and manipulating an object or assembling devices, inevitably involve direct interaction with the environment. Contact between the robot and the environment may also occur unpredictably due either to the presence of unknown obstacles in the robot's workspace or to the imprecision in positioning the robot end-effector. All the above situations may result in the application of excessive and uncontrollable forces between the robot and its environment. The goal of a general force control methodology is to control these interaction forces in order to assure correct and safe execution of the robot task.

Whitney [1] was the first one to report on the use of force feedback techniques in a computer-controlled manipulator. Since then, various force control methodologies have been developed which can be classified in the following three major axes: impedance control, explicit force control and hybrid control.

Impedance control [2] is essentially a position control scheme where force feedback is used to modify the apparent inertia of the robot seen from the environment. The goal of this methodology is to explicitly regulate the compliance of the manipulator, i.e. its ability to yield under the application of external forces. In explicit force control, on the contrary, the variable being directly measured and controlled is the external force. Most existing work uses some subset of PID servo loop together with some form of linear or nonlinear filtering [3]. A methodology that tries to combine the advantages and the potential of a pure force and a pure position control scheme is the hybrid force/position control. Mason [4] presented a formalisation of this methodology in terms of defining the geometry of a compliant task and the appropriate control strategies.

The two major problems generally encountered by a force control methodology are:

- The problem of dynamic stability in case of unpredictable contact with a stiff environment.
- The problem of uncertainty in the parameters of the robot dynamics and of compensation for its nonlinear characteristics.

We must also note that the use of force derivative or angular acceleration feedback in the control law must be avoided due to the noisy nature of signals supplied by the force sensor and the optical encoders.

The system considered in this paper is a single leg of a pneumatic-driven quadruped robot, called RALPHY, developed in our laboratory to study the dynamic problems related with walking machines. Our goal here is to design a force controller for a single leg in interaction with the ground, taking into account the above mentioned problems. To robustify the control system with respect to these external disturbances we develop an adaptive impedance control scheme.
 consisting of two stages:
- A first stage that compensates for the nonlinear characteristics and the uncertainty on the dynamic model of the leg, performing an on-line estimation of its dynamic parameters.
- A second stage of adaptation is necessary during contact with the ground, in order to deal with the problem of uncertainty in the dynamic parameters of the ground and ensure the desired force trajectory tracking.

The paper is organised as follows. In section 2 we present the dynamic model of the system used for the simulations. Section 3 presents a fixed impedance control law based on the computed torque control concept. The two stages of adaptation are introduced in section 4 and a stability analysis is performed. Simulation results obtained for RALPHY’s leg are presented in section 5. Finally, section 6 offers brief concluding remarks.

2. Modelling of the system

2.1. Dynamic model of a leg

Each leg of RALPHY has the kinematic structure of figure 1. It consists of a supporting platform and two rigid links connected together with two rotational joints. An incremental encoder is mounted on each joint to measure the angular displacements. In addition to that, a force sensor is mounted on the endpoint of the leg in order to measure the interaction forces with the ground. Each link is equipped with a pneumatic cylinder, an electropneumatic servovalve to control the pressure applied on the piston, and a piezoresistive sensor to measure the differential pressure \( Z \) between the two chambers of each actuator. The linear motion of the piston is transformed in rotational motion through a cable.

![Figure 1. Leg model](image)

The dynamic model of this rigid two link system can be written as:

\[
D(q) \cdot \ddot{q} + h(q, \dot{q}) = \tau + J^T F_e
\]

(1)

where \( q \) denotes the 2x1 vector of joint angular positions \( q = [q_1, q_2]^T \), \( D(q) \) is the 2x2 generalised inertia matrix of the robot, \( h(q, \dot{q}) \) contains the Coriolis, centrifugal and gravitational terms, \( J \) is the Jacobian matrix of the robot, \( \tau \) the actuator torques and \( F_e \) the external force applied on the endpoint of the robot.

2.2. Robot-environment interaction: modelling issues

The models that are most often used to study the contact between a robot and its environment are the linear models of type inertia-damping-stiffness [5]. Let for instance \( K_e \) be the effective stiffness of the whole {force-sensor / ground} and \( B_e \) the relevant damping coefficient. The whole {robot + controller} can be ideally represented by the desired, 2nd order impedance \( (M, B, K) \) imposed by the control law. We can then write the following equations:

\[
F_e = K_e (x_e - x)
\]

(2a)

where \( x_e \) is the position of the ground, \( F_e \) the force applied on the endpoint of the robot, and

\[
\left\{ M_p^2 + (B + B_e) \right\} \cdot \dot{x} + (K + K_e) \cdot x = - F_e + K x_d + K_e x_e
\]

(2b)

\( x_d, F_d \) are the position and force reference signals respectively and \( x \) the endpoint position of the robot. In steady-state we obtain:

\[
F_{ef} = F_e (t \to \infty) = \frac{K_e}{K + K_e} F_d + \frac{K K_e}{K + K_e} (x_e - x_d)
\]

(3)

This equation will be used in paragraph 4.2 to study the force tracking capacity of the impedance controller during contact with the ground.

2.3. Control architecture.

The control architecture of the system is decomposed into two levels, as shown in figure 2.

The coordinator-level generates the position and force reference trajectories \( \dot{x}_d \) and \( F_d \) respectively, which are afterwards supplied as command signals to the low-level control of each leg. In this control level we perform the second stage of adaptation, which is presented in paragraph 4.2.
3. Computed-torque impedance control law.

The first step in implementing an impedance control scheme is to define the desired dynamic behaviour of the robot, that is the target-impedance. We choose a linear, second order model as the desired impedance of the robot:

\[ \mathbf{M} \cdot (\ddot{\mathbf{x}} - \dot{\mathbf{x}}) + \mathbf{B} \cdot (\dot{\mathbf{x}} - \dot{\mathbf{x}}) + \mathbf{K} \cdot (\mathbf{x} - \mathbf{x}) = \mathbf{F}_d - \mathbf{F}_e \]  

(4)

where \( \mathbf{x}_d \) is the desired trajectory for the end-point of the leg \( \mathbf{F}_d \) is the desired force reference trajectory and \( \mathbf{M}, \mathbf{B}, \mathbf{K} \) are the desired apparent inertia, damping and stiffness matrix respectively.

This dynamic equation is expressed in the cartesian coordinate frame \( \mathbf{R}_q \) fixed on the platform (see fig.1). The dynamic model of the robot (1) rewritten in the same coordinate frame has the following form:

\[ \mathbf{D}^* \cdot \ddot{\mathbf{x}} + \mathbf{h}^* = \mathbf{F} + \mathbf{F}_e \]  

(5)

where \( \mathbf{D}^* \) is the generalised inertia matrix expressed in the cartesian coordinate frame. We have:

\[ \mathbf{D}^* = \left( \mathbf{J} \cdot \mathbf{D}^{-1} \mathbf{J}^T \right)^{-1} \quad \text{and} \quad \mathbf{h}^* = \mathbf{J}^T \cdot \mathbf{h} - \mathbf{D}^* \cdot \dot{\mathbf{J}} \cdot \dot{\mathbf{q}} \]

where the kinematic and statics equation of the robot has been used.

Assuming a perfect knowledge of the dynamic parameters of the robot, a linearizing control law for the implementation of the target-impedance can be written as follows:

\[ \tau = \left( \mathbf{J}^T \mathbf{D}^* \right) \cdot (\mathbf{u} - \dot{\mathbf{J}} \cdot \dot{\mathbf{q}}) + \mathbf{h} - \mathbf{J}^T \cdot \mathbf{F}_e \]  

(6)

In order to assure that the closed-loop behaviour of the system is identical to the target impedance, the auxiliary control signal \( \mathbf{u} \) must be chosen equal to:

\[ \mathbf{u} = \mathbf{s}_d + \mathbf{M}^{-1} \cdot \left[ \mathbf{K} \cdot (\mathbf{x}_d - \mathbf{\Gamma}(\mathbf{q})) + \mathbf{B} \cdot (\mathbf{s}_d \cdot \mathbf{J}(\mathbf{q}) \cdot \dot{\mathbf{q}}) \cdot (\mathbf{F}_d \cdot \mathbf{F}_e) \right] \]  

(7)

where \( \mathbf{s}_d = \mathbf{\Gamma}(\mathbf{q}) \) is the direct geometric model of the robot. The characteristics \( \mathbf{M}, \mathbf{B}, \mathbf{K} \) of the target impedance are chosen so as to achieve the following goals:

- Ensure a satisfactory trajectory tracking for the free motion of the leg.
- Ensure the stability of the whole system in case of contact with a stiff ground. For this reason \( \mathbf{M}_c, \mathbf{M}_s \) must be chosen greater than some minimum critical values, in order not to excite the unmodelled high-frequency modes of the robot.

4. Two-stage adaptive impedance control

4.1. First-stage: on-line estimation of the leg’s parameters

The impedance control law presented in the previous paragraph assumes a perfect knowledge of the parameters in the dynamic model of the leg. This control law is now replaced by the relation:

\[ \tau = \left( \mathbf{J}^T \hat{\mathbf{D}}^* \right) \cdot (\mathbf{u} - \dot{\mathbf{J}} \cdot \dot{\mathbf{q}}) + \hat{\mathbf{h}} - \mathbf{J}^T \cdot \mathbf{F}_e \]  

(8)

where \( \hat{\mathbf{D}}^* \) and \( \hat{\mathbf{h}} \) denote the estimates of \( \mathbf{D}^* \) and \( \mathbf{h} \) respectively, and their values are adjusted on-line by an adaptation law. The goal here becomes that of designing such an adaptation algorithm in order to assure the stability of the whole system despite the existence of the modelling uncertainty.

One can easily show that dynamic equation (8) is linear on a set of robot parameters \( \theta \). If we consider the inertial parameters as the main source of uncertainty in the dynamic model of the robot, this equation can be written in the form:

\[ \tau = \mathbf{J}^T \cdot \left( \hat{\Phi}(\mathbf{q}, \dot{\mathbf{q}}, \mathbf{u}) \cdot \dot{\mathbf{\theta}} - \mathbf{F}_e \right) + \tau_e \]  

(9)

where
\[ \Phi^*(q, q, u) \cdot \dot{\theta} = \hat{\Phi}^* \cdot u + \hat{h}^* - J^T \tau_e \]  \hspace{1cm} (10)

\( \Phi^* \) is the so-called \textit{regression matrix}, \( \dot{\theta} \) a vector that contains the estimates for the inertial parameters of the robot and \( \tau_e \) the constant part of the torque.

Let \( \tilde{\theta} = \theta - \hat{\theta} \) be the \textit{estimation error} for the parameters of the robot and \( \tilde{\xi}(\epsilon_d, \epsilon_f) \) an error signal defined as

\[ \tilde{\xi}(\epsilon_d, \epsilon_f) = u - \hat{\epsilon} = \epsilon_d + M^{-1} \left[ B \cdot \dot{\epsilon}_d + K \cdot \epsilon_d - \epsilon_f \right] \]  \hspace{1cm} (11)

Combining equations (5), (9) and (10) we have:

\[ \Phi^* \cdot \tilde{\theta} = \hat{\Phi}^* \cdot \tilde{\xi}(\epsilon_d, \epsilon_f) \]  \hspace{1cm} (12)

This is the cartesian-space \textit{error-dynamics} equation of the system. The error signal \( \tilde{\xi}(\epsilon_d, \epsilon_f) \) can be interpreted as the so-called \textit{impedance error}, that is an error with respect to the target-impedance dynamic model. Let us define now a function \( \xi(\epsilon_d, \epsilon_f) \) such that:

\[ \dot{s} + A \cdot s = \xi \]  \hspace{1cm} (13)

where \( A \) is a positive definite matrix. Integrating this equation we obtain:

\[ s(t) - s(0) = -\frac{1}{2} A \cdot s(t) dt + \epsilon_d + M^{-1} \left[ B \cdot \epsilon_d + K \cdot \epsilon_d - \epsilon_f \right] \]  \hspace{1cm} (14)

that gives the value of \( s(t) \) directly from the available sensory information.

A similar methodology has been presented by [7] and [8], that have introduced an impedance error in the following manner: \( \zeta = s_d \cdot (F_d - Z_d) \) where \( Z_d \) is the target-impedance imposed on the robot. This definition leads to a different formalization for the error-dynamics of the system. The main difficulty of this approach in practice is the presence of the force derivative in the algorithm for the computation of \( s \), used thereafter in the adaptation law. This problem is here solved by equation (14) where we make use only of the position \( \epsilon_d \), velocity \( \dot{\epsilon}_d \) and force \( \epsilon_f \) feedback.

Let us now define as a Lyapunov-candidate the non-negative energy function \( V(s) \):

\[ V(s) = \frac{1}{2} \left[ \tilde{\theta}^T \Gamma \tilde{\theta} + s^T \Phi^* s \right] \]  \hspace{1cm} (15)

Defining the following relation:

\[ \dot{s} = \Gamma^{-1} \left( \Phi^* \right)^T \cdot s \]  \hspace{1cm} (16)

we obtain for the derivative of \( V(s) \):

\[ \dot{V}(s) = -\left( s^T \cdot (\Phi^T \cdot A) \cdot s \right) \leq 0 \]  \hspace{1cm} (17)

(\( \Phi^* \): positive definite and \( A = \text{diag}[a_1, a_2] \) with \( a_1, a_2 > 0 \))

Equation (16) defines the adaptation law which gives us the necessary modifications of the robot parameters estimates. It constitutes, in fact, an \textit{Integral Parameter Adaptation Algorithm}.

4.2. Second-stage: adaptation in face of an unknown environment

The key idea of the method presented in this paragraph is to make an on-line estimation of the ground parameters \( K_s \) and \( y_s \) and then compute the desired end-point position trajectory, using these estimates. The first-stage impedance adaptive controller is maintained intact, with no modification between the two different phases of motion and constitutes the kernel of the control system.

As we have seen in paragraph 2.2 the force applied from the ground on the end-point of the leg, in steady-state, is given by equation (3). In order, therefore, to ensure the desired force trajectory tracking \( F_{dF} = F_d \) during contact with the ground, the position reference signal can be commanded using the following equation:

\[ x_d = \hat{x}_s - \frac{1}{K_s} \cdot F_d \]  \hspace{1cm} (18)

where \( \hat{x}_s \) and \( \hat{K}_s \) are estimates of the ground parameters.

The position reference signal \( x_d \) is therefore the one that is going to be modified during contact with the ground to assure a good force trajectory tracking. This method is proposed in [9]. Here it is integrated, as the second-stage of adaptation, in the coordinator-level of the leg's impedance control structure.

The adaptation law used in this stage is

\[ \begin{cases} \hat{K}_s = \gamma_{11} \cdot x \cdot (\hat{K}_s - K_s) \\ \hat{x}_s = \frac{\hat{K}_s - K_s}{\gamma_{12} - \gamma_{11} \cdot x \cdot \hat{x}_s} \end{cases} \]  \hspace{1cm} (19)

where \( \gamma_{11}, \gamma_{12} > 0 \) are the adaptation gains and \( \hat{K}_s \) is a prediction of the measured force \( F_s \) defined as follows

\[ F_s = K_s \cdot (\hat{x}_s - x) = \hat{K}_s \cdot (\hat{x}_s - K_s \cdot x) \]  \hspace{1cm} (20)

For the steady state equation of the closed-loop system we obtain:

\[ \left( I + \frac{\hat{K}_s}{K_s} \right)(F_d - F_s) = 0 \iff \left( F_s = F_d \right) \]

which was the objective of the adaptive control during the leg-ground contact phase.

5. Simulation results

5.1. Fixed control law and effect of the different uncertainty sources.
We first apply the computed-torque, fixed control law described in section 3. The target-impedance characteristics are chosen as: \( M_x = M_y = 1 \), \( B_x = B_y = 30 \) and \( K_x = K_y = 225 \). The ground is supposed to be very stiff with \( K_S = 2 \times 10^3 \) (N/m), \( B_S = 150 \) (N·sec/m) and \( y_S = -0.5 \) m.

We start considering the different sources of uncertainty and monitor their influence on the dynamic behaviour of the system. We suppose that the parameters of the leg are known with a 20% error. We also add an imprecision of 1cm on the estimated position of the ground. The simulation results obtained, for the complete motion of the leg during the first 10 sec, are shown in figure 3 and 4. The control objectives are: position trajectory tracking during free-motion of the leg (2 sec < t < 4 sec) and desired force tracking during contact with the ground (4 sec < t < 6 sec). These phases of motion repeat themselves periodically as shown by fig. 3. Fig. 4 shows the force applied on the endpoint of the leg for the same period of time.

Each source of uncertainty has its own effect in the degradation of the system's performance. The error in the dynamic parameters of the leg results in the existence of a steady state positioning error as well as a small force tracking error. The uncertainty on the parameters of the ground adds on the top of this a new component for the steady state force error deteriorating even more the force tracking characteristics of the system. In the following paragraph we see how the two-stage adaptive impedance control, proposed in this paper, deals with this problem, compensating for the uncertainty in the dynamic parameters of the system as a whole.

5.2. Two stage adaptive impedance control.

We now implement the two stages of adaptation, as described in section 4. Let \( \tau_1(t = 0) = 0.5 \) kg and \( I_1(t = 0) = I_2(t = 0) = 0 \) be the initial estimates for the leg parameters. The gains used in the adaptation procedure are \( \gamma_1 = \gamma_2 = 0.001 \), \( \gamma_3 = \gamma_4 = 2 \), \( A = \text{diag}[a_j] \), \( j = 1, 2 \) with \( a_1 = 15 \) and \( a_2 = 10 \). The simulation results obtained, for the same motion of the leg, are shown in figures 5, 6 and 7.

From figures 5 and 6 we derive the following conclusions:

- The steady state position tracking error is now eliminated, thanks to the on line estimation of the leg parameters. This adaptation stage thus robustifies the system with respect to imprecisions or unpredictable changes on the dynamic model of the leg for the complete, free-space or constrained, motion.
- Thanks to the second stage of adaptation the steady state force tracking error is also completely eliminated and the transient response of the system is satisfactory.

Figure 7 shows the adaptation procedure for the robot and ground parameters \( m_1 \), \( I_1 \) and \( K_S \), \( y_S \) respectively. Similar results are obtained for the rest of the robot parameters \( m_2 \) and \( I_2 \).

6. Conclusion

A two-stage adaptive impedance control was proposed and implemented on a single leg of a pneumatic driven robot. The first stage linearizes the dynamic behaviour of the robot imposing the desired mechanical impedance. It is based on a computed torque impedance control law where the robot parameters are estimated on-line using an integral parameter adaptation algorithm. Measurements of joint acceleration as well as force derivative are not needed. The second stage performs an on-line estimation of the ground parameters adapting afterwards the position reference signals to ensure the desired force tracking during contact with an unknown environment. It constitutes in fact an external force control loop closed around the first stage adaptive impedance controller. Simulation results obtained for a pneumatic driven leg show the effectiveness of the proposed control scheme in case of considerable uncertainty both in the robot and ground parameters.

References


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Figure 3. Motion of the leg’s endpoint \([x, y]\) and reference position trajectory \([x_d, y_d]\) (Fixed control law).

Figure 4. Force tracking (fixed control law).

Figure 5. Position trajectory tracking

Figure 6. Force tracking (Stage I and II).

Figure 7. Adaptation procedure