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MOTION\FORCE CONTROL OF ROBOTIC MANIPULATOR

par

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0. Summary

A procedure for the design of a motion/force controller for a manipulator, the end-effector of which maintains a stiff contact with the environment, is presented. Based on the computed torque approach and on projections on the motion and force subspace, this procedure leads to decoupled controllers that are capable of ensuring a global stability and are applicable to stationary as well as to mobile contact surfaces.

1. Introduction

In many industrial applications like, for example, automatic assembly, deburring and grinding operations, the end-effector of a robotic manipulator has to maintain contact with the environment. The manipulator's controller has then the dual objective of ensuring a desired motion of the end-effector and of the end-effector exerting a specified force-torque on the contact surface.

When the contact between the end-effector and the environment is stiff most of the available design procedures rely on a hybrid scheme where the controller action is the sum of two components (Raibert and Craig (1981)). The first component, intended to satisfy the motion requirements, is computed as a function of a projection of the position/orientation error into the subspace of velocities that are compatible with the contact constraints. A second component, intended to satisfy the contact force requirements, is computed as a function of the projection of the contact force error into the subspace of admissible forces.

Typical among various refinements of this scheme is the work of Faessler (1990) which gives a procedure for the design of a motion/force controller in the task-space, and the work of McClamroch and Wang (1990, 1993) which offers a similar procedure using the space of generalized coordinates. Issues concerning physical implementation have been discussed by many authors including Yoshikawa and Sudou (1993), Wilfinger et al. (1994), and Ferretti et al. (1995). Also of interest here is the paper by Ferretti et al. (1993) which considers the integration of the above controllers into currently available industrial hardware.

While adequate for many applications, a drawback of most of these developments is that they lead to controllers that can only guarantee feedback stability in a local sense, that are decoupled only within a certain approximation, and that are only applicable to stationary contact surfaces. These difficulties, explicitly recognized by Raibert and Craig, McClamroch and Wang and Ferretti et al., also appear to be present in the procedures proposed by other authors (like, for example, An and Hollerbach (1989), Faessler (1990), Fisher and Mujtaba (1992), Yoshikawa and Sudou (1993)).

The objective of this paper is to present a design approach whereby, at least in principle, stability and decoupling may be ensured in a global sense, and applicability carries over to mobile contact surfaces. A distinctive feature in pursuing this objective is that we require the desired contact force-torque to be specified as a function of the end-effector's actual position and orientation, rather than as a function of time independent from these elements (as it is the case in the available procedures).

2. Problem statement

In the joint space, the dynamics of a manipulator is modeled by the following equation (see for example Craig (1989), p. 205)

$$\tau = D\ddot{q} + H \tag{1}$$

where τ is a vector representing the generalized forces provided by the actuators; q is a vector representing joint variables; D is the manipulator's mass-matrix; H represents the generalized forces produced by Coriolis, centripetal and gravitational accelerations.

From eqn 1, we obtain that the dynamics in the workspace of the end-effector is given by (Craig (1989), p. 211)

$$\omega = M\dot{\nu} + V \tag{2}$$

where ν represents the linear and angular workspace velocities of the end-effector; ω is a force-torque representing the influence of the forces produced by the actuators on the end-effector's workspace dynamics; V represents the influence of the forces produced by Coriolis, centripetal and gravitational accelerations. The entries of eqns 1 and 2 are related as follows

$$M = J_E'^{-1} D J_E^{-1} \tag{3}$$

$$V = J_E'^{-1}\{H - DJ_E^{-1}\dot{J}_E\,\dot{q}\} \tag{4}$$

$$\nu = J_E\,\dot{q} \tag{5}$$

$$\tau = J_E'\omega \tag{6}$$

$$\chi = f(q). \tag{7}$$

Here, J_E is the Jacobian matrix associated with the end-effector, J_E' is its transpose, χ is a vector representing the end-effector's workspace position and orientation, and f(.) denotes the manipulator's direct kinematic function.

When the end-effector is in contact with the environment, eqns 1 and 2 are replaced with

$$\tau = D\ddot{q} + H + \tau_c \tag{8}$$

and

$$\omega = M\dot{v} + V + \omega_c \tag{9}$$

where τ_c and ω_c represent (respectively in generalized- and in workspace-coordinates) the force-torque that the end-effector exerts on the contact surface.

Denoting with $\chi_D(t)$ the end-effector's desired position and orientation and with $\omega_{cD}(\chi(t))$ the specified force-torque to be exerted to the contact surface, the problem is to design a motion/force controller that receives as input χ, v and ω_c (or equivalently q, $\dot{q}$ and τ_c), and gives as output τ such that

$$\lim_{t \to \infty} \chi(t) = \chi_D(t) \tag{10}$$

and

$$\lim_{t \to \infty} \omega_c(t) = \omega_{cD}(\chi(t)). \tag{11}$$

3. Some structural properties

A stiff contact implies that the end-effector satisfies a set of position-orientation constraints of the form

$$h_i(\chi(t))=0, \qquad i=1,..,m, \tag{1}$$

where scalar functions $h_i(.)$ depend on the geometric properties of the end-effector and the contact surface.

It follows from eqn 1 that q may be represented as

$$q = [q_1' \; q_2']' \tag{2}$$

with $q_1 \varepsilon R^{\ell}$, ℓ=n-m, $q_2 \varepsilon R^m$, and

$$q_2 = g(q_1) \tag{3}$$

where g is a function implicitly defined by h_i. From eqns 2 and 3 we also have

$$\dot{q} = J_g \, \dot{q}_1, \tag{4}$$

where the nxℓ matrix J_g is described by

$$J_g := \begin{bmatrix} I_\ell \\ \nabla g \end{bmatrix} , \tag{5}$$

I_ℓ denotes the ℓ-dimensional identity matrix and ∇g is the Jacobian of g. By combining eqn 2.5 with eqn 4 it follows

$$\nu = J\dot{q}_1, \tag{6}$$

where $J := J_E J_g$.

Remark 3.1. In writing eqns 2 and 3 we have tacitly assumed h_i and f to satisfy the conditions required by the implicit function theorem (Isidori (1989), p. 404).

Remark 3.2. Eqn 4 suggests that the columns of J_g span the subspace in the joint space of the manipulator velocities that are compatible with the contact constraints (eqn 1). Similarly, eqn 6 suggests that the columns of J span the subspace of admissible end-effector velocities in the workspace. This subspace is called the motion subspace.

Remark 3.3. Under a stiff contact, the work done by the force-torque exerted by the end-effector on the contact surface is null and therefore we must have

$$J'\omega_c = 0. \tag{7}$$

This means that the contact force-torque belongs to the orthogonal complement in the workspace of the motion subspace. We call this orthogonal complement the force subspace.

Remark 3.4. The matrices

$$\Pi_m := J(J'J)^{-1}J' \tag{8}$$

and

$$\Pi_f := I_n - \Pi_m = I_n - J(J'J)^{-1}J' \tag{9}$$

are self-adjoint, mutually orthogonal projection operators. In particular, the columns of Π_m span the motion subspace, the columns of Π_f span the force subspace, and $\Pi_m \nu = \nu$, and $\Pi_f \omega_c = \omega_c$.

4. The design procedure

Following common practice, we consider a controller structure made up of the parallel combination of a motion controller and a force controller. Accordingly, the workspace dynamics of the end-effector may be viewed as given by

$$\omega_m + \omega_f = M\dot{\nu} + V + \omega_c, \tag{1}$$

where ω_m and ω_f denote the influence of the motion and the force controllers. We design the motion controller so that it produces a force-torque ω_m capable of providing the desired motion

$$\lim_{t \to \infty} \chi(t) = \chi_D(t) \tag{2}$$

under the contact constraints

$$h_i(\chi(t)=0, \qquad i=1,..,m. \tag{3}$$

We design the force controller so that it produces a force-torque ω_f capable of satisfying the force requirement

$$\lim_{t \to \infty} \omega_c(t) = \omega_{cD}(\chi(t)) \tag{4}$$

under the constraint of not influencing the motion of the end-effector.

Before carrying out these steps, it is helpful to observe the following. By pre-multiplying both members of eqn 1 by J' and by taking into account eqn 3.7, we have

$$J'\omega_m + J'\omega_f = J'M\dot{\nu} + J'V. \tag{5}$$

It follows that the constraint of ω_f not influencing the motion of the end-effector imposes

$$J'\omega_f = 0. \tag{6}$$

Eqns 1, 5 and 6 taken together imply that ω_m and ω_f must satisfy

$$J'\omega_m = J'M\dot{\nu} + J'V \tag{7}$$

and

$$\omega_f = (I_n - J(J'J)^{-1} J')\{M\dot{\nu} + V - \omega_m\} + \omega_c. \tag{8}$$

To design the motion controller, consider now the joint-variable vectors q and q_D such that

$$\chi = f(q) \tag{9}$$

and

$$\chi_D = f(q_D). \tag{10}$$

Observe that, since

$$\lim_{t \to \infty} \chi(t) = \chi_D(t) \tag{11}$$

is equivalent to

$$\lim_{t \to \infty} q(t) = q_D(t), \tag{12}$$

from eqns 3.3 and 3.3, eqn 11 is equivalent to

$$\lim_{t \to \infty} q_1(t) = q_{1D}(t). \tag{13}$$

Also observe that from eqn 3.6 we have

$$\dot{\nu} = J\ddot{q}_1 + \dot{J}\dot{q}_1 \tag{14}$$

and therefore that eqn 7 can be rewritten as

$$J'\omega_m = J'MJ\ddot{q}_1 + J'\overline{V} \tag{15}$$

where (using eqns 2.3 and 2.4)

$$\overline{V} = V + MJ\dot{q}_1. \tag{16}$$

Consider now the control

$$\omega_m = MJ\{\ddot{q}_{1D} + K_P e + K_D \dot{e} + K_I\int_0^t edt\} + \overline{V} \tag{17}$$

where K_P, K_D and K_I are positive-definite diagonal matrices and

$$e := q_{1D} - q_1. \tag{18}$$

By inserting this control into eqn 15 gives

$$J'MJ\{\ddot{e} + K_P e + K_D \dot{e} + K_I \int_0^t edt\} = 0 \tag{19}$$

which implies, since J'MJ is a positive definite matrix,

$$\{\ddot{e} + K_P e + K_D \dot{e} + K_I \int_0^t edt\} = 0. \tag{20}$$

This implies in turn eqn 13 and therefore eqn 11.

Proceeding to design the force controller, note that, by virtue of eqns 8 and 17, we can satisfy eqn 4 by simply setting

$$\omega_f = (I - J(J'J)^{-1}J')\{M\dot{\nu} + V - \omega_m\} + \omega_{cD} = \omega_{cD}. \tag{21}$$

However, this open-loop control not being particularly robust with respect to perturbations, it may be preferable to opt instead for a feedback control of the type

$$\omega_f = \omega_{cD} + K_F(\omega_{cD} - \omega_c) \tag{22}$$

where K_F is a positive definite diagonal matrix.

By combining eqns 17 and 22, the motion/force control becomes

$$\omega = MJ\{\ddot{q}_{1D} + K_P e + K_D \dot{e} + K_I\int_0^t edt\} + \bar{V} + \omega_{cD} + K_F(\omega_{cD}-\omega_c). \quad (23)$$

By now multiplying both sides of this equation by J_E' and by taking into account eqns 2.3, 2.4, 2.6 and 16, we obtain the vector of forces to be supplied by the actuators

$$\tau = DJ_g\{\ddot{q}_{1D}+K_P e+K_D\dot{e}+K_I\int_0^t edt\}+H+D\dot{J}_g\dot{q}_1+J_E'\{\omega_{cD}+K_F(\omega_{cD}-\omega_c)\}. \quad (24)$$

Remark 4.1. The controller described by eqns 23 and 24 is made up of a computed-torque controller modified by the parallel addition of a force component (Figure 1). In the particular instance of unconstrained free motion, that is when $I_g=I_n$, $\omega_c=0$, and $\omega_{CD}=0$, it coincides with the computed-torque controller (see for example Craig (1989), eqns 10.4.12-.16). As in the classical case, the dynamics of the errors in our controller are globally stable, completely decoupled, linear and time invariant, and characterized by eigenvalues with arbitrarily assignable values.

Remark 4.2. We have tacitly assumed the contact surface to be stationary with respect to the workspace. If the contact surface is mobile, our procedure remains valid by simply replacing eqn 16 and eqns 3.1-.7 with the following equations

$$\bar{V} = V + M\{J\ddot{q}_1 + \frac{d(J_E\,\bar{g})}{dt} \quad (16')$$

$$h_i(\chi(t),t)=0, \qquad i=1,..,m, \tag{3.1'}$$

$$h_i(f(q(t),t)=0, \qquad i=1,..,m. \tag{3.2'}$$

$$q_2 = g(q_1,t) \tag{3.4'}$$

$$\dot{q} = J_g \dot{q}_1 + \bar{g} \tag{3.5'}$$

$$\nu = J\dot{q}_1 + \dot{J}_E J_g \dot{q}_1 \tag{3.7'}$$

where

$$\bar{g} = [0_\ell \quad \frac{\partial g'}{\partial t}]' . \tag{3.7''}$$

Remark 4.3. In an actual implementattion our motion/force controller will have to be modified so as to work well under the inevitable presence of joints flexibility, sensors resonances and time lags, viscous and Coulomb friction, external perturbations, and similar physical factors. While a detailed discussion of the required modifications falls behind the scope of the present brief, their nature should be the same as that discussed by, among other authors, Yoshikawa and Sudou (1993), Wilfinger at al. (1994), Yousef-Toumi and Gutz (1994), and Ferretti et al. (1995). The ad hoc correctives that these authors have found effective in ensuring a robust performance for their controllers should prove to be equally effective in the case of our controller. In particular, the introduction a control component proportional to the integral of the force error should play an important role in improving robustness in many practical applications. In spite of its general acceptance, however, a word of caution concerning this corrective is in order. Because $J'(\omega_{cD}-\omega_c)=0$ does not necessarily imply $J' \int(\omega_{cD}-\omega_c)\,dt=0$ (though it does in most of the cases considered in the cited literature), the integral of the force error could lead to a control ω_f that does not necessarily satisfy eqn 6 and which could interfere with the desired motion of the end-effector.

5. An illustration example

Consider the task of having the end-effector (P) of the planar manipulator in Figure 2 maintain a stiff contact with the circular line ($x^2+y^2=\ell^2$), move along this line so that $y_{PD}(t)=.5\ell\sin t$, and apply at the point of contact a vertical force of intensity equal to $\alpha(1+y^2/\ell^2)$.

This task can be carried out by applying the control described by eqn 24 where K_P, K_D, K_I, and K_F are positive scalars and entries D, H and J_E are as follows (Craig (1989), p. 204)

$$D=\begin{bmatrix} m_2\ell^2(1+2c_2)+(m_1+m_2)\ell^2 & m_2\ell^2(1+c_2) \\ m_2\ell^2(1+c_2) & m_2\ell^2 \end{bmatrix} \qquad (1)$$

$$H=\begin{bmatrix} -m_2\ell^2 s_2\dot{q}_2^2-m_2\ell^2 s_2\dot{q}_1\dot{q}_2+m_2\ell g c_{12})+(m_1+m_2)\ell g c_1 \\ m_2\ell^2 s_2\dot{q}_1^2+m_2\ell g c_{12} \end{bmatrix} \qquad (2)$$

$$J_E = \begin{bmatrix} -\ell s_1 - \ell s_{12} & -\ell s_{12} \\ \ell c_1 + \ell c_{12}) & \ell c_{12}) \end{bmatrix}, \tag{3}$$

where $s_1 := \sin q_1$, $c_1 := \cos q_1$, $s_{12} := \sin(q_1+q_2)$, $c_{12} := \cos(q_1+q_2)$.

The constraint $x^2 + y^2 = \ell^2$ implies that

$$\ell^2\{c_1^{\,2} + c_{12}^{\,2} + 2c_1c_{12} + s_1^{\,2} + s_{12}^{\,2} + 2s_1s_{12}\} = \ell^2 \tag{4}$$

and therefore that

$$q_2 = -\,2\pi/3. \tag{5}$$

It follows, from eqn 3.6, $J_g=[1\ 0]'$ and $\dot{J}_g=[0\ 0]'$.

The values of q_{1D}, $\dot{q}_{1D}$ and $\ddot{q}_{1D}$ are as follows

$$q_{1D}(t) = \pi/3 + \text{arc\_sin}\{y_{PD}/\ell\} \tag{6}$$

$$\dot{q}_{1D}(t) = \dot{y}_{PD}/\cos(q_{1D}-\pi/3) \tag{7}$$

$$\ddot{q}_{1D}(t) = \{\ddot{y}_{PD}/\ell + \sin(q_{1D}-\pi/3)\,\dot{q}_{1D}^{\,2}\}/\cos(q_{1D}-\pi/3). \tag{8}$$

The value of $\omega_{CD}(\chi)=\omega_{CD}(x,y)$ is equal to $\{\alpha(\ell^2 + y^2)/\ell^3\}[x\ y]'$.

With the application of this control position and force errors are decoupled and the error dynamics is globally stable, time invariant, and characterized by arbitrarily assignable eigenvalues. These properties would not have materialized had we approached the same task by applying the available design procedures (as, for example, those adopted in the cited literature).

Conclusions

The proposed controller is made up of a motion controller that produces the desired motion for the end-effector and a force controller that generates the required force between end-effector and environment. The motion controller is obtained by applying the computed torque approach and the force controller by adding a proportional force feedback.

This controller ensures a global feedback stability, is completely decoupled and is applicable to stationary as well as mobile surfaces of contact. These properties exist partly because we have formulated the motion/control problem by requiring the desired contact force-torque to be a function of the end-effector's actual position and orientation rather than a function of time independent from these elements (as is the case in the available literature). In addition to being amply justified from a physical point of view, this formulation appears to considerably simplify the design and to lead in a natural way to the sought after controller properties.

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References

1. An, C. H., Hollerbach, J.M., 1989, The Role of Dynamic Models in Cartesian Force Control of Manipulators, **The Int. Journal of Robotics Research**, Vol. 8, pp. 51-72.
2. Craig, J.J, 1989, **Introduction to Robotics**, Addison Wesley.
3. Fisher, W.D., Mujtaba, M.S., 1992, Hybrid Position/Force Control: A Correct Formulation, **The Int. Journal of Robotics Research**, Vol. 11, N.4, pp. 299-311.
4. Isidori, A., 1989, **Nonlinear Control Systems**, Springer-Verlag.
5. Faessler, H., 1990, Manipulators Constrained by Stiff Contact: Dynamics, Control, and Experiments, **The Int. Journal of Robotics Research**, Vol. 9, N.4, pp. 40-58.
6. Ferretti, G., Maffezzoni, C., Magnani, G., Rocco, P., 1993 Decoupling Force and Motion Control in Industrial Robots, **Control Engineering Practice**, Vol.1, N.6, pp. 1019-1027.
7. Ferretti, G., Magnani, G., Rocco, P., 1995, On the Stability of Integral Force Control in Case of Contact with Stiff Surfaces, **ASME Journal of Dynamic Systems, Measurement, and Control**, (to appear).
8. McClamroch, H., Wang, D., 1990, Linear Feedback Control of Position and Contact Force for a Nonlinear Constrained Mechanism, **ASME Journal of Dynamic Systems Measurement and Control**, Vol. 112, pp. 640-645.
9. Raibert, M.H., Craig, J.J., 1981, Hybrid Position/Force Control of Manipulators, **ASME Journal of Dynamic Systems Measurement and Control**, Vol. 102, pp. 126-133.
10. Yoshikawa, T., Sudou, A., 1993, Dynamic Hybrid Position/Force Control of Robot Manipulators: On-Line Estimation of Unknown Constraints, **IEEE Trans on Robotics and Automation**, Vol. 9, N.2, pp. 220-225.
11. Wang, D., McClamrock, N.H., 1993, Position and Force Control for Constrained Manipulator Motion: Lyapunov's Direct Approach, **IEEE Trans on Robotics and Automation**, Vol. 9, N.2, pp. 308-313.
12. Wilfinger, L.S., Wen, J.T., Murphy, S.H., 1994, Integral Force Control with Robustness Enhancement, **IEEE Control Systems**,Vol.14, N.1, pp. 31-40.
13. Yousef-Toumi, K., Gutz, D.A., 1994, Impact and Force Control:Modeling and Experiments, **ASME Journal of Dynamic Systems Measurement and Control**, Vol. 116, pp. 89-98.

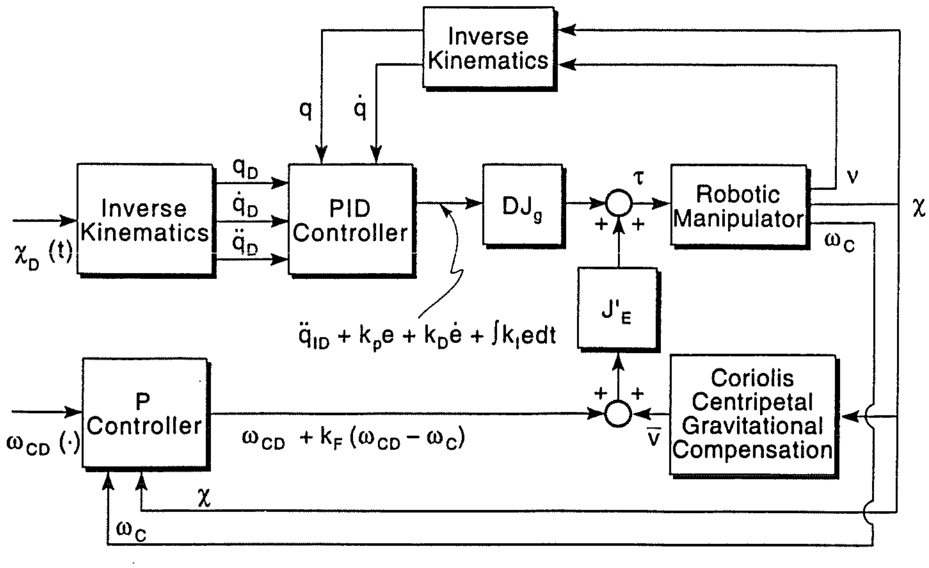

Figure 1: The Structure of the Motion/Force Controller

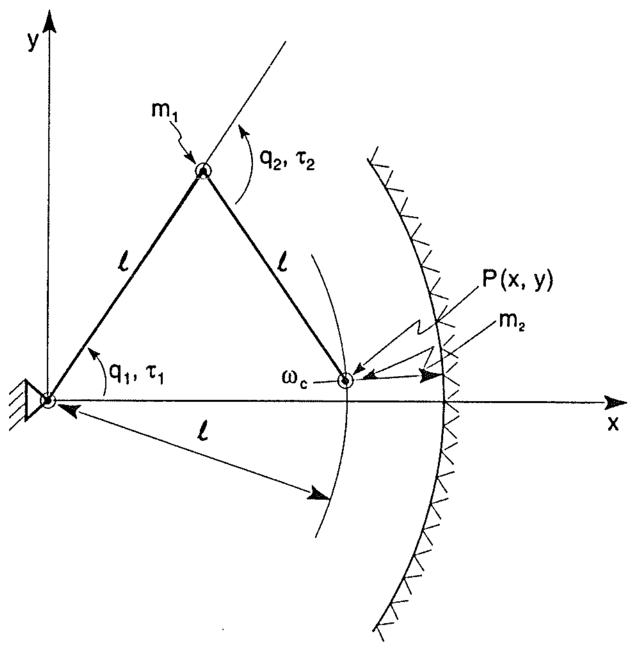

Figure 2: A 2 dof Planar Manipulator (Craig (1989), p. 240)

Nomenclature

χ: vector representing position and orientation of the manipulator's end-effector in the workspace;

ω_c: vector representing force and torque that the manipulator's end-effector applies to the contact surface;

τ: vector of generalized forces supplied by the actuators;

q: vector of generalized coordinates (joint variables);

τ_c: vector of generalized forces produces by ω_c;

f(.): the (direct kinematic) function relating q to χ;

χ_D, ω_{cD}, q_{1D}, τ_{cD}: desired values of χ, ω_c, q_1, and τ_c;

D: mass-matrix of the manipulator;

J_E: the Jacobian matrix of the end-effector;

J_E': transpose of J_E;

$h_i(.)$: function describing a holonomic contraint;

q_1: component of q the value of which is not constrained by the contact between the end-effector and the environment;

ℓ: dimension of q_1;

q_2: component of q the value of which, in view of the contact between the end-effector and the environment, is a function of q_1;

g: the function relating q_2 to q_1;

∇g: the gradient of g;

J_g: a Jacobian matrix in the space of generalized coordinates;

Π_m: a matrix projecting the space of generalized coordinates into the motion subspace;

Π_f: a matrix projecting the space of generalized coordinates into the force subspace;

ω_m: motion component of ω;

ω_f: force component of ω.

ℓ: length of the links of the planar manipulator.