Gauge Based Collision Detection Mechanism for a new Three-degree-of-freedom Flexible Robot (*).

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0. ABSTRACT

Flexible robots have given rise to numerous investigations and their use is easily justified in two main cases: 1) when the weight of the robot has to be minimized 2) when collisions of the robot with the environment are to be foreseen, as a flexible lightweight robot delivers less impact energy.

There is a lot of work done by different authors on the position control of flexible robots by using feedback of the tip position or tip acceleration. However the use of these sensing devices is problematic in practical applications of flexible arms: 3-D tip position sensing is very expensive, and occlusions appear at some arm configurations; and accelerometers can not be used when contact of the tip with the environment is expected because these sensors can not stand the high negative accelerations produced at the impact (unless very low speed motions were performed).

In most up to date analysis the force control is performed beginning from a known contact point at a given collision time. But in a more realistic approach an accurate detection of the collision would be needed before dealing with the force control.

This paper analyzes the possibility of carrying out the collision detection as a first step towards the position/force control of a three-degree-of-freedom flexible arm by using gauges placed at some distance of the tip (where contact is expected) in such way that they can easily stand the impact.

Simulated results over a prototype three-degree-of-freedom flexible arm are presented.

1. INTRODUCTION

As robots are becoming more usual in industry, new applications are being developed where their interaction with the environment is more necessary. New control methods have been obtained to enhance the robot behavior under these circumstances, where the force, measured using different kinds of sensors, is of special importance [11].

Industrial robots are composed of stiff heavy links whose movement involves large kinetic energy that has to be absorbed somehow in case of impact with the environment. The impact energy can be reduced by using lighter links in building the robot. This also makes them flexible so that their progressive deformation minimizes the rebounds and gives a larger actuation time to the force controllers.

Some authors have developed new force control techniques [7], [11], but they have just been analyzed for stiff robots. Others have even achieved the impact response control of a one link flexible arm [1], but the sensing systems and the complicate models used make these control methods impossible to be applied on more complex arms. The increasing interest for the contact problem in flexible robots and its difficulty makes some researchers face it one step at a time, beginning with the impact problem but without undertaking the control at this first stage. This way in [5] a flexible hammer has been mounted at the tip of a stiff robot in order to analyze the impact response of the system. In [8] the impact has been analyzed for a one-degree-of-freedom flexible robot colliding with the environment, and in [10] similar methods have been applied to the development of a sensing antennae.

In [3] we made a detailed analysis of a collision detection mechanism for a one link flexible robot that used the information obtained from a strain gauge. We propose here to generalize that method for its use in a more complex arm.

In this paper we focus our research in allowing a three-degree-of-freedom flexible robot to collide with the environment as a previous step for the development of a reliable force controller. In order to avoid damage, a fast collision detection is needed, this way it will be possible to stop the motors as soon as the robot collides. We intend to use here sensors and simplified techniques that can also be used in the further development of the force controller as well as to control the robot position.
In Section 2 a dynamic description of the robot used has been carried out. In Section 3 a model for the collision has been established. In Section 4 the collision detection mechanism is discussed and an application example is proposed, and some conclusions are stated in Section 5.

2. DYNAMIC DESCRIPTION OF THE PROTOTYPE

This Section is devoted to describe briefly the main characteristics of our three-degrees-of-freedom flexible arm prototype. More detailed information can be found in [9].

2.1 Mechanical specifications

Our flexible robot was designed to fulfill the next mechanical specifications:

1) The arm must be lightweight enough so that just the tip mass would have to be considered.

2) Kinematics of the arm assumed as rigid must be approximately uncoupled in spherical coordinates.

3) Robot features have to be similar to those of a typical industrial robot. We have chosen as model the industrial robot PUMA™ 560:

- Spheric sector working volume of radius 0.92m.
- Maximum load of 2.3Kg.
- Tool acceleration/velocity: 1g/1.0m/s.

To fulfill the first specification the arm was built of aluminium bars. Furthermore all the drivers have been placed at the basis of the arm so that the movement of the elbow is transmitted from the basis by using a four-bar-linkage mechanism.

The second specification was fulfilled by properly designing the four-bar-linkage by using optimization techniques, and by mounting the motor responsible of the span of the arm on the axis of the motor responsible of the elevation angle. A detailed analysis of this can be found in [2].

The third specification was accomplished by an adequate selection and dimensioning of the different elements of the robot.

Fig. 1 shows the prototype developed under these specifications, and Fig. 2 shows the scheme used for the following analysis.

![Fig. 1: Experimental prototype.](image)

![Fig. 2: Experimental system definitions.](image)

2.2 Rigid arm dynamics

The dynamics of our mechanism has some advantages. First, torque coupling does not exist among actuators. This means that the torque from a motor does not produce any reaction torque on any of the other two motors, which simplifies the control. Second, the mechanism actuates orthogonally on the tip load so that the actuators never work in opposition with one another, contrarily to what happens in conventional robots. Third, we have assumed that all the mass is concentrated at the tip of the arm. These features lead to a very simple dynamic model for the arm assumed rigid. In the next Subsection we will add the dynamics associated to the flexibility of the arm by means of the compliance matrix.

The position of the robot tip can be expressed in spherical coordinates. Thus it is possible to define a tip position as \( \mathbf{P} = f(\phi, \varphi, \rho) \) where \( \phi \) stands for the lateral angle, \( \varphi \) for the elevation angle and \( \rho \) for the tip radius (Fig. 2).

Assuming that all the mass \( m \) is concentrated at the tip, and assuming that the inertia moments are negligible, the equation of motion of the whole arm is reduced to

\[
\mathbf{F} + \mathbf{F_g} = m \cdot \mathbf{a}
\]
where $\mathbf{F} = \mathbf{F}_g + \mathbf{F}_a$, $\mathbf{F}_g$, $\mathbf{F}_a$, $\mathbf{J}$ represents the motion tip force produced at the tip by the actuators, $\mathbf{a} = [a_{\rho}, a_{\phi}, a_\rho, a_\phi]$, $\mathbf{a}_\rho, \mathbf{a}_\phi$, represents the tip acceleration, and

$$\mathbf{F}_g = -m \cdot g \cdot (0 \cos(\phi) \sin(\phi))$$ (2)

is the gravitational force, all of them expressed in relation to the tip frame defined above (see Fig. 2).

Tip acceleration in the tip system of coordinates can be easily obtained and is composed of a motion acceleration term, a Coriolis acceleration term and a centripetal acceleration term:

$$\mathbf{a} = \begin{pmatrix} a_\rho \\ a_\phi \\ a_{\rho} \\ a_\phi \end{pmatrix} = \begin{pmatrix} \rho \phi \\ \rho \phi \\ \rho \cos(\phi) \phi \\ 2 \rho \phi \end{pmatrix} + \begin{pmatrix} 0 \\ 2 \rho \phi \\ 2 \rho \cos(\phi) \phi \\ 2 \rho \cos(\phi) \phi - 2 \rho \sin(\phi) \phi \end{pmatrix}$$ (3)

The controlled motion of the tip is produced by force $\mathbf{F}$. The torques $\Gamma$ that the three actuators need to produce in order to obtain a given force $\mathbf{F}$ at the tip, are calculated as follows.

Given the uncoupling existing among actuators, as consequence of our special mechanical design, the following expression can be obtained by applying the principle of virtual work ([6], e.g.):

$$\Gamma = \begin{pmatrix} \Gamma_1 \\ \Gamma_2 \\ \Gamma_3 \end{pmatrix} = \mathbf{J}^T (\xi, \phi) \cdot \mathbf{F}$$ (4)

where $\Gamma_i$ denotes the torque generated by actuator $i$, and $\mathbf{J}$ is the Jacobian matrix that can be approximated as in [9].

2.3 Compliance

The flexibility of the arm is considered now. Its effects on the dynamics of the arm can be easily modeled in our prototype by using the compliance matrix.

For the robot shown in Figs. 1 and 2 we made the following assumptions:

- All links are flexible.
- Tip mass $m$ is considered punctual so that it does not generate torques at the tip.
- Masses $m_2$, $m_3$, $m_4$ located at the joints, and the link masses are negligible compared to $m$.
- All links are slim and homogeneous so they can be considered as simple bars.
- The friction at the passive joints is considered negligible.

The flexible structure shown in Fig. 1 would be deformed if any torque or force were applied at its tip. It is a well known property of flexible structures that the stiffness of a three-dimensional system can be defined by three orthogonal stiffness vectors. The directions of these vectors form an orthogonal frame that will be, in general, rotated with respect to the reference system frame. The norms of these vectors are named stiffness eigenvalues.

The general relationship between tip deformations and tip forces is

$$\Delta \mathbf{P} = \mathbf{C}(\xi) \cdot \Delta \mathbf{F}$$ (5)

expressed in the tip frame. In this case, the compliance matrix $\mathbf{C}$ depends only on the variable $\xi$. The inverse of this equation is

$$\mathbf{F} = \mathbf{K}(\xi) \cdot \Delta \mathbf{P}$$ (6)

where $\mathbf{K} = \mathbf{C}^{-1}$ is the stiffness matrix, being both matrices symmetrical and positive definite.

In our particular structure, the stiffness matrix is of the form:

$$\mathbf{K}(\xi) = \begin{pmatrix} k_{11}(\xi) & 0 & 0 \\ 0 & k_{22}(\xi) & k_{23}(\xi) \\ 0 & k_{23}(\xi) & k_{33}(\xi) \end{pmatrix}$$ (7)

The eigenvalues $k_i(\xi), i = 1, 2, 3$ of this stiffness matrix give the natural vibration frequencies of the structure at the tip for each angle $\xi$:

$$\omega^2(\xi) = \frac{k_i(\xi)}{m}$$ (8)

and the eigenvectors of this matrix are the principal directions of stiffness.

2.4 Complete Dynamics Model

The complete dynamics model is obtained by assembling the previous submodels. Fig. 3 shows a block diagram of the dynamics of our flexible arm, where the coupling among the previous submodels can be observed. Friction in the flexible mechanism has been neglected because friction in the passive joints is very small and the viscous friction between air and the
3. SENSING SYSTEM

It is possible to develop the stiff arm dynamics making the assumption of a single mass lumped at the tip. By using Lagrange or Newton-Euler equations the following relation can be obtained:

\[
\begin{bmatrix}
F_x \\
F_y \\
F_z
\end{bmatrix} = m \begin{bmatrix}
\rho \ddot{x} + \rho \dot{x} \dot{\phi} \\
\rho \ddot{y} + \rho \dot{y} \dot{\phi} \\
\rho \ddot{z} + \rho \dot{z} \dot{\phi}
\end{bmatrix} + \begin{bmatrix}
0 \\
0 \\
0
\end{bmatrix}
\]

where \( F = \{F_x, F_y, F_z\} \) stands for the tip force expressed in its lateral, elevation and radial components and \( m \) is the tip mass. Due to the mechanical uncoupling between the motors and to the spherical representation and by using the virtual work principle, the relation between motor torques \((\Gamma_1, \Gamma_2 \text{ and } \Gamma_3)\) and the tip force can be obtained as:

\[
\begin{bmatrix}
\Gamma_1 \\
\Gamma_2 \\
\Gamma_3
\end{bmatrix} = \begin{bmatrix}
\Gamma_x \\
\Gamma_y \\
\Gamma_z
\end{bmatrix} = \begin{bmatrix}
2L \cos \xi \cos \phi & 0 & 0 & F_x \\
0 & 2L \cos \xi & 0 & F_y \\
0 & 0 & 2L \sin \xi & F_z
\end{bmatrix}
\]

In order to develop a force control loop it will be necessary to get the value of the tip force components.

Now it would be necessary to relate all this with the information we have from the sensors. In order to improve the capacity of the system to stand impacts we are using strain gauges placed over the structure as in Fig. 2. Here we can use the approximated relationships developed in [4] that allows to calculate the tip force from the gauge measures as:

\[
K_{\text{ref}} = \frac{12}{l^3} \begin{bmatrix}
-6\cos \xi \\
\cos \phi \\
\sin \phi
\end{bmatrix}
\]

where \( \gamma_j = [\gamma_1, \gamma_2, \gamma_3] \) are the gauge measures, \( K_{\text{ref}} \) are constants relating the gauge measures with the structure deformations, and \( A \) the bar cross section. This relationship was already used in [4] for the position control of this robot. It has to be noted that \( \xi \) is related to \( \sigma \) through

\[
\xi = \frac{\pi}{4} - \frac{\sigma}{2}
\]

And for the reference systems used (Fig. 2) and just for the force control development we can make the approximations \( F_x = F_{\phi}, F_y = F_{\phi}, \text{ and } F_z = F_{\rho} \)

4. COLLISION MODEL

The transference function relating the contact force at the robot tip \( F \) with the motor torque \( \Gamma \) was obtained in [4] for the one-degree-of-freedom robot and it was:

\[
F(s) = \frac{-K \cdot L}{J \cdot s^2 + 2 \cdot v \cdot s + K \cdot L^2} \cdot \Gamma(s)
\]

where \( J_m \) stands for the inertia at the motor, \( v \) for the viscous damping at the motor shaft, \( E \) for the bar Young modulus, \( I \) for the inertia moment of the bar cross section, \( K \) for the bar stiffness, and \( L \) for the bar length.

\( \Delta \theta_{\text{nc}} \) stands for the increment (hence the symbol \( \Delta \)) of the motor angle from the one at the contact.

On the other hand, the mechanism used in our three-degrees-of-freedom prototype (first presented in [2]) has some dynamical advantages. First, there does not exist torque coupling between the actuators. That means that the torque from a motor does not produce a reaction torque on any of the other two motors, which simplifies the control. Second, the mechanism actuates orthogonally over the tip load so that actuators never work in opposition with one another in the way that is usual in conventional robots.
This way we can assume that the whole robot structure has the equivalent transfer function (9) for every given position an for each motor at a time. Now \( K \) stands for the equivalent stiffness of the whole structure and \( L \) becomes equivalent to the radial coordinate of the tip. This means that we have different transfer functions for each motor and for each specific robot configuration which would make infinite of them. However we will show in further communications that it is possible to develop a set of robust robot controllers for the contact whose performance would be acceptable for a good range of positions.

5. COLLISION DETECTION

A method was developed in [4] for the free movement control of the three-degree-of-freedom flexible arm. This control was based on the information generated by strain gauges placed at the robot structure. Now it is necessary to develop a collision detection mechanism reliable enough to be able to switch between this controller and another one to be developed for the control of the robot when in contact with the environment. A previous analysis was carried out in [3] for the one-degree-of-freedom flexible arm, also based on the information provided from strain gauges. Here we are going to extent that method for its use in the new three-degrees-of-freedom arm.

We take as \( \theta_i \) the set of motor angles that the robot would need to get the desired tip position provided that its structure was rigid. This way it is possible (as was done in [3]) to calculate this angular tip position of the arm \( \theta_i \) from the gauges and encoders signals as:

\[
\theta_i = \theta_m + R \cdot \gamma
\]  

(14)

where \( R \) stands for the matrix that relates the tip displacement due to the structural deformation expressed as gauge measures with the motor angles needed to compensate them. This matrix can be easily obtained from the relations introduced in [4] for their use in the tip position control; which can be the one used in [9], once adapted to the gauges signals as in [4].

Therefore it can be deduced the existence of collision when:

1) The angular position of the arm tip differs from its reference more than a given threshold value \( \lambda \).

\[
|\theta_i - \hat{\theta}_i| > \lambda
\]  

(15)

This condition was already analyzed in [3] for the one-degree-of-freedom flexible arm and it was found that the required signals were highly affected by noise so that the filtering process was critic.

2) The tip velocity modulus approaches zero more that a given threshold value \( \zeta \).

3) The tip angular velocity \( \dot{\theta}_i \) differs from its reference \( \hat{\theta}_i \) more than a given threshold value \( \varepsilon \).

\[
|\dot{\theta}_i - \hat{\dot{\theta}}_i| > \varepsilon
\]  

(17)

The angular velocity can be obtained as the time derivative of \( \theta_i \). This means that \( \dot{\theta}_i \) can be very affected by noise notwithstanding the previous filtering of the gauges signals. However, an appropriate combination of the three previous conditions and their thresholds \( \lambda, \zeta \) and \( \varepsilon \) lead to a very accurate detection.

As \( \theta_i \) is being calculated it is possible to determine the exact position of the impact surface, and with further calculations it will be also possible to determine its direction. We will find this useful in the future development of the position/force controller, even more so when it has to contemplates the possibility of sliding.

6. SIMULATED EXPERIMENT

This collision detection method has to be used together with a force controller which is under development and that will be the object of further communications. This way it would be possible to shift from the position controller to the force controller by using the collision detection mechanism presented above.

The collision detection mechanism has been implemented in the prototype but safe experiments can not be carried out without first discussing the force controller.

In order to analyze the performance of the collision detection mechanism it has been necessary to introduce our system into a complex simulation system capable of dealing with the flexible links of our robot. Here we have used the Adams™ simulation package where our prototype gets the appearance shown in Fig. 4.

![Fig. 4: Simulated flexible robot.](image)
For the experiment the first motor of the robot ($\theta_1$) rotate 0.2 rad in 1 sec, making the robot collide with a surface when the tip angle reaches 0.15 rad while the two other angles remain $\theta_2=0$ and $\theta_3=\pi/2$.

The robot stiffness for this position is considered to be $K=275$. In order to allow the convergence of the simulation the system switches to a rough force controller when the collision is detected. The controller used is a simple PID controller with a zero in -2.8, a pole in -10, and gain of $K_c=1$, this controller is used for a reference force of 10 Nw.

The threshold values used for the experiment are $\lambda=0.004 m$, $\zeta=0.1 m/sec$. For this specific experiment the value of $\varepsilon$ is not relevant.

The simulation showed that the collision could be detected at the time $t=0.67$ sec when it happened a $t=0.63$ sec, which gives a detection time of $t_d=0.04$ sec. This way the collision forces are the ones shown in Fig. 5. This figure shows how a better force controller would be desirable, however the simulation was carried out for a contact surface of infinite stiffness and a perfectly elastic collision, in the real system a better performance is to be expected, even for this rough controller.

![Fig. 5: Tip force at the simulation.](image)

The fast and accurate collision detection can be easily understood by looking at the tip velocity evolution shown in Fig. 6.

![Fig. 6: Tip velocity at the simulation.](image)

7. CONCLUSIONS

The possibility of performing the position control of the three-degree-of-freedom flexible robot by using strain gauges was analyzed in [4].

In this paper we analyze the possibility of detecting a collision of the robot with the environment as a further step towards the position/force control.

Results obtained by simulating the system show a good performance of the mechanism (a simplified version was first introduced in [3]), which will allow us to begin the development of a new force controller.

8. REFERENCES