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STUDY OF THE USE OF A COMPLIANT ELEMENT FOR IMPROVING THE CONTROL FORCES FOR INDUSTRIAL ROBOTS

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Abstract. *Additional forces and moments are necessary on robot joints to perform displacements for robotic tasks requiring contact with the environment. If these forces and moments on end-effector are not controlled properly, the end-effector may fail to accomplish the task satisfactorily or damage itself. The use of robots for the tasks requiring contact with the environment is limited due force/moment sensors generally producing noisy signals. This paper proposing a solution to improve the performance of closed-loop force control strategy applied on a serial industrial robot. A compliant element is used between the end-effector and the force/moment sensor to minimize the noise in force control. However due to compliant element there occur a buffer between the desired goal and the actual one and it is necessary to compensate this buffer. An online path planning is developed for repositioning the robot, according to the forces and moments applied on end-effector which is used to compensate the buffer due to the compliant element. The proposed solution is developed in a 3R planar robot using its kinetostatic model with the dynamical model of the compliance. As a result, the robot joints trajectories compensating the forces/moments applied on end-effector are shown graphically.*

Keywords: *force-control, path planning, robotics*

1. INTRODUCTION

Robotics was created to handle dangerous materials without exposing the workers to risks. Thus, mechanical manipulators "master-slave" were created. Later, these manipulators were improved with the inclusion of electric motors. (WHITNEY, 1987).

Once the manipulators were improved, they started to be used in several areas, although their focus have been kept in repetitive activities, previously programmed into the manipulators and without environment interaction. According to the Robot Institute of America (RIA), a robot is "a reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed functions for the performance of a variety of task". (SCIAVICCO; SICILIANO, 1996).

According to Acevedo (2012), most manipulators are inspired by the human arm functionality, and its function are to provide solutions in the industry such as increase productivity, reduce costs and improve the quality of products. Into the industry, these robots can be used to make cooperation activities, manipulation, and tasks like machining, packaging, welding and assembly. (SCIAVICCO; SICILIANO; 1996).

In accordance with Golin (2002), the control system of a manipulator robot can be represented according to Fig. 1, and it is composed by a control and supervision block, an actuation block and feedback from sensors. The control and supervision block is responsible to send control signs to the manipulator joints, i.e., to plan properly the robot movements. The actuation block is responsible to act the robot joints as was planned by the control and supervision block.

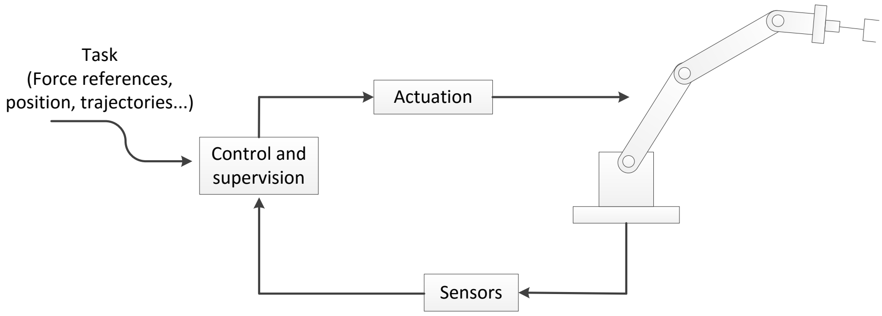

Figure 1. General components of a manipulator robot

Thus, there is a movement in the end effector created by the control and supervision block together with the actuation block. However, for checking possible trajectory errors, it is necessary a feedback with a sensors block. This block makes possible to verify the executed trajectory and provides data feedback in the control and supervision block. Hence, the desired and the executed trajectories can be analyzed and any needed corrections can be determinate.

In this sense, the robot manipulator control is an essential element in order to guarantee that the robot will follow the desired trajectory. Besides, in accordance to Acevedo (2012), the robot manipulator control is important in tasks that require precision in both end-effector trajectory and applied forces.

According to Gorinevsky et al (1997), the use of force data provides good solutions to different problems. One of the simplest uses of force sensors is monitoring the execution of tasks without modifying the robot's movement. It makes possible a safe robot operation. (CRUZ, 2010).

Considering the researches developed in this area and developed in Professor Raul Guenther Robotics Laboratory (LRRG), this paper aims to achieve the force control of an ABB industrial robotic manipulator through information obtained by a force sensor. Additionally, it is intended to use a compliant element acting between the force sensor and the end-effector in order to minimize noise read by the sensor and enable trajectory adjustments. In this way, it is intended to compensate the deformation generated in the compliant element when external forces act on the robot while it performs tasks with environment interaction.

2. FORCE CONTROL ON MANIPULATOR ROBOTS

According to Golin (2002), among the robotics there are some applications in which robots interact with the environment, such as machining. According to Stemmer (2007), the machining process generates forces as exposed in in Fig. 2 and detailed in Table 1.

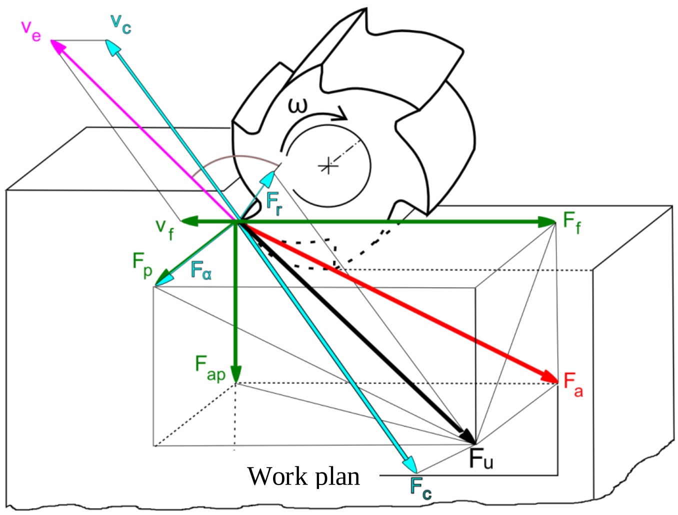

Figure 2. Forces of a machining process

With these forces being generated between the tool and the piece, for this machining process, it is clear that is necessary the control of forces and trajectories, to get a good formed piece at the end of the machining process, with dimensions specified and the manipulator does not suffer or cause some damage.

Table 1. Description of the forces on a machining process.

F_a	Active Force
F_x	Axial Force
F_c	Shear force
F_f	Feed force
F_e	Effective shear force
F_r	Compression force or radial force
F_{ap}	Supporting force
F_p	Passive force or depth force

According to Oliveira (2009), a robot controller performs control by generating signals which are originated from the difference between the desired position and the current position of the system. Some control laws have been developed to enable the iteration between a robot and the environment, though the implementation of these methods needs the robot reaches a certain position and apply a certain force to accomplish the task.

Thus, according to Golin (2002), the force control of robot manipulators involves modeling aspects of the environment as a feedback variable. This makes it possible to classify the control strategies into 4 groups, which are: (Zeng and Hemami, 2007).

- Stiffness Control;
- Impedance Control;
- Parallel force / position control; Hybrid force / position control and hybrid impedance control; and
- Explicit force control.

In the stiffness control the amount of force that the manipulator exerts on the environment is estimated from the position and the middle rigidity and controlling the position of the end effector. Cruz (2010) adds that the force is not explicitly controlled in stiffness control, but indirectly controlled by position control.

In the impedance control, to specify a desired behavior for the end-effector, as a mass-spring-damper system, the indirect control of the robot is held. On this strategy there is no explicit control force loop, you can not specify the force applied to the enviroment. Although not being directly specified the resultant force, the effector movement is given in terms of the contact force. (GOLIN; 2002).

In parallel force / position control there is a parallel control action to a force control action, so you can directly specify the desired force in contact, beyond the trajectory of the position. It is true to say that as the force control takes precedence over the position grid, position errors are tolerated to ensure the regulation of force at a desired level. (GOLIN; 2002).

In the hybrid force / position control, the control strategy is based on the partition of space in directions that control only the force and movement. The directions of the position and force control are given by restrictions of natural calls, where the environment imposes a restriction of position or force to the end effector, and artificial calls where the controller can control only the variables that natural restrictions are not subject. (Sciavicco; SICILIANO, 1996).

. In the hybrid impedance control, the hybrid and impedance control are combined for the greater flexibility in choosing the impedance of the manipulator. Thus it is possible to distinguish the impedance in the direction of force and motion, so that the force trajectory is controlled.

In the explicit force control the actuation force at the end effector is directly controlled, making it possible feeds it to a power control loop causing the drive torques are system outputs. (ZENG; Hemami, 1997).

According Gorinevsky et al (1997), the use of force information provides optimal solutions to different problems. One of the simplest uses of force sensors is monitoring the execution of tasks without modifying the robot's movement, ensuring that the robot can perform a safe operation.

Gorinevsky et al (1997) also emphasizes that information on force is essential for a large group of applications such as milling, deburring, polishing, and others.

In order to use as feedback for the control the forces generated in the manipulator, the JR3 force sensor is used, which can inform to the control system the components of force and moment in the three axes (x, y, z). The sensor can be seen in blue in Figure 3 attached in an ABB IRB140 robot.

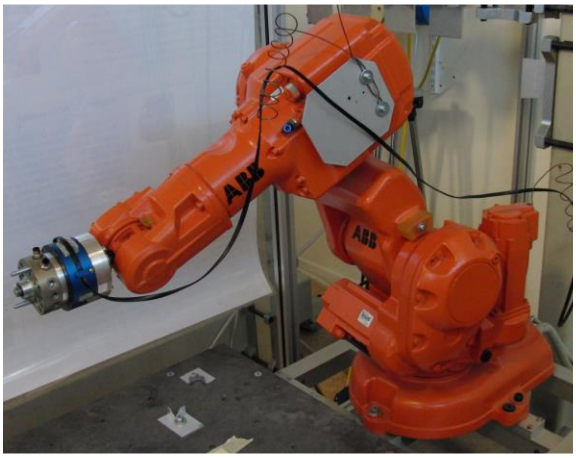

Figure 3. ABB IRB140 robot with JR3 force/torque sensor

With the sensor attached to the robot performing the reading of the acting forces on the manipulator, this work aims to accomplish the robot control through the readings of the forces performed with the JR3 sensor acting on the control position.

3. STATICS OF SERIAL MANIPULATOR WITH COMPLIANCE

Davies (1983) states that static analysis is usually performed based on the solution of the equilibrium equations that characterize the system. As robots are mechanisms that need to be actuated and which have at least one degree of freedom, they need external actions so that the robot has static equilibrium. These external actions can be torques and forces of actuators, robot interaction forces with the environment and gravitational forces. (WEIHMANN, 2011).

Cazangi (2008), said static mechanisms can be resolved using various methods, such as dual quaternions, vector method, dual vector method and Davies method for both the serial and parallel robots.

The static analysis performed on the robot in this work is done taking into consideration the the method presented by Davies (2006), which relates the forces and moments on joints of the robot with the forces and moments applied to the end effector. (FRANTZ, 2015).

Rincon (2015), states that the method proposed by Davies (1983) makes use of knowledge from the Graph Theory for the representation of the mechanism through a graph and get the equilibrium equations by applying the adaptation of the Kirchhoff Cutset Law and Screw Theory. (REIS, 2013).

The representation of a planar 3R robot and both internal and external actions are represented below, as shown in Figure 4a. The joints of the robot are represented by lower case letters (a, b and c), the point of contact with the environment of the robot by letter p and the links with numbers. External actions are represented by the green and red colors while the internal actions by the blue color.

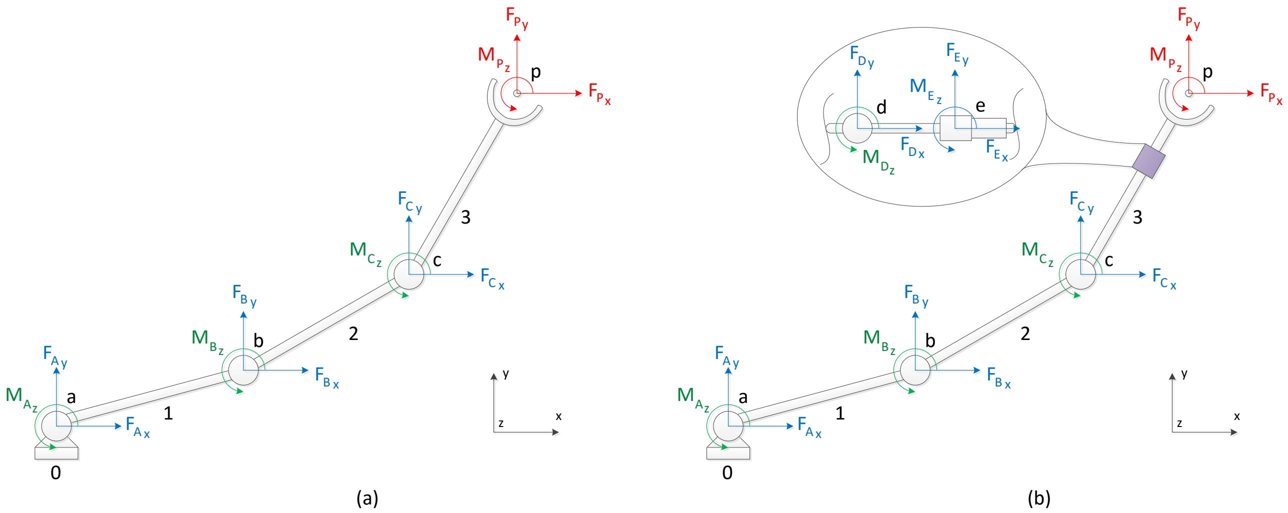

Figure 4. Representation of both internal and external actions on a standard and with compliance 3R planar robot

But in this paper the use of a compliant element for the reduction of noise in reading force / torque on sensor has been proposed, therefore the compliant element used must be considered when calculating the robot statics. As the robot is planar, *ie*, moves only in the x-y plane, the deformation of the compliant element due to the action of forces in the manipulator is a rotation about the z axis and a translation, thus it was modeled as a revolute and prismatic joint, as shown in Figure 4b.

As can be seen from Figure 4b, the 3R robot with the compliant element has 18 restrictions and constraints of a liquid level of restriction equals 3, i.e., the system needs three variables to solve statically the robot.

Thus, the graph of the actions of the mechanism is illustrated in Figure 5, where the wrenches that act at each joint are represented by the symbol $.

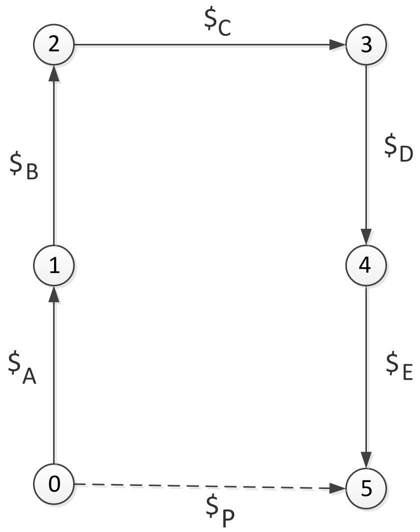

Figure 5. Action graph of the 3R planar robot with compliance

According to the Davies' method it is possible to find the joints torque and the moment on the revolute joint which represent the angular displacement of the compliance by the following equation:

$$\{\vec{\Psi}_S\}_{(\lambda k\times 1)} = -\left[\hat{A}_{N_s}{}^{-1}\right]_{(\lambda k\times \lambda k)}\left[\hat{A}_{N_P}\right]_{(\lambda k\times C_n)}\{\vec{\Psi}_P\}_{(C_n\times 1)} \tag{1}$$

Where Ψs represents the magnitude of the secondary variables, $\hat{A}_{Ns}$ the unit action matrix of the secondary variables $\hat{A}_{Np}$ the unit action matrix of the primary variables, Ψp represent the primary variables, Cn the liquid degree of restriction, k the number of graph cuts and λ the robot workspace.

Applying Equation (1) to find the torques on the joints a, b and c of the robot when applied over the joint d which represents the angular variation of the robot compliance, the Equation (1) can be rewritten as:

$$\begin{bmatrix} M_{d_z} \\ M_{a_z} \\ M_{b_z} \\ M_{c_z} \end{bmatrix} = -\begin{bmatrix} eq_1 & eq_2 & eq_3 \\ eq_4 & eq_5 & eq_6 \\ eq_7 & eq_8 & eq_9 \\ eq_{10} & eq_{11} & eq_{12} \end{bmatrix} \times \begin{bmatrix} F_{P_x} \\ F_{P_y} \\ M_{P_z} \end{bmatrix} \tag{2}$$

With this, you can find the torques required in the joints of the robot and the moment acting on the revolute joint that represents the angular displacement of the compliant element. By applying Hooke's Law, you can calculate the angular displacement of complacency which corresponds to the applied rotation on the revolute joint d as shown in Equation (3).

$$M_{d_z} = K\Delta_\theta \tag{3}$$

Where K is the elastic coefficient of the material used on the compliant element of the robot. Isolating Δθ you can find the angular displacement of the compliant element according to the moment applied to it. Similarly to the angular displacement, the linear displacement can be found according to Equation (4).

$$F = Kx \tag{4}$$

Where isolating x in Equation 4, the linear displacement is obtained represented by the prismatic joint and in Figure 4b.

4. NOISE REDUCTION WITH THE USE OF A COMPLIANT ELEMENT

According to Yüksekkaya (2010), it is common to face noise problems during the measurement and processing of the signal digitally, because the noise could appear from many different sources, with different characteristics and affecting the measurement systems.

As proposed on this paper, it is used a JR3 force/torque sensor attached on the robot arm, which reads the force and torques on the robot manipulator, but the signal of the reading is noisy, so this work propose the use of a compliance system attached to the force/torque sensor to attenuate the noisy read by the sensor.

The linear movement of the compliance system can be simulated as a spring-mass-damper system, as shown on Figure 6.

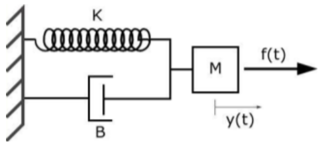

Figure 6. Spring-mass-damper system

Where K is the spring coefficient of elasticity, B is the absorber damping coefficient, M is the mass of the system, f(t) is the force applied by the enviroment on the compliance and y(t) is the displacement of the compliance due to the forces applied on the mass.

Appling this concept to the problem in question, the dynamic model of the robot system was modelled as shown on Figure 7.

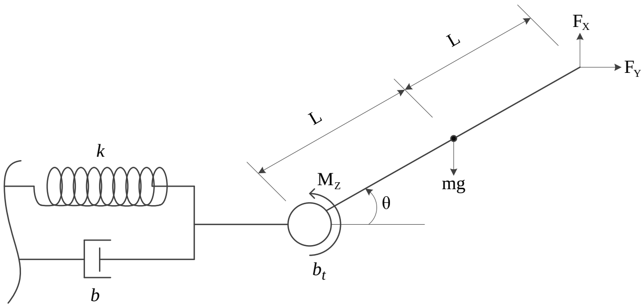

Figure 7. Compliance dynamic model

According to Figure 7, the spring-damper simulates the linear displacement and the torsion spring simulates de angular displacement of the compliance.

The dynamic model of the system shown on Figure 7 is shown on the Equation 5:

$$\begin{cases} I\ddot{\theta} + b_t\dot{\theta} + k_t\theta = L\left(F_y cos(\theta) - F_x sin(\theta)\right) + Lsin(\theta)(-kx - b\dot{x}) \\ m\ddot{x} + b\dot{x} + kx = mL\left(cos(\theta)\dot{\theta}^2 + sin(\theta)\ddot{\theta}\right) + F_x cos(\theta) + F_y sin(\theta) \end{cases} \tag{5}$$

As the compliance element is too small if compared to the robot dimensions, the deformation is only related to small quantities, so considering angles very close to 0 and isolating the desired forces, the system can be linearized and simplified as shown on the Equation 6

$$\begin{cases} I\ddot{\theta} + b_t\dot{\theta} + k_t\theta = F_y L \\ m\ddot{x} + b\dot{x} + kx = F_x \end{cases} \tag{5}$$

So, both transfer functions can be easily found after the linearization, and can seen from the Equation (8), we have a second order system, which through the Bode Diagram the cutoff frequency can be obtained, which proves that the compliance reduce the noisy signals read by the force/torque sensor.

5. READJUSTMENT OF THE ROBOT TRAJECTORY

Due to use of a compliant element there occur a buffer between the desired goal and the actual position of the manipulator, so using the Hooke's Law for displacement, the statics shown on section 3 and the inverse kinematic of the robot, the buffer is readjusted to the initial target.

The Figure 7 show the initial configuration of the robot without forces/moments acting on it.

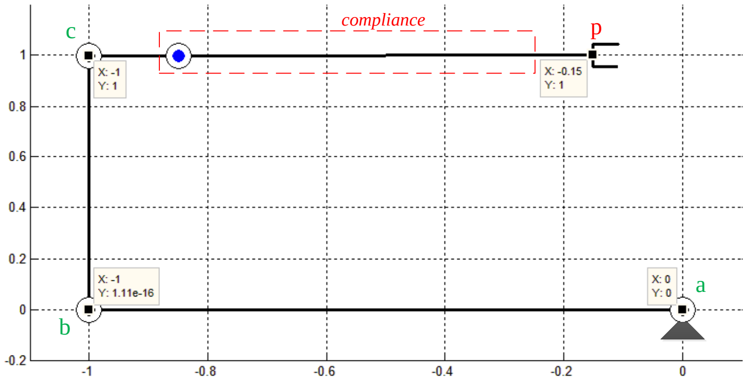

Figure 7. Initial configuration of the robot without the action of forces

As we can see on Figure 7, the desired position of the robot is the position (-0.15, 1) and the joints a, b, c where located on the positions (0, 0), (-1, 0) and (-1, 1) respectively.

Simulating forces of 150N and -150N acting on the x and y axis respectively and the spring constant being 2.5kN, the deflection of the manipulator is compensated and the new joints positions in order to achieve the desired position (-0.15, 1) were calculated, as shows Figure 8.

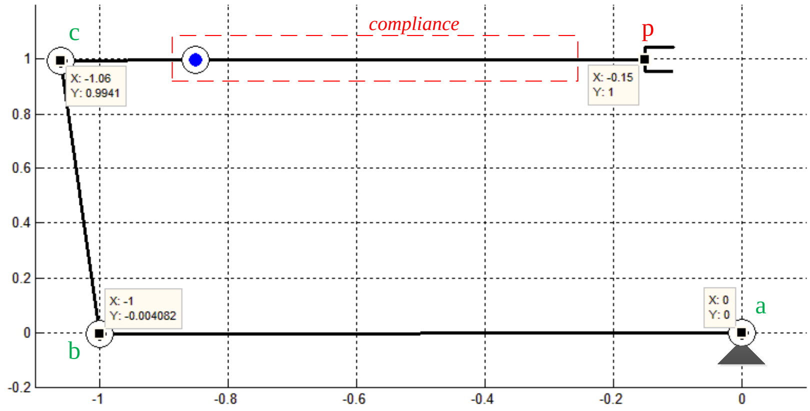

Figure 8. Robot repositioning due to forces applied on the end-effector

6. CONCLUSIONS

The work presents a solution to reduce the noisy on the readings of the force/torque sensor attached to the manipulator's arm by using a compliant element. To compensate the deflection imposed on the compliant element by the forces applied on the end effector the statics and the Hooke's Law was used to calculate de deflection and compensate it using the inverse kinematics

In order to illustrate the results, a case using a 3R planar robot was presented and the work can be extended to spatial cases considering torsion, axial displacement and deflexion.

The results of this work can be used on tasks which requires accuracy and interaction with the environment such as machining, drilling, etc.

7. ACKNOWLEDGEMENTS

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