ROBOT FORCE CONTROL METHODS

METODE UPRAVLJANJA SILOM KOD INDUSTRIJSKIH ROBOTA

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REZIME
Robotski manipulatori se najčešće koriste u industrijskim primjenama za izvršavanje brojnih praktičnih zadataka. Veoma bitan dio izvršenja praktičnih zadataka jeste interakcija između robota i okoline. Kontrola navedene interakcije je od krucijalne važnosti za uspješno izvršenje industrijskih procesa. Tipične praktične primjene robota su sljedeće: ravnanje, mašinska obrada, sklapanje, poliranje, zavarivanje i dr. Glavni problem se svodi na odgovarajući izbor strategije upravljanja kontaktnom silom između robota i okoline. Postoje dvije osnovne metode upravljanja silom:

- *Indirektna metoda upravljanja silom*
- *Direktna metoda upravljanja silom*

Osnovni cilj ovog rada je da ukratko predstavi navedene metode te da eksperimentalnim putem utvrdi maksimalne kontaktne sile koje se javljaju prilikom izvršavanja zadataka u zavisnosti od konfiguracije i brzine kretanja robotske ruke.
Eksperimentalni dio rada je izvršen na robotskom sistemu FESTO RV2AJ pomoću piezoelektričnog dinamometra KISTLER 5070. Rezultati mjerenja su prikazani tabelarno i grafički, nakon čega je izvršena analiza rezultata. Na osnovu analize rezultata donešeni su određeni zaključci koji ukazuju na važnost upravljanja robotskom silom za uspješno izvršenje praktičnih zadataka.

Professional paper

SUMMARY
Robot manipulators are usually used in many industrial apllications where a number of practical tasks should be executed. The very important part of that execution is interaction between robot and environment. Control of the interaction is crucial for successful execution of industrial processes. Typical applications include deburring, machining, assembly, polishing, welding and others. The main problem is to find or to choose a proper strategy to control contact force between robot and environment. There are two basic methods of robot force control:

- *Indirect force control*
- *Direct force control.*

The main content of this paper is a brief description of these methods and experimental determinatiom of maximal contact forces, depending on the configuration and the speed of the robot arm
Experimental work has been done using robotic system FESTO RV2AJ with the help of piezoelectric dynamometer KISTLER 5070. The results of measuring are presented and analyzed by table and graphic. According to results of analysis the proper and useful conclusions are made which are pointing on the importance of robot force control for successful execution of practical tasks.

1. INTRODUCTION

Robot force control is one important issue for the assurance of the quality of final product for given task. Robot contact force is a force of interaction between an end-effector and environment. The model of manipulator and environment is very important to be known for the purpose of precise execution of given task. The basic methods of robot force control are presented in this paper. Indirect and direct force control are two basic methods of robot force control. First one is based on impedance and compliance control. On the other hand, the second one is based on force error between desired and measured value. Also, the results of executed experiment are presented and discussed. The purpose of that experiment is measuring of maximum contact force between an robot end-effector and environment, where the RV2AJ robot system is used. Important parameters for that experiment are motion velocity and position of robot end-effector. The results of experiment are analyzed and shown in graphic presentation.

Robot systems in industrial applications have been in use over 50 years. The first industrial robot was used for handling operations in General Motors facilities. Nowdays, many different applications can be done by robots. As a result of that, sensors system is a crucial part of robotic cell. Without sensors many applications would not be so easy to execute. Sensor can be mounted on different parts of robotic cell. The main reason why the sensors in robotic applications are used, is to have feedback information about influential parameters such as value of force and torque, temperature, vision, presence of obstacle and others. These parameters are necessary for successful execution of practical tasks [5, 2, 3].

2. ROBOT FORCE CONTROL

Interaction control strategies can be classified into two gropus [2, 3]:

- Indirect force control
- Direct force control

2.1. Indirect force control

Indirect force control is usually used in case when the geometry of environment is known with less precision. It is used to ensure a proper complain behavior during interaction between robot and environment. Thereby, compliance and impedance control are introduced as an effective tools for indirect force control strategy [2, 3].

In the case of compliance control we need to mention passive and active compliance control. The term compliance in industrial robotics refers to flexibility and suppleness. To define what compliance is, we need the definition of non compliance. A non-compliant (stiff) robot end effector is a device which is designed to follow predetermined positions or trajectories, no metter what kind of external force is exerted. On the other hand, compliant robot endeffector can reach several positions and exert different forces on a given object[5].

Passive compliance is appliedduring the setup of the robotic cell and it will stay active in background for purpose of safety. Examples of passive compliance are: torque limitation device on end effector, or joints. Also, it can be collisiondetector to preventcollisions which can be harmful for robotic cell [5].

Active compliance is setup by user and will vary for different applications. Examples of active compliance are different types of sensors such as vision, force, torque sensors [5].

So, in case of no null contact force and moment, an active compliance is applied to gain compliant behavior of robot end effector [2, 3]

Compliant behavior of end effector refers to position and orientation of end effector as it is described in equations 2.1. and 2.2., respectively: [2, 3]:

$$\Delta p_{de} = K_p^{-1} f \qquad (2.1.)$$

$$\Delta \varphi_{de} = K_{p_o}^{-1} T^T(\varphi_e)\mu \qquad (2.2.)$$

Δp_{de} and $\Delta \varphi_{de}$ represents compliant position and orientation, f and μ represents force and moment, K_p^{-1} plays a role of active compliance. According to 2.1. and 2.2. it can seen that compliance control is designed for static behavior of the interaction [2, 3].

On the other hand, impedance control is designed for dynamic behavior of interaction. A robot under impedance control is described by one equivalent mass-spring-damper system. So, beside the stiffness, impedance control consider actual mass and damping at the contact. An active impedance is described with equation 2.3.: [2, 3]

$$\Delta\ddot{x}_{de} + K_D\Delta\dot{x}_{de} + K_P\Delta x_{de} = H^{-1}(\varphi_e)J(q)B^{-1}(q)J^T(q)h \qquad (2.3.)$$

Equation 2.3. establishes a relationship through a generalized impedance between contact force and moment h and the end effector position and orientation Δx_{de}. [2, 3]

2.2. Direct force control

In the previous chapter an indirect force control of contact force has been presented. Indirect force control in basic consists of compliance and impedance control [2, 3].

On the other hand, direct force control is quite different approach of force control. Direct force control operates with force error between the desired and the measured value [2, 3].

Thereby, strategy of direct force control consists of several approaches such as force regulation, force and motion control and force tracking [2, 3].
Force regulation in basics operates with the static and dynamic model of behavior [2, 3].
Static model of force regulation is described through desired contact force and moment which refers to proper position and orientation of end effector. That is shown in equations 2.4. and 2.5., respectively [2, 3]:

$$\gamma_p = K_{p_p}\Delta p_{ce} + f_d \quad (2.4.)$$

$$\gamma_o = T^{-T}(\varphi_e)K_{P_o}\Delta\varphi_{ce} + \mu_d \quad (2.5.)$$

Dynamic model is described through the linear and angular accelerations shown respectively in equations 2.6. and 2.7 [2, 3]:

$$\alpha_p = -K_{D_p}\Delta\dot{p}_e + K_{P_p}\Delta p_{ce} \quad (2.6.)$$

(2.7.)

Force and motion control are based on idea of parallel control. Parallel control consists on composing compliant position with desired position of robot end effector. That is shown in equation 2.8. [2, 3]:

$$p_r = p_c + p_d \quad (2.8.)$$

$$\alpha_o = T(\varphi_e)(-K_{D_o}\Delta\dot{\varphi}_e + K_{P_o}\Delta\varphi_{ce}) + \dot{T}(\varphi_e,\dot{\varphi}_e)\dot{\varphi}_e$$

Force tracking approach consists on control stiffness adaptation. It has been shown that the actual value of stiffness does influence on transient behavior during the interaction [2].

2.3. Industrial robots sensors

In the industrial world, machine, robots needs proper systems for successful execution of practical tasks. A lot of sensors can be added to different robots systems to increase their adaptibility. Sensors provide required information which is needed for proper robot force control. There are different types of sensors such as 2D and 3D vision, force/torque sensors, collision detection sensors, safety sensors, tactile sensors and others [4].
2D and 3D sensors work as video camera used for detecting movement or localization of an object. Force torque sensors detect different values of force and moment [4].
Collision detection sensor is used for detecting different types of obstacles in robot working area. The main application of these sensors is to provide a safe working environment for human workers. Safety sensors in industrial applications are mounted on collaborative robots to protect human workers. Examples of sensors are shown in Figure 1 [4].
Tactile sensors are used for force detection and they are mounted on a gripper of an robotic arm [4].

3. EXPERIMENTAL WORK: MEASURING AND ANALYSING OF MAXIMAL CONTACT FORCE ON ROBOTIC SYSTEM FESTO RV2AJ

Experimental work consists of measuring of the maximal contact force between robot end effector and an object from environment. Measuring is executed on robot MITSUBISHI FESTO RV2AJ. Basic specifications will be presented later. The device which is used for force detecting is piezoelectric dynamometer 5070 as a part of Kistler equipment.

Kistler dynamometer 5070 is 3-component dynamometer for measuring three orthogonal components of force. The dynamometer has a very good rigidity which is good condition for precise measuring. Also, it is universal aplicable but the most suitable for cutting force measurement.

An contact object is placed on dynamometer as it is shown in Figure 2. Object of manipulation or contact object is anprizmatic steel rod with cross section 20x25 mm.

Figure 1. *Different types of sensors: force/torque, vision and tactile.(from left to right) [4]*

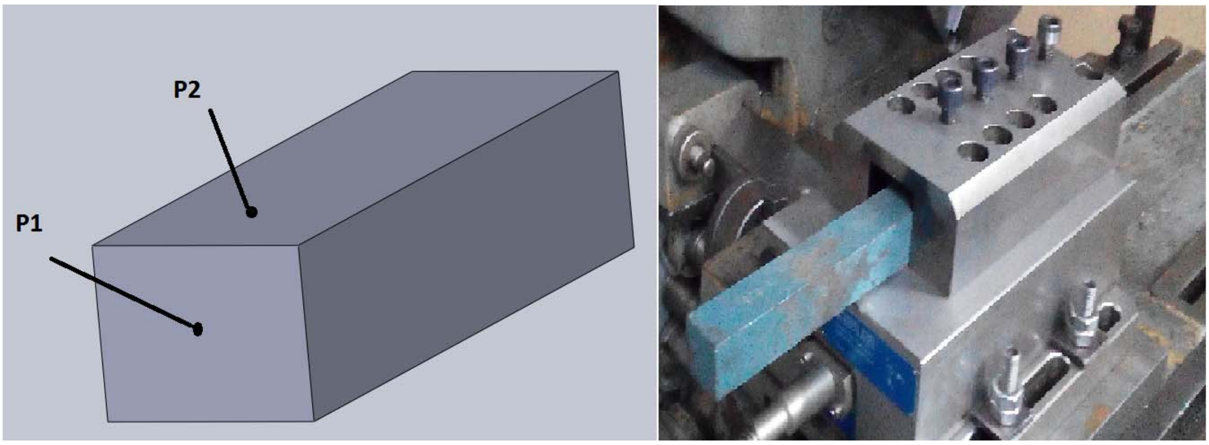

Figure 2. *Kistler dynamometer with contact object mounted*

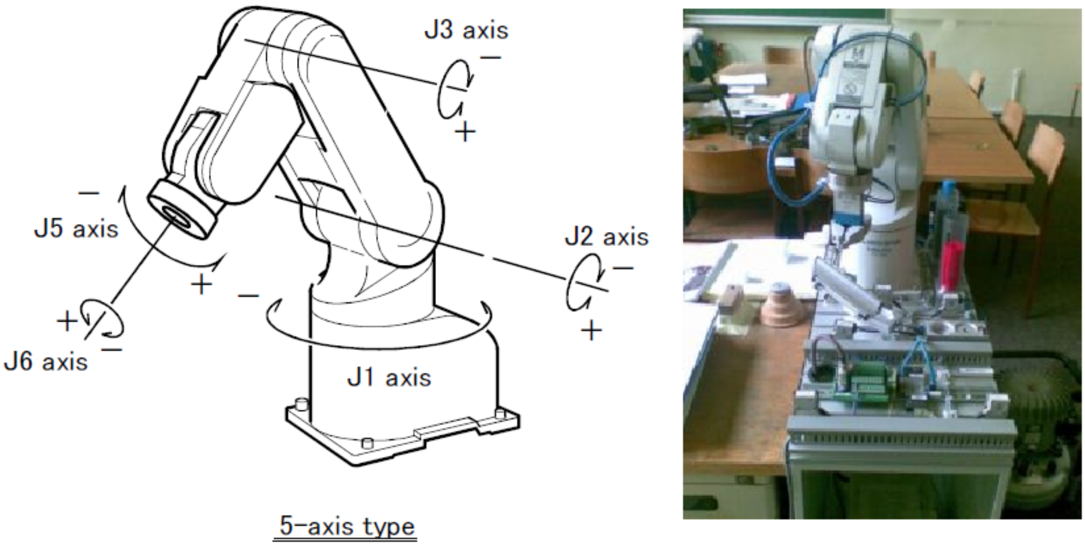

Figure 3. *Mitsubishi festo RV2AJ*

The basic specifications of MITSUBISHI FESTO RV2AJ shown in Figure 3.:

- Motion degrees-of-freedom: 5
- Motor drive: AC servomotor
- Position detection: Absolute encoder
- Maximum load capacity: 2 kg
- Arm lenght: 250+160 mm
- Maximum radial reach: 410 mm
- Weight: 17 kg.

The main objective of experimental work is to detect and analyse contact force between robot and object. The simple program is made in MELFA-BASIC software for robot programing. According to that program, robot arm should achieve an contact with object in two points P1 and P2 as it is shown in Figure 2. Important parameters are maximum and minimum distance which robot can reach to achieve contact with points P1 and P2. Also, the experiment is executed with three different values of speed v_1, v_2 and v_3. The results of measuring are shown in Table 1.

P1max, P1min, P2max, i P2min represents different position of robotic arm for two contact points P1 and P2 (Figure 5). The graphic results of experimental work will be presented in the figures below (Figure 6. and Figure 7). The device which is used as a contact element between end effector and object is an cone element shown in Figure 4.

Table 1. *Results of contact force measuring*

	P_{1max}	P_{1min}	P_{2max}	P_{2min}
v_1=5 mm/s	930 N	323 N	360 N	400 N
v_2=10 mm/s	928 N	325 N	360 N	400 N
v_3=20 mm/s	925 N	327 N	360 N	400 N

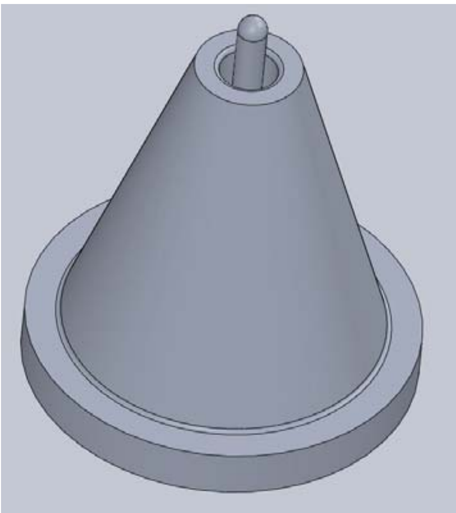

Figure 4. *Contact device between robot and object*

Figure 5.*P1max, P1min, P2max, i P2min robot arm positions*

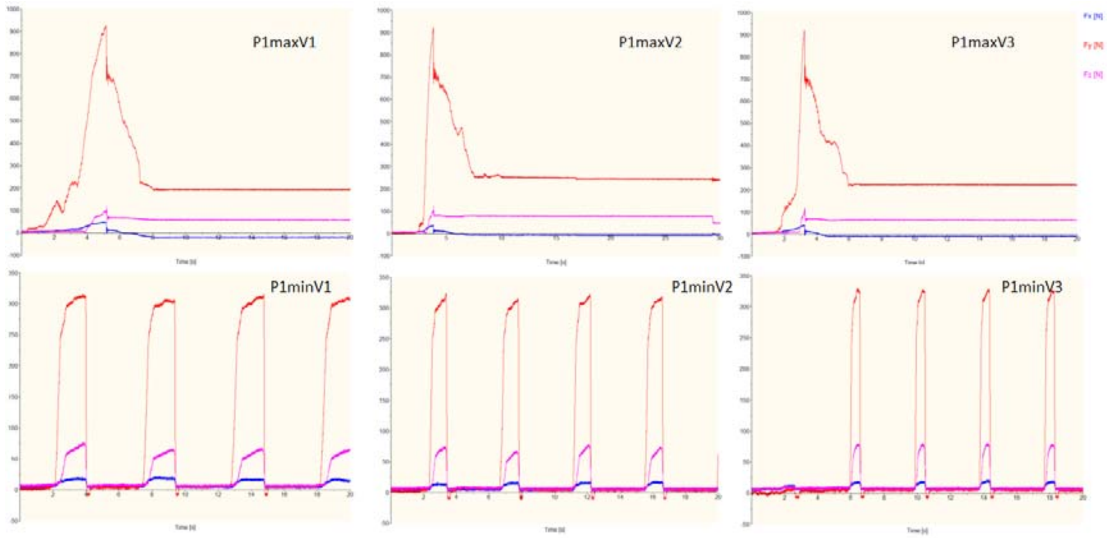

Figure 6. *Results for case of P1max and P1min*

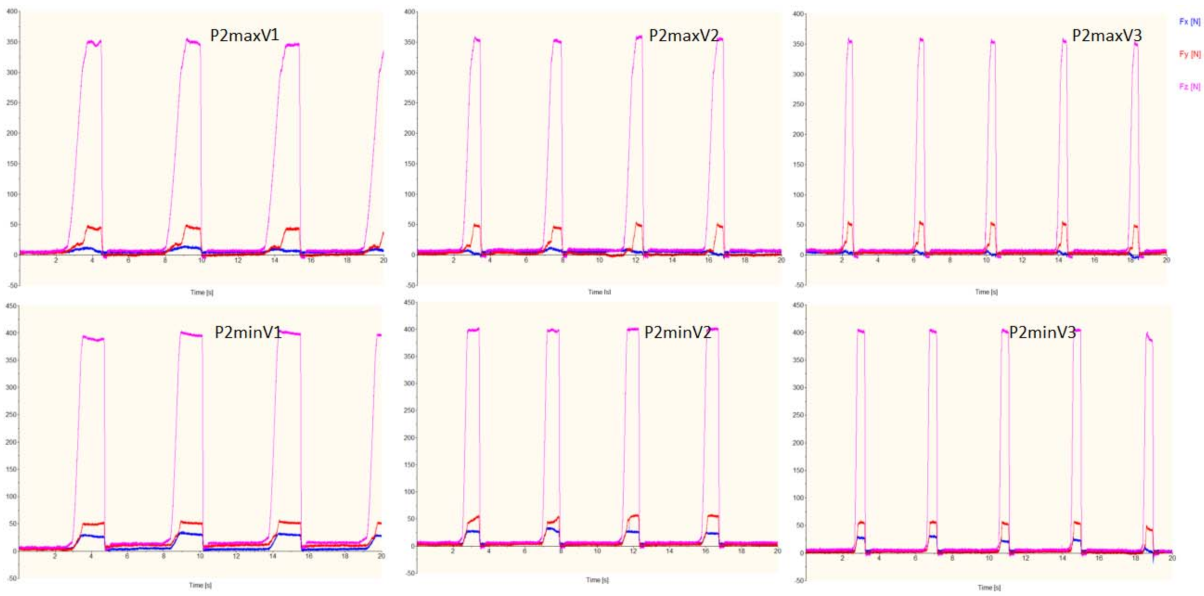

Figure 7. *Results in case of P2max and P2min*

According to results shown in Table 1., and graphic results shown in Figure 6. and Figure 7., several conclusions can be made:

- Maximal contact force measured on RV2AJ is much greater then the maximum load capacity.
- The value of measured contact force does not change significantly with the variation of velocity.
- By the increasing of the value of velocity, the frequency becomes greater and the period of single force cycle becomes shorter.
- By varying robot arm position from P1max to P1min and P2max to P2min the value of contact force becomes different as it is shown in Fig 8., FR1>FR2 for P1max and P1min, FR2>FR1 for P2max and P2min.

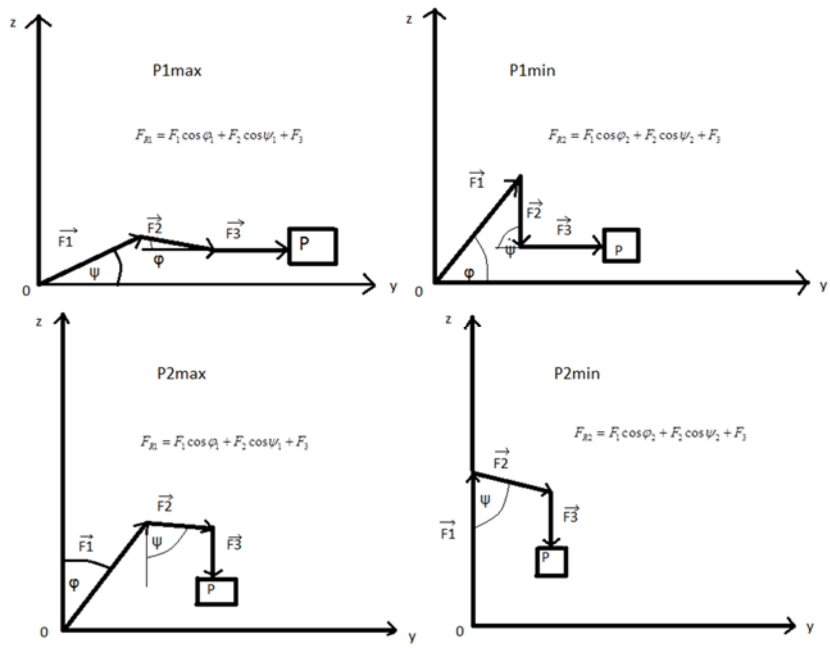

Figure 8. *Analysing the result value of contact force through graphic describing*

4. CONCLUSION

Robot force control is one important issue in industrial robotic applications. The usage of different methods of force control is necessary to achieve required final results of practical tasks.

Indirect force control is used in case of less known geometry of environment and consists on compliance and impedance control.

Direct force control consists on force error between measured and desired value of contact force.

Sensors system is important part of robotic cell and it is necessary for achieving required results. The most important role of sensors is feedback information that sensors give to robot and user. Also, sensors are important for human workers safety.

Without adequatly force control it would be impossible to solve complex situation in industrial robot applications.

By the design of a system for robot force control it is very important to know the maximal contact forces that occur in the robotic cell. Therefore, a set of experiments was conducted, which showed that the maximal contact force is much greater then the maximum load capacity. The maximal contact force also depends on the configuration of the robot arm and on the force direction. The speed of the robot arm does not influance the maximal contact force significantly.

5. REFERENCES

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