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REVIEWS - LETTERS - REPORTS

FORCE CONTROL OF INDUSTRIAL ROBOTS: A CONCISE REVIEW

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Since the beginning of 80-ties of the past century many papers and some reviews have been published on the present state of robot force control with industrial robots. Most of these articles paid no attention to the way of the implementation of algorithms, only few of them could show experimental results, and most of them showed just simulation results. This article will give an overview of possibilities to implement the robot control with some serially produced industrial robots, and of the conditions under which this kind of control is possible and which robots are developed to implement it.

K e y w o r d s: industrial robots, force control, force/torque sensors

1 INTRODUCTION

The force control of robots has to do with robots functioning in contact with their working environments. There is a high demand for robots with this capability. We can think of assembly, deburring, or grinding, to mention just a few of possible applications.

The force control of robots is the object of intensive research since the beginning of the 70-ties of the last century, which continues until the present time with somewhat lower intensity. This research was probably most intensive in the 80-ties. In this period of time well known force control techniques have arisen, e.g., hybrid force and position control and impedance control. Corresponding to this situation was the high number of publications concerning this topic. Since that time some review articles have been published which tried to sort out the attained results [7,10,11,12]. Most of these publications were theoretically oriented and their results were verified by simulation. They have only rarely taken into account the available technical means of existing robots, e.g., the structure of their servo systems. Besides, serially produced industrial robots did not give the possibility to implement developed algorithms as their architectures were not open to the user. Practically oriented researchers built their own robots and control systems. Some of them dealt with this problem in such a way that they built their own control systems over the existing industrial manipulator and power electronics and thus gained an open control architecture. The second way was very popular at some German universities, the manipulator being one of Siemens Manutec r2, r3 or r15 manipulators. The up-to-date version of this approach may be demonstrated with STÄUBLI robots. This producer offers the possibility to have access to motor currents under the condition of resigning the guarantee. This access is enabled with the help of a password accepted from the producer.

In parallel with this research the six axis force-torque sensors (FTS) were being developed. Though some specialised industrial firms began producing these sensors quite early, some researchers continued constructing their own ones. From among those firms the following were well established on the market: Barry Wright Corp. and JR3, Inc. in USA, Schunk GmbH & Co. [9] KG, Hitachi Construction Machinery Co., Ltd. etc. All of them with the exception of the first one still produce. The product line of these firms is so wide that special developments are only seldom necessary. Some of the FTS producers cooperate with the producers of robots. JR3, Inc., e.g., [1] co-operates with the producers ADEPT and STÄUBLI AG. The control systems of the latter of both firms is taken over from the first one although they develop their own PC-based control system.

In spite of the developments described above the force control of robots is far from being the standard outfit of modern industrial robots. This can very well document the gap which sometimes exists between theoretical and practical developments. One cannot say, however, that the responsibility is on the side of producers who are too conservative. That would be too simplistic. Requirements of the industrial practice are very stringent and the algorithms are only one small part of them.

2 PRESENT STATE OF FORCE CONTROL IN INDUSTRIAL ROBOTS

The need for industrial robots able to contact its working environment in a controllable and predictable way is quite high. Producers of industrial robots cannot ignore

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this need and they have to offer some solutions. This concerns mainly those producers who want to apply their robots on one of the fields where the controlled contact is necessary. As it is not known to the best knowledge of the authors that any robots producing firm would offer sophisticated force control with their robots, according to our opinion there are just two or three possible approaches how to let the user to work with the force or moment. All of them assume the possibility to connect at least one type of force-torque sensor to the control system of the robot:

- Certain minimum requirements on the force control will be fulfilled on the side of the producer. This may include some rudimentary operations with the force or moment.
- Producer lets the user the possibility open to influence the desired position and/or velocity with readings of force-torque sensor.
- The third possibility consists in combining the two previous ones. Although these requirements are not too tough, only few types of industrial robots can fulfil them.

Few firms, *eg* , ADEPT, STÄUBLI (identical control systems) or KUKA offer the user some possibilities. We would like to present here concisely one solution of the first two firms as an example of an industrial approach. As we have one STÄUBLI robot RX90b equipped with JR3 force-torque sensor, we will present this approach. The common hardware and software determined for the force-torque control of STÄUBLI robots is known under the name AdeptForce [1].

There is the possibility to connect one of JR3 six-axis force-torque sensors with the control system of one of four STÄUBLI robots. These force and torque sensors can provide measurements of three forces in the Cartesian co-ordinate system of this sensor and three moments around the same axes. No other FTS type besides JP3 FTS may be connected with this control system. For the purpose of connecting the sensor there are some boards available according to the desired bus. For VME bus the VME Force Interface Board (VFI) is available. VFI board is mounted in the control system and connects the FTS with VME-bus. Another possibility is given by PCI-bus receiver board, which is provided for control system console PC. This board together with its driver can read, process and visualize the FTS data on the PC monitor. With the delivered dll file also visualisation with MATLAB is possible. Both boards work with 40 Mips Analog Devices DSP, which performs 8 kHz filtering and force and torque vector multiplying with calibration matrix. Five cut-off frequencies of filters may be set in software.

There are seven models of JR3 FTS, all of them have further sub-models with different measurement ranges. In this way one can choose from among 21 FTS sensor types. Their measurement ranges go from 100 N to 1000 N for forces and from 4 Nm to 160 Nm for moments. Their resolution is 1:4000. The choice of a FTS convenient for the particular robot and application is thus no major problem. Some versions of these sensors have also the possibility to perform measurements of three translation and further three rotational accelerations within the same co-ordinate system. These versions of the sensors are thus 12 axis sensors.

Besides the above described force-torque hardware the force-torque software is necessary to perform the desired force-based tasks. (The word "forces" will mean forces and moments in the sequel). Ten special keywords are integrated for this purpose in the programming language V+ used for programming ADEPT and STÄUBLI robots. One of them, FORCE.FRAME, defines co-ordinate frame, force reference frame (FRF), in which forces are measured. Another one, FORCE.MODE, performs one of the two modes of force operations: guarded mode and protected mode, which will be described later. The keyword FORCE.OFFSET lets the programmer to compensate for loads held by the robot so that pure contact forces and moments can be measured. Other keywords play an important role with programming, STATE, *eg* , returns the information about the state of a robot working in the guarded mode - one of two force control modes. SELECT selects one of force-torque sensors if there are several in the system, *etc.*

The guarded move was one of the first force control approaches known. Its basic principle may be expressed in the following way: Move until the contact force reaches some threshold value. This simple open loop control was mentioned in the very first publications on force control [12]. The conditions causing halt can be multiple. On the other hand, the protected mode causes the robot to turn power off and stop when the robot crashes against the environment and the predefined level of force is exceeded. The difference between these two modes consists mainly in the fact the in the second case the power is taken away from servos. To be able to continue, the power has to enabled. In the case of the guarded mode the robot is able to continue working immediately after the crash. There are two threshold conditions for every force or moment: lower and upper thresholds. Three kinds of conditions are used for stops on force: directional, planar or resultant. In the first case the conditions are laid on the force or moment in X, Y or Z direction. The other forces or moments will be ignored. In other two cases only the magnitude of the force or moment but not the direction will be observed in a given plane or in 3D-space. The values are now only positive as just the absolute value is relevant.

This arrangement is very simple but robust. With some degree of invention some application relevant problems may be solved. Major disadvantage of this arrangement consists in big force overshoots after the stop on threshold. In some applications this overshoot cannot be tolerated. More intricate problems, however, corresponding to the true capabilities of modern industrial robots cannot be solved in open loop control. Some kind of force feedback is desired. As with electrical machines the electrical current is proportional to the motor torque and this generates forces and moments of the robot, the motor current feedback would be quite promising. To let the user a free access to electrical currents of the robots is not very safe. We have already mentioned above under what conditions this is possible with STÄUBLI robots. While the forces and moments are so important in some application, the position or velocity is even more important with industrial robots. Velocity oriented force control may be useful in some applications, e.g., in medicine. Therefore, it seems more convenient to introduce the force feedback on position or velocity control level. The full benefit from existing software of industrial robots, which is predominantly position oriented, can be gained with force control on the position level.

3 TRYING TO ENHANCE THE QUALITY OF FORCE CONTROL WITH INDUSTRIAL ROBOTS

The idea behind the position oriented force control consists in utilizing the industrial robot in that state as it is delivered from the producer including guarantee conditions. Other solutions would be of need for additional work with hardware and software and they could require also additional development costs. They could also get into conflict with existing hardware or software.

The basic principle consists in generation (Fig. 1a) modification (Fig. 1b) of desired positions and orientations with readings of force and torque sensors, see Fig. 1 for one-dimensional case (implicit force control).

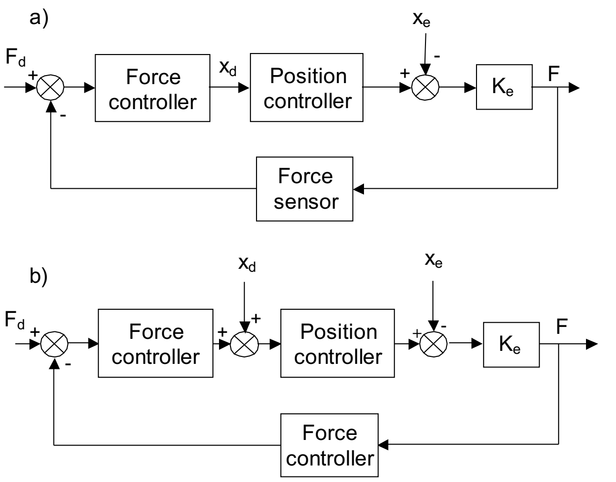

Fig. 1. Basic position-based force control scheme

In Fig. 1, F_d is the desired value of force, x_d is the desired value of position, x is the position, xe is the position of the environment, K_e is the stiffness of the environment and F is the output force. It can be seen that the force control error is generated or modified by the force controller. This approach needs a simple access to the desired value of position. This is not quite a simple matter within the languages of present industrial robots as the path planning does not count with continual modifications of it during the execution. Easier force control with industrial robots would probably require more flexible trajectory planning and its incorporating within the robot programming language. Besides, designing a force controller optimal in certain sense is possible only under the condition that the dynamic properties of underlying position controller are known. Most often the criterion is as high bandwidth of force control loop as possible. The data necessary to optimize the bandwidth are not given by manufactures because of obvious reasons.

In spite of this, certain robots have some restricted possibilities to influence the desired values of translational or angular position. With STÄUBLI, *eg* , the instruction MOVE location may be modified during the execution if it is not followed by another instruction BREAK. In the latter case it is waited until the instruction is completed. In the former case a new value of x_d (Fig. 1) is defined and executed although the influence of the former desired value x_d is still observable. This new value may be computed on the basis of measured forces or moments thus allowing to implement elementary closed loop implicit force control with standard programming means. A similar or maybe even somewhat more flexible possibility of fore control was given with the prototype of assembly robot PR 300, which was built at the end of 80-ties in former Czechoslovakia by co-operation of the state machinery firm ZTS and the Institute of Engineering Cybernetics, Slovak Academy of Science. Unfortunately, although conceptually progressive at that time, this robot could not be serially produced at the end.

Some researchers aware of the important role of the implicit force control in industrial robotics have proposed their solutions [2,3,6,8]. Authors of [2,3,8] propose also hybrid control and authors of [3] impedance control with their schemes. All of them are designed with classical means of control theory. For example, [6] uses the frequency based control techniques, [3] is based on a structure very similar to the Smith predictor and [8] is designed with classical multivariable control theory.

4 FUTURE TRENDS

The idea to control the external forces and moments by means of control of servo motor currents mentioned above has found another implementation with some researchers in the form of integrated torque servos. This idea appeared and was promoted in more research laboratories, we will mention here representatively just the results of the German Airspace Centre DLR [4] who have brought this line of research very far. With the aid of torque servos they have built already the third generation of the so-called DLR lightweight robot. This robot has seven degrees of mobility and can therefore serve as the first approximation of the human arm. With the use of the integrated torque servos they attained the weight of 13 kg and the load capacity very near to this value. Typical power consumption is 100 W. New developments of this robot appear regularly at the Hannover Exhibition of Machinery with big success. Besides special material used for robot construction (carbon fibre) the innovative construction of modular joints including torque servo allowed these exquisite properties.

To achieve such results basic research of components had to be performed. This led, *eg* , to a new construction of the electrical motor different from common commercial motors, position and torque sensors, new brake technologies and new lightweight harmonic drive with 60% weight reduction. In the construction of new joints position and torque sensors are built-in together with necessary electronics. Two position sensors are mounted in an integrated joint: one is mounted with the motor the other one behind the harmonic drive - on the output shaft. On the output shaft also a joint torque sensor is mounted, in the last generation of joints this sensor is strain gage based, in the first generation it was inductive. This sensor measures the output torque of the whole assembly. With these sensors the servo may become position, velocity or torque servo. Each integrated joint is equipped with a DSP processor, which implements the advanced control algorithms. In our context the torque servo is of interest. With this servo various control strategies may be implemented: explicit (or implicit) force control, impedance control or hybrid position and force control. Explicit force control, *eg* , may be implemented in a very simple way by making direct use of Jacobian matrix of the manipulator:

$$\tau = J^{\top}(q)F$$

where $F^{\top} = (F_x, F_y, F_z, M_x, M_y, M_y)$ is the vector of Cartesian forces and moments connected with robot end-effector, $\tau^{\top} = (\tau_1, \tau_2, \dots \tau_n)$ is the vector of joint torques, $\boldsymbol{J}(q)$ is the $6 \times n$ Jacobian matrix of the manipulator and $q^{\top} = (q_1, q_2, \dots q_n)$ is the vector of joint variables. The desired external Cartesian forces and moments are resolved with Jacobian into the joint torques i, which are easily implemented by torque servos. Fig. 2 illustrates this situation.

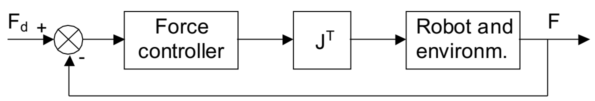

Fig. 2. Explicit force control scheme

Explicit force control is also part of hybrid position and force control in one implementation of this scheme. It can be therefore assumed that also hybrid control schemes are easily implementable although the designers of this robot do not explicitly state it. The torque servo together with computing power render it possible to implement also impedance control schemes, which is explicitly stated by the designers of the robot.

5 CONCLUSION

This article describes how different force control schemes may be implemented with present or future industrial robots. Under the future industrial robots we understand those ones which are already developed but are still not serially produced. Their costs are certainly very high at the moment but one may await that within the time horizon of say 10 years the situation could change. Even with somewhat higher costs the future industrial robots will be economically effective in certain application, *eg* , in space, for which this robot was primarily constructed. However, one has to be cautious with similar statements. In the 80-ties a rather similar situation arose with the boom of direct drive robots and despite of this they are not widely used until the present time.

Until that time and in many applications even after that time implicit force control schemes may serve well. Higher flexibility towards force control implementation in trajectory planning and in the programming languages of serially produced robots would be welcome. Also, the dynamic properties of position control loops of commercial robots should be known to the user or some recommendations should be given by the producer so that the user be able to design and implement implicit force controllers with bandwidth corresponding to the desired application.

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