Impedance Control of an Industrial Manipulator

Jovan Šumarac, Aleksandar Rodić and Kosta Jovanović

***Abstract*—This paper presents an algorithm for implementation and simulation of impedance control for industrial robots.** **Force control has increasingly found its uses in industry as well as been a focus of academic research. Since its proposal in 1984 impedance control has become one of the most studied and applied fields of force control. The goal of this paper was to implement an impedance controller and use it for task space control of an industrial robot with six degrees of freedom. The controller model was realized and simulation was done in Matlab/Simulink with the industrial UR5 robot as a case study. The robot was given tool position and forces as control inputs. Position and force responses are presented using computer simulation; positions were calculated and forces were estimated based on the impedance control law.**

***Index Terms*—Impedance control; Contact force; Industrial manipulator**

I. Introduction

Force control is increasingly applied in modern robotics, and it is gaining further momentum as a result of advances in electronics, computer power, and especially force and torque sensors. It is one of the key technologies for integrating robots into human or unknown environments. Its main advantage is making the robot react as soon as it detects an obstacle, preventing damages to itself and/or its surroundings. It is also used for tasks in which there is interaction between the robot and its environment and therefore it is more important to control the force applied by the end effector rather than just its position. Some examples of such tasks are finishing, welding, drilling and the more sophisticated precision assembly tasks, surgery assistance etc.

On the other hand, the classic position control is still the predominant way of programming industrial robots. Typically, the end effector tool follows a prescribed trajectory in space which has been pre-programmed or "teached" before run-time. This type of control is suitable for routine tasks, in which robot surroundings are completely known and no workspace changes or obstacles are expected.

So other approaches were developed over the years, many focusing on combined control of both position and force. One such technique is called impedance control. Since its proposal by Neville Hogan [1][2], impedance control has become one of the most prominent force control fields and arguably one of the most successful.

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Although it has been researched and used in innovative applications impedance control can be a very complex task to achieve and new studies have continuously been published since its proposal. Authors have applied it to robot human interaction systems [3], systems with collaboration between two robots [4] as well as for simulation of human muscle movements [5]. It shows that this technique and its integration into various robotic systems are still of academic interest.

This paper presents a concise explanation of the impedance control algorithm and its application on an industrial robot. The robot in question is a typical serial manipulator with six revolute joints and six degrees of freedom. The controller and the system were modeled, simulated and the results presented and analyzed.

II. Impedance Control

The hypothesis of paper [1] which originally proposed impedance control is that no controller can prevent the robot from appearing as a physical system to its environment. As a consequence a dynamic interaction between the two must exist. By analogy with electric circuit theory which defines impedance as the voltage/current ratio, mechanical impedance is defined as the ratio between the end effector force and its position. By controlling that ratio the idea is to implicitly control the resistive force of the environment i.e. the dynamic interaction between the robot and the environment. The general strategy is often to control the robot's position as well as to give it a disturbance response in the form of impedance.

The difference between this approach and the conventional position control is that the impedance controller seeks to control the dynamic ratio between force and position instead of independently controlling one of those variables.

As task space (Cartesian) control is a well-developed technique, modelling the environment with dynamic parameters is simplified when done in Cartesian coordinates. The main problem is which control law to adopt. Since linear control has many advantages and simplifies the problem significantly feedback linearization is an appropriate choice. It is applied in this case as a linear control law of the second order modeled on a mass-spring-damper system. It is also a multivariable control law since the controller is applied to a 6 DoF (degree of freedom) robot and so there are $n=6$ control variables. To comply with the given task the desired impedance of the robot end effector is given as:

$$\boldsymbol{M}_d(\ddot{\boldsymbol{x}} - \ddot{\boldsymbol{x}}_d) + \boldsymbol{B}_d(\dot{\boldsymbol{x}} - \dot{\boldsymbol{x}}_d) + \boldsymbol{K}_d(\boldsymbol{x} - \boldsymbol{x}_d) = \boldsymbol{f}_e. \quad (1)$$

Where $\boldsymbol{M}_d$, $\boldsymbol{B}_d$ and $\boldsymbol{K}_d$ are constant, diagonal, positive-definite $n \times n$ matrices representing the desired inertia, damping and stiffness system matrices. Vectors $\boldsymbol{x}_d$ and $\boldsymbol{x}$

represent the desired and actual end effector positions. Vector $\boldsymbol{f_e}$ represents the generalized interaction force between the robot and its environment. The variables are in bold font to indicate that they are matrices and vectors rather than scalar values.

The basic idea of impedance control is that if the robot can follow the acceleration reference given by:

$$\ddot{\boldsymbol{x}}_r = \ddot{\boldsymbol{x}}_d + \boldsymbol{M}_d^{-1}(-\boldsymbol{f}_e + \boldsymbol{B}_d(\dot{\boldsymbol{x}}_d - \dot{\boldsymbol{x}}) + \boldsymbol{K}_d(\boldsymbol{x}_d - \boldsymbol{x})). \quad (2)$$

then it will behave as described by (1). [1][6] So $\ddot{x}_r$ is the reference signal for the acceleration control loop that linearizes and decouples the manipulator's non-linear dynamics. Such a controller will seek to follow the position reference. While the tracking is good, with small position error values the resulting force will tend to return to zero. If the error increases, the interaction force will increase as well, in order to make the controller move the robot in a direction that will decrease the error.

The force vector in (1) can have different interpretations. In case of (1) the controller will seek to minimize any interaction force and that force will be close to zero if the position tracking is good. However if there is a desired contact force value for a certain robot task, then that value can be given to the controller [7]. In that case the force vector would have a value of $\boldsymbol{f_d} - \boldsymbol{f_e}$, the index d signifying a desired value. A practical realization of such a controller would mean having a force sensor that could measure and obtain the actual end effector forces. They could be indexed with s to imply sensor values. In this case the controller would seek to maintain the desired force value.

A key problem of impedance control is calculating the $\boldsymbol{M_d}$, $\boldsymbol{B_d}$ and $\boldsymbol{K_d}$ matrix values. As stated, they represent the modeled environment inertia, damping and stiffness. There is often a great deal of uncertainty when modelling and estimating these parameters. They are usually estimated by estimating one by one matrix, while the rest remain constant [8]. Since these are diagonal matrices similar values are usually used for each direction, or at least one set of similar values for linear movement directions and another for angular. The inertia matrix $\boldsymbol{M_d}$ affects the system's response speed. If lower values are chosen the resulting response will be faster, but it will also result in large tool acceleration values. The opposite is true for larger matrix values. $\boldsymbol{B_d}$ matrix models the system damping and therefore is mostly significant during the transient state. If it were equal to zero matrix the transient response time would be infinite, and the system would be completely undamped. As the matrix values increase the system becomes more damped and the transient time is shorter. Finally $\boldsymbol{K_d}$ models the environment's stiffness and has the greatest influence on the tracking itself. With greater matrix values the tracking is better, and the achieved positions and forces are closer to their references.

However, too large values for these matrices can result in too big acceleration values and compromise the system's stability. That is another very important factor in choosing the matrix values. Looking at (1) it is possible to analyze its transfer function in Laplace domain. The admittance, e.g. the position error-tool force ratio has a transfer function given by:

$$\boldsymbol{W}(s) = \frac{1}{\boldsymbol{M}_d s^2 + \boldsymbol{B}_d s + \boldsymbol{K}_d}. \quad (3)$$

If the parameters of these matrices on the main diagonal are all positive, then those matrices are positive-definite. It has been shown that in that case the controller will be stable too [6]. If the model of the controlled robot is stable as well and the controller matrix values are not too large as to affect it, then the stability of the whole system will not be compromised.

This is the guide to choosing the matrix values. Although some proposed tuning methods and the order of magnitude for these values can be found in literature [4] this tuning process is often based on the researcher's experience, as it depends heavily on the type of robot and especially its environment.

The structure of a conventional impedance controller is shown on figure 1:

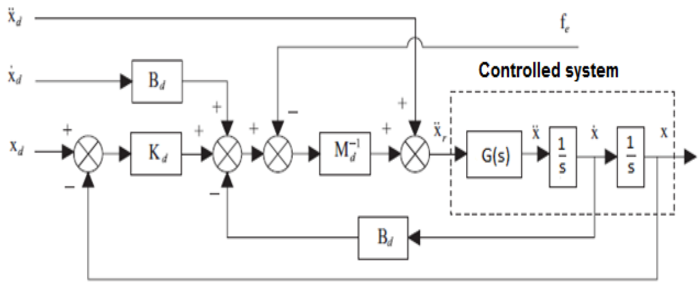

Fig. 1. The structure of a typical impedance controller.

So the controller is realized as given by (1) and the controlled system is added. Sometimes, if there is not an accurate enough dynamic model, the system can be represented just as a double integrator, in which case the G matrix is equal to an identity matrix of the order of the system. However since the dynamic model of the UR5 robot used in this paper is known, G function used in this case represents the robot's dynamic model, and will be more detailed in the next chapter.

III. Simulation and Results

The robot and the controller were modeled and the simulation was done in Matlab/Simulink. In recent years Matlab's Robotics Toolbox package has added models of many commercially available robots including UR5. A large number of ready-made functions are available including the computing of forward and differential kinematics, calculating dynamic equation matrices, trajectory planning, robot 3D animation, etc.

The control scheme given in figure 1 has been slightly altered for Matlab implementation. Since a very good robot model is implemented in Matlab, that model is used instead of the G function in figure 1. Its inverse and forward dynamics were calculated, and implemented in Simulink with S-function blocks. Also, since the controller is made for task space control and the dynamics calculated in joint space, kinematics blocks were used for transformations from one space to another. The final scheme is given by figure 2:

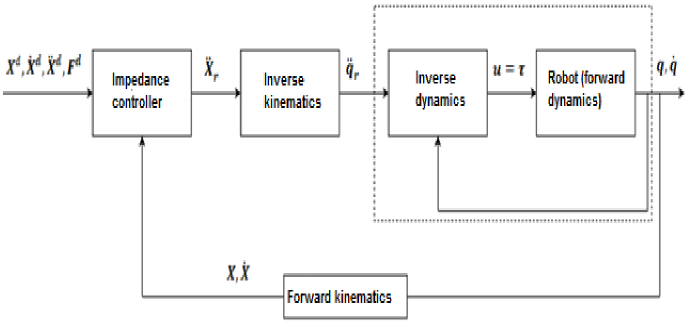

Fig. 2. Impedance control scheme used in simulation.

So, the controller gets the task space coordinates which include the desired tool position, velocity and acceleration as well as the desired contact forces. After getting the controlled values, they are converted to joint space in an inverse kinematics block and given to the robot model. Joint torques are calculated, and joint coordinates are then obtained via forward dynamics. They are returned to the controller after being converted to task space coordinates in a forward kinematics block.

Simulation results are shown in figures 3-8. It should be noted that the position values were obtained in the simulation itself, and shown as such. Force values were then estimated using those values, from the impedance control law as described by (1).

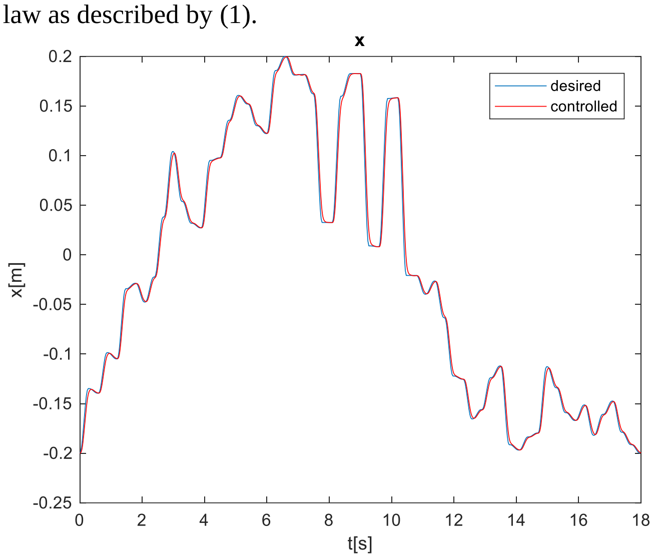

Fig. 3. *x* coordinate of the tool.

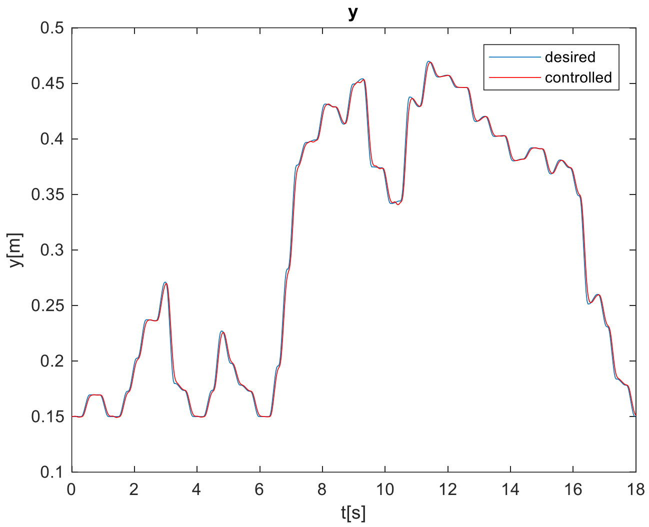

Fig. 4. *y* coordinate of the tool.

Figures 3 and 4 show *x* and *y* tool coordinates, respectively. The reference signal in those cases was not a constant value. Rather the signals are constantly changing in a range of approx. 30 to 40 centimeters. The goal was to see how well the controller can follow such signals. It can be seen that there is a very good tracking, the controller can react to the changes relatively quickly and the error is within 2 per cent margin.

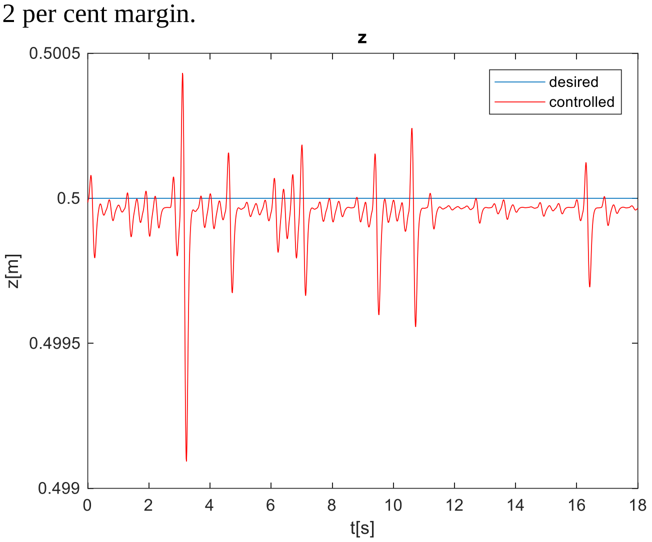

Fig. 5. *z* coordinate of the tool.

Figure 5 shows the tracking of a constant reference. The tracking is very good in this case too, with the error well below the 2 per cent margin.

The same is true for angular components. They represent the tool’s orientation and they were given zero references.

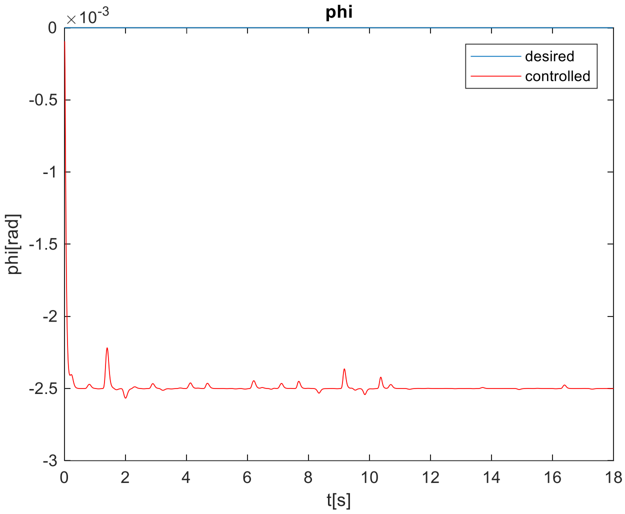

Fig. 6. φ coordinate of the tool.

Figure 6 shows good tracking but also a constant error. The error margin is very small, 0.25 per cent. It is a compromise on the part of the controller in order to satisfy the desired impedance. This is also the case for the remaining two coordinates, ψ and θ. Since the results are very similar, they are shown in a joint, smaller figure.

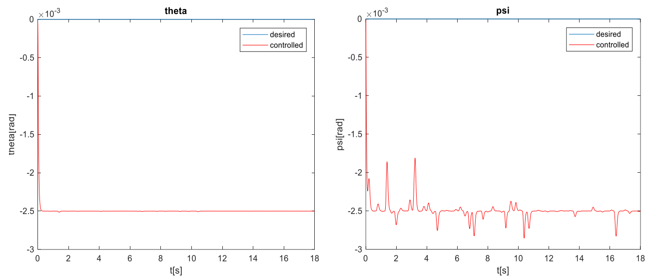

Fig. 7. ψ and θ coordinates of the tool, respectively.

Figures 3 to 7 have shown very good position control. These values were obtained directly from the simulated model and have confirmed the expectations of the impedance control law given by (1). As stated, the forces are now also expected to behave as described by this law.

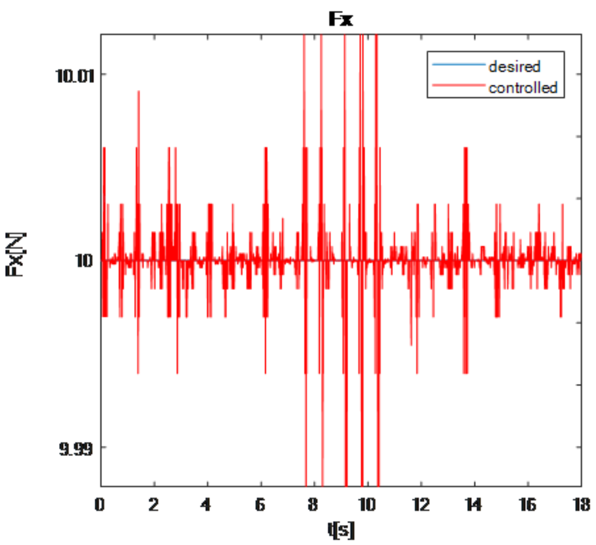

Fig. 8. F_x coordinate of the tool.

Precise tool force estimation is a complex task that in practice requires knowledge about the robot, its technical specifications (e.g. motor currents or other variables), its environment etc. In this case force values were formed as in (1), after obtaining the actual values for tool position, velocity and acceleration. Since the values are very similar for all six directions of the force, only the force component along the *x*-axis is shown here.

Figure 8 shows that the expected result for F_x is equal to the desired value (10N), which again confirms (1) and (2).

IV. Conclusion

The results obtained in this simulation were close to the expected ones and have shown a good impedance controller. Position values, which were obtained directly from the simulation, have confirmed a very good position tracking, with error margins well below 2 per cent. The force values were not estimated in the simulation but were formed according to the impedance law using the obtained tool position, velocity and acceleration values. Those expected force values are very close to the desired ones.

This paper presents a good starting point for the practical development of an impedance controller. Future work could include developing such a controller for commercial use, combining it with other control methods like admittance control, precisely estimating and measuring the controlled tool forces and other.

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