Torque Control for Collaborative Robot to interact with Human in Industry

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***Abstract*—Collaborative robot or Cobot for short is a new robotic technology for industry 4.0, that interact with each other or human worker. To avoid damage between them, cobots will be provided for more control techniques. Some like control the motion for external force, torque, inner force control, generation of trajectory to avoid obstacle, impedance control, etc. For this article, the torque control based in LQR optimization was considered. Finally the generation of new trajectory for motion planning will be taken into account.**

***Index Terms*—Cobot, DOF, LQR, Coriolis Matrix, Optimization.**

I. Introduction

Nowadays in information age, new ideas for industry application appears. The term of industry 4.0 is a big project that currently is apply in europe countries. This technology is inmersed in branches of technologies like: Robotics, Artificial Intelligence, Big Data, IoT, 5G Technology, Mixed Reality and so on. The industry is a field that will take place this new technology altogether.

The robots play a important role here, mainly the collaborative robots or cobots for short. This robots are industrial robots which have additional features that make them more specials. These are able to get external information like force, and then the robot has to update information to control their dynamic and avoid collision with human or another machine.

In a collaborative workspace safety is ensured with four possible methods

a) safety-rated monitored stop
b) hand guiding
c) speed and separation monitoring
d) power and force limiting

In the bibliography there are many research about that, to make the robot more robust and more reliable to interact with human to make job.

Burak T. in 2018 presents a HRI study using nearest–point approach with Microsoft Kinect v2 sensor's depth image (RGB–D). The approach is based on the Euclidean distance which has robust properties against different environments. The study aims to improve the motion performance of Universal Robot–5 (UR5) and interaction efficiency during the possible collaboration.

Lina. Y and Yueying shows A new active fault-tolerant control scheme for a nonlinear collaborative system which contains two subsystems. The scheme is to use the fault-free subsystem to compensate the fault influence of the faulty subsystem on the whole system. When one faulty subsystem could not repair its own fault to the influence on the whole system, the controller of the fault-free subsystem is reconfigured using the fault diagnosis information.

Weihua. S in 2015 presents an integrated learning framework that enables humanoid robots to perform human–robot collaborative manipulation tasks. Specifically, a table-lifting task performed jointly by a human and a humanoid robot is chosen for validation purpose. The proposed framework is split into two phases: 1) phase I—learning to grasp the table and 2) phase II— learning to perform the manipulation task.

Heonseop S. suggests a method of controlling the velocity of the robot at the allowable maximum velocity to ensure human safety even when the distance between the robot and the person becomes inevitably closer than the safe separation distance. The allowable maximum safe velocity is calculated using the collision model which predicts the collision peak pressure and the peak force between the robot and the human in the case of collision.

Xinbo Y. proposed an adaptive neural admittance control strategy for collision avoidance in human-robot collaborative tasks. In order to ensure that the robot endeffector can avoid collisions with surroundings, robot should be operated compliantly by human within a constrained task space. An impedance model and a soft saturation function are employed to generate a differentiable reference trajectory.

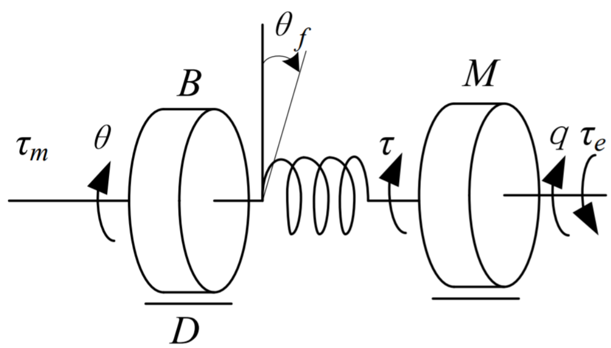
Fan Z. proposes an external force/torque calculation algorithm based on dynamic model identification to replace the six-dimensional force/torque sensor; the algorithm can reduce the costs while achieving a flexible assembly.To ensure the accuracy of the assembly, the compliant control method of this paper uses the PD-based position control as the control inner loop and the impedance control as the control outer loop.

For this article will be consider a torque control based on LQR controller and impendance controller to make robust in front of external force applied to the end effector. This will be divided in 3 parts:

1) Description of the dynamic model
2) Design the control strategy
3) Simulation in CoppeliaSim

A. Dynamic Model of the Joint

Basically the collaborative robot must have flexible joints to reduces the torque and make it more adaptable to external operator forces. The representation of the cobot joint could be expressed like the figure:



Mathematically based on the dynamic of the joint. This can be expressed as the following Second Order system equation:

$$M(q)\ddot{q} = \tau + \tau_e \tag{1}$$

$$\tau = K(\theta - q) \tag{2}$$

$$B\ddot{\theta} + \tau = \tau_m - \tau_f \tag{3}$$

Where τ_f is the friction generated and is expressed as:

$$\tau_f = \tau_k sgn(\theta) + D_v\dot{\theta} \tag{4}$$

τ_k = coulomb friction
D_v = Viscous friction

As the formulation of the joint interaction represented for the model before mentioned. Now, for the dynamic model of the robot, the model will be based on lagrange formulation, where is defined the mass matrix, gravity and the colioris matrix.

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau + DK^{-1}\tau\tau + \tau_e \tag{5}$$

$$\tau = K(\theta - q) \tag{6}$$

$$B\ddot{\theta} + DK^{-1}\dot{\tau} = \tau_m - \tau_f \tag{7}$$

Where K represent la stiffness coefficient between the flexible joint and the link.

The representation of the second order differential equation represent a mass of the dynamic for robot arm (M(q)) and the Coriolis term relies on the derivative of the joints position.

In order to design the control strategy this dynamic equation will be enough. Take in mind that the equation have to be solve based on the D.O.F of the robot, dynamic of the actuator, external forces, motion, etc.
With this generic idea, we present the torque control law.

B. Controller

To design the controller is necessary the feedback of the variable. We don't have the measurement of all variable and will be recommend consider the dynamic model of the robot to feedback "q" The feedback signal make possible the control strategy for torque variable.

1) LQR controller: The theory of optimal control is concerned with operating a dynamic system at minimum cost. The case where the system dynamics are described by a set of linear differential equations and the cost is described by a quadratic function is called the LQ problem. One of the main results in the theory is that the solution is provided by the linear–quadratic regulator (LQR), a feedback controller whose equations are given below. The LQR is an important part of the solution to the LQG (linear–quadratic–Gaussian) problem. Like the LQR problem itself, the LQG problem is one of the most fundamental problems in control theory.

Trying to get the optimal solution for full-state feedback , we have to solve some equation.

Based on the state space equation of the system like this expression:

$$\dot{x} = Ax + Bu \tag{8}$$

$$y = Cx \tag{9}$$

The loss function for optimization problem is:

$$J = x^T F x + \int (x^T Q x + u^T R u + 2x^T N u)dt \tag{10}$$

For linear quadratic formulation:

$$L = \frac{1}{2}x^T Q x + \frac{1}{2}u^T R u \tag{11}$$

The feedback control law to minimize the value is:

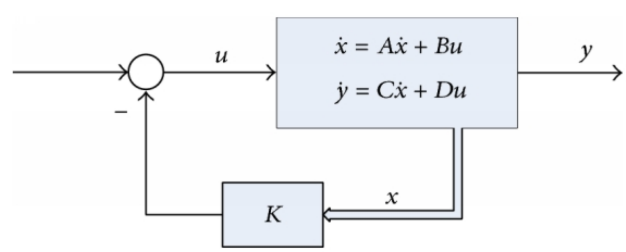
$$u = -Kx \tag{12}$$

Where:

$$K = R^{-1}(B^T P + N^T) \tag{13}$$

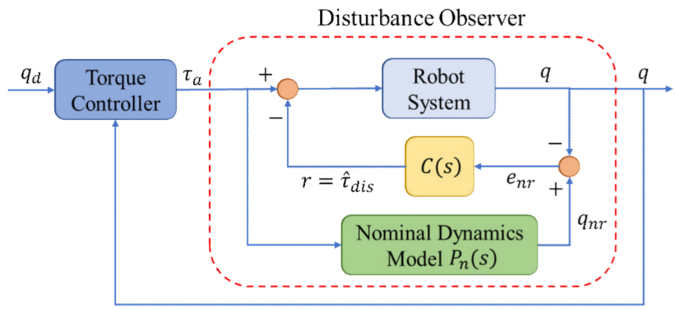
P is the matrix in continuous space solved by the Riccati differential equation

$$A^T P + PA - (PB + N)R^{-1}(B^T P + N^T) + Q = -\dot{P} \tag{14}$$

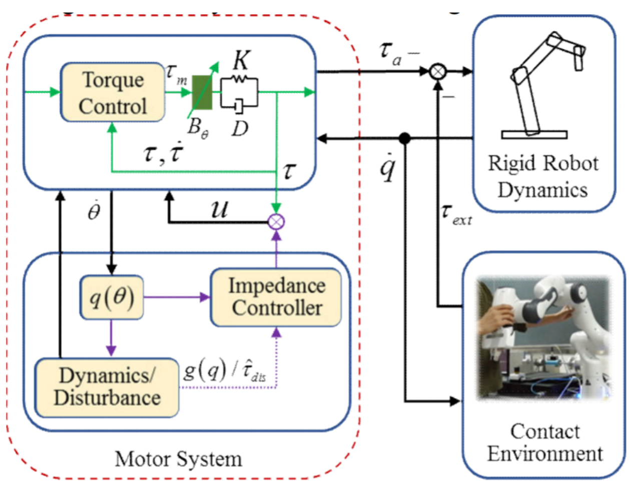


2) Compensation of external force: Based in the desired position of each joint the optimal control generated torque for over the motor, but the collaborative robot is exposed to external forces like: human forces or any obstacle in the trajectory of the robot. To make possible the collaborative approach is used a compensation for external force based on the dynamic model of the robot.

Finally the representation of the controller for torque and compensation could be expressed as the next block diagram (figure(2)).



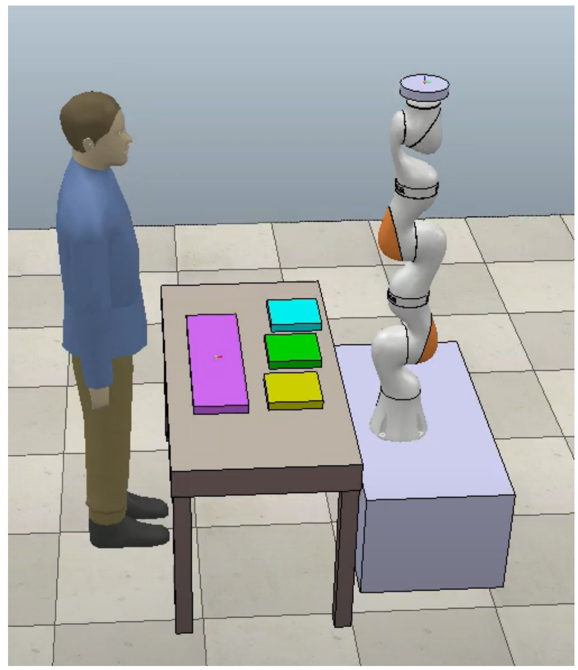
In the literature there are some idea for improving the performance of the collaborative robot, for instance. This paper shows as a compensation of impedance control and generation of trajectory to avoid obstacle. This topic is quite important. In this article will be take in consideration for regeneration of trajectory for motion planning and compensation. The next figure show the final representation of the controller for collaborative robot.



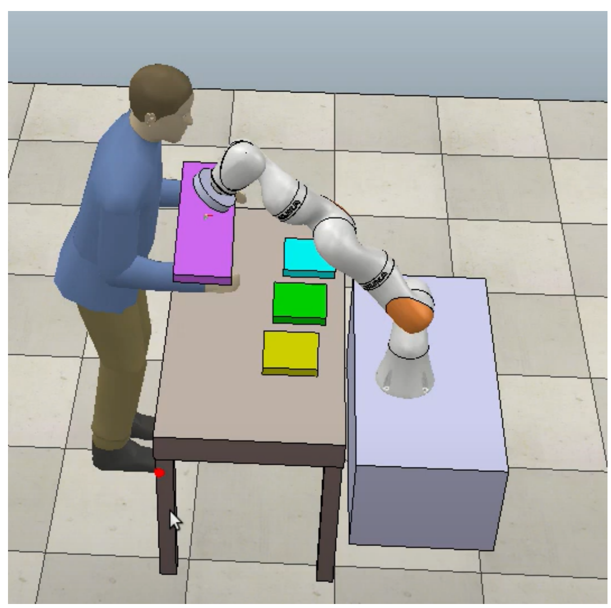
C. Result

In thi article was used the LBR 7-R800 Robot of KUKA company. This robot has 7 degrees of freedom and is a redundat robot. This figure shows you the real robot:

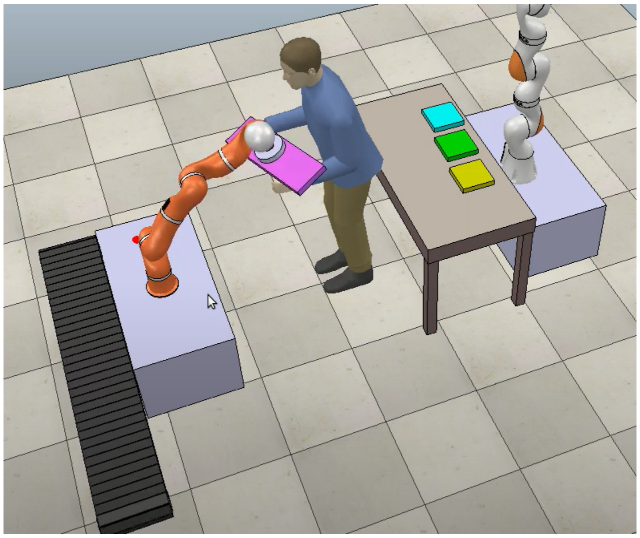
There are more detail to talk about this robot for future. Now, this robot will be simulated thanks to coppealiaSim simulator. The robot is available for Vrep and another KUKA robot as well as ABB an Universal Robot. For this case, the interaction with human is the topic. This simulation tries to emulate how could be the interaction between human and robot. The robot will be provide with torque control and impedance compensation to make safe the human integrity. The robot will be provided with magnetic end tool to pick up the object over the table.



The robot interacts with the human giving him the object, always keeping the torque control to avoid to damage the human worker. In each time the torque an impedance controller controls the effort of the robot.



Will be 2 robots interacting with the human, the next one as the first has to get the object and put over the conveyor.



Finally. This simulation try to emulate the industrial interaction between collaborative robots and human worker. This is actually important for industry nowadays.

II. Conclusion

This article shows how the cobot can interact with human without damage him.
This solution was made possible using optimal control strategies for torque and impedance compensation.
The result was simulated using coppealiaSim that is a widespread software for robotics.
IIWA robot is a powerful robot for industry and for industry 4.0 as collaborative robot.
The concept for this article is summarized and for future article will be tried deeper collaborative robot control, perception, etc.

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