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Serial Robot Collision Reaction Using Joints Data at Stationary Position

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***Abstract*—** This paper present a method for detecting collision occurs in the robot manipulator and reacting according to collision direction. An experiment was conducted to read the joints speed during collision of the UR3 robot at static position, where the joints speeds are supposed to be zero. The experiment showed that when collision occurs within the manipulator there is oscillatory speed produced in joints, which is suggested to be duo to the stiffness of the harmonic drive. The harmonic drive is a flexible transmission generates stiffness behavior, as a spring, between the motor and the link. The collision is determined from the oscillatory speed produced in robot joints at static position. The method successfully identified the collision impact at joints, and reacted according to the collision direction. The experimental setup and the results are presented in this paper.

***Keywords*—** Collision Detection and Reaction, Flexible Robot, Harmonic Drive, Human Robot Interaction.

I. Introduction

This paper addresses a hot topic for robotics research in the recent years, which is the human robot collaboration. The coexistence of human in the robot workspace and interacting with it is not suitable in many of the existing robotics applications, particularly the robot manipulators, for several reasons. One of the most significant reasons is the safety factor[1]–[4]. Robots which have the capability of interacting and collaborating with Human should fulfill some parameters to achieve this task[5]. These robots should be flexible and compliant to achieve the collaboration and interaction. Therefore it needs some consideration in the mechanical structure design of the robot manipulator and in choosing the hardware devices. In the other side it requires implementing complex control techniques[6]. There should be certain control strategies to detect the physical collisions and interactions within the robot manipulator as to make it able to collaborate with humans physically. In this direction, there are several methods used for determining these actions. Some works in literature utilize external sensing such as using force sensors, tactile sensors, etc.[7]–[11]. There are also other detection collision/ interaction techniques without using external sensors, such as in[12], [13].These methods mainly based on the knowledge of robot model. Robot modeling can be separated into two main sectors; kinematics and dynamics. The kinematics describes the robot relative pose for each link to their coordinate frames, and consequently to the ground frame. Accurate kinematic model is the main factor for accurate motion control and better robot performance[14]. The dynamic model of the robot is very significant in advanced robotics applications such as working in unstructured or unknown environment, application that required force control and advanced human robot collaboration[1], [5], [15]. Other methods for collision detection without the need for robot modeling presented in [16]. Also we had the chance to present a method for collision detection in [4]. This paper discussing the collision behavior in a static position and reacting against, it consider an extension for the collision detection step. The proposed method in this paper would not require pre-knowledge about the robot dynamics. The method is based on the joints flexibility, this flexibility is due to harmonic drive. The harmonic drive is a flexible transmission produce stiffness behavior, as a spring, between the motor and the link[17]. The harmonic drive is widely used in serial manipulators due to negligible backlash, compact design, and a high torque-to-weight ratio[18]. Moreover it can achieve the desired flexibility in robot joints. Once we are able to detect the speed change from the robot real time interface, a control action is given to the robot to react. The UR3 robot, one of the popular human collaborative robots in the market[19], is used for the implementation of this work. A review for the robot design and its forward and inverse kinematics analysis are presented in[14], [20], [21]. The robot has a TCP/IP interface that allows accesses to some readings in real time. In this work the actual speed and position readings are used for the method implementation. This paper is arranged as follows; section 2 shows the robot joints structure. Section 3 explains the methodology for collision detection and reaction. Section 4 presents the implementation, includes the experimental setup and the results.

II. ROBOT JOINTS STRUCTURE

The UR robot has harmonic drive in each joint for achieving the compliance and flexibility required for interaction. The robot joints structure and its components are shown in Fig. 1. Modeling and controlling robot with flexible joints, as in this robot case, needs detection of the motor and link position. That is why they use two encoders, one for the motor and the other for link position. The flexibility in the harmonic drive system can be modeled as a spring with stiffness (k). Schematic for the joint with flexible transmission is illustrated in Fig. 2. The dynamic model for robots with flexible joints is represented as

$$M(q)\ddot{q} + \mathrm{C}(\mathrm{q},\dot{\mathrm{q}})\dot{\mathrm{q}} + \mathrm{G}(\mathrm{q}) = k(\theta - q) \quad (1)$$

$$I_m\ddot{\theta} + k(\theta - q) = \boldsymbol{\tau}_{\mathrm{m}} - \boldsymbol{\tau}_l \quad (2)$$

Equations (1) and (2) are referred to as the joint and the motor equations, respectively. Where $\mathrm{M(q)}$ is inertia matrix robot links, $\mathrm{C(q,\dot{q})}$ is the Coriolis and centrifugal velocity terms, $\mathrm{G(q)}$ is gravitational terms, and $\boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}}$ respectively are the vector of generalized joints positions, velocities and accelerations. θ is the vector of motors position. I_m is the motors inertias matrix (reflected through the gear ratios), k is joints stiffness matrix, $\boldsymbol{\tau}_{\mathrm{m}}$ are the motor torques, and $\boldsymbol{\tau}_l$ are the losses and dissipative torques due to friction as seen from the motor side.

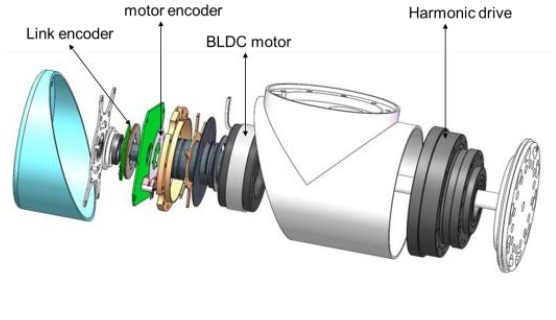

Fig. 1. Flexible joint structure and components

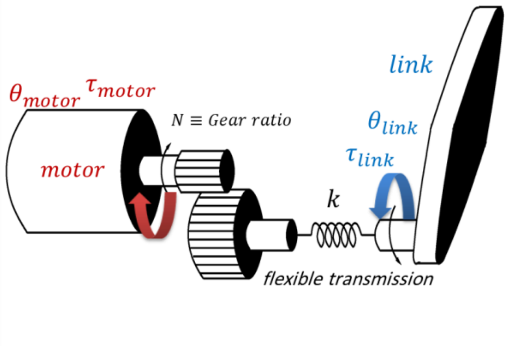

Fig. 2. Joint with flexible transmission schematic

However in our case, the information about the motors encoders is not available. As the robot controller is handling the relation between the encoders, and only provides the average between the two encoders without giving details about the model. Moreover the dynamic model is not required in this work, as we only use the kinematics information of the joints position and speed. The methodology for collision detection and reaction is presented in next section. More about modeling Robots with flexible elements can be found in [22], [23].

III. METHODOLOGY

The method utilized in this work based on the distribution of the collision force on the robot joints. This collision force produces moments at the joints. Hence the highest moment/ torque occur at the joints that have axis of rotation perpendicular to the force direction. Illustrating example is shown in Fig. 3. In Fig. 3(a) the force is applied on link 2 and it is perpendicular to the axes of rotation of joint1, hence the highest moment/torque is produced in joint 1. In Fig. 3(b) the force is applied on link 3 and it is perpendicular to the axes of rotation of joints 2 and 3, hence the moments/ torques produced in these joints higher than the other joints. Since the existence of the harmonic drive, these torques/moments generate oscillatory speed in the joints been impacted.

An experiment was conducted to read the joints speed during Collision while the robot at static position, from experiment we found that there is speed variation at the joints. Thus this information can be used for detecting the collision and its direction.

Since the robot at static position then the joints position $\mathrm{q_{i,0}}(\mathrm{i} = 1 \rightarrow 6)$ are known, and the joints speed $\dot{\mathrm{q}}_{\mathrm{i,0}}$ $(\mathrm{i} = 1 \rightarrow 6)$ should be zero. But practically the $(\dot{\mathrm{q}}_{\mathrm{i,0}})$ are not zero, it have very slight value around zero due to the noise, we give it a threshold value $\alpha_{\mathrm{thr}} \rightarrow \left(|\dot{\mathrm{q}}_{\mathrm{i,0}}| \leq \alpha_{\mathrm{thr}}\right)$. If the joints actual speed absolute value $|\dot{\mathrm{q}}_{\mathrm{i,act}}|$, from the real time interface, detected to be higher than α_{thr} this means that collision occurred. And from the $\mathrm{sign}(\dot{\mathrm{q}}_{\mathrm{i,act}})$ the direction of the collision can be determined. Such that if $(\dot{\mathrm{q}}_{\mathrm{i,act}} > 0)$ means the collision is in the forward direction, and if $(\dot{\mathrm{q}}_{\mathrm{i,act}} < 0)$ means the collision is in the backward direction. Then we can control the impacted joint position to move in the direction of the collision as

$$\mathrm{q_{i,new}} = \mathrm{q_{i,0}} + \dot{\mathrm{q}}_{\mathrm{i,act}}.\Delta \mathrm{t} + \mathrm{sign}(\dot{\mathrm{q}}_{\mathrm{i,act}}) * \varphi \quad (3)$$

Where φ is the value of reaction in terms of position, this φ could be a variable that is adjusted relatively to the force impact. The integral term of the speed in the equation compensate the slight displacement occurred from collision impact due to joint flexibility. The reaction algorithm for instantaneous collision force at static position is shown in Fig. 4. As when collision occurs, the robot reacts by moving away of collision point. Thus φ should be proper value in (rad) to let the robot link move away from collision point. We means by instantaneous collision that it is discontinue force, and not persistent such as stuck object on the robot link. So that the algorithm assumes that while the robot is moving away of the collision point, the collision impact fades. In practice we found that the best range of φ that allows the robot to move away a proper distance from collision point is between $(5{\sim}10\ \mathrm{deg} \equiv 0.087{\sim}\ 0.17\ \mathrm{rad})$. The experimental setup for reading the data from the robot interface, and the procedures for collision detection are presented in Next section.

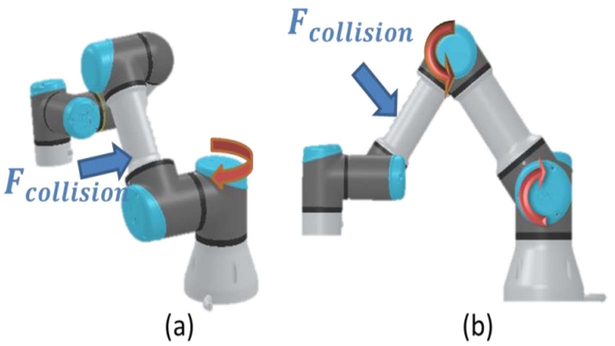

Fig. 3. Collision force that produces moments at the joints in two different examples (a) and (b)

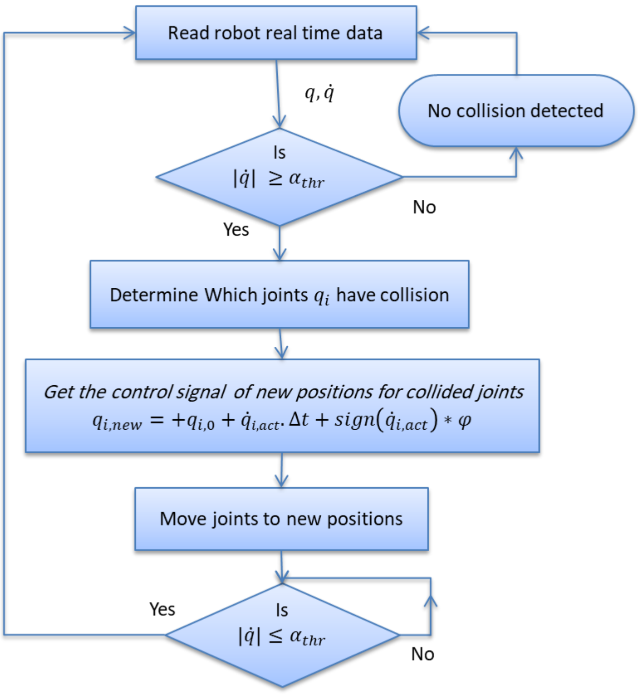

Fig. 4. Collision reaction algorithm at statistic position

IV. Implementation

In order to observe the collision impact on the robot joints, we carried out an experiment to record joints behavior during collision. The robot controller have TCP/IP real time interface at 125Hz. We developed a program to record the data and control the robot through the interface. The program architecture is shown in Fig. 5 . Communication with the robot controller implemented in Python. It is parallel Architecture, where receive socket thread is used to read the real time data in parallel to the main loop. A force applied to the robot manipulator, as shown in Fig. 6. The joints behaviors were plotted in real time. In this figure the force applied on link 2, but it produce torque at joint 1 and 2. In addition the direction of the collision could be detected. The collision force applied on link2 and the data recorded. Fig. 7 shows the response of the 6 joints for an instantaneous collision impact on link2 at the robot position shown in Fig. 6

From experiment results we can see that the collision force is not affecting only the joint have rotation axis perpendicular to the force, but also other joints got affected as shown in Fig. 7. Also the resonance of the joints speed is obvious, that during collision the speed is resonating around the zero value and return to rest again in nonlinear behavior, modeling this behavior is complicated. We take advantage from the behavior to detect collision occurrence and its direction and react to it. The collision is detected from the sudden joints speed variation if $(|\dot{q}_{i,act}| \geq \alpha_{thr})$, while the robot is at static. And the direction determined from the first peak of the speed. The reaction algorithm in Fig. 4 implemented successfully to react at instantaneous discontinuous collision force. In case of continuous collision such as stuck object on the link, which is not discussed in this work, identifying the collision direction using the speed readings might not be accurate because the oscillatory response of the speed is unpredictable. For that, more information should be involved for identifying the direction such as the torque or current information. Fig. 8 shows the current response for joint 1 and 2, the two joints that have collision impact. As it can be seen from the currents figure that the impact period is happened between the two peaks of the speed. The direction of impact of joint 1 and 2 are opposite to each other. The impact direction for joint 1 is in the +ve direction, while for joint 2 is in the –ve direction.

In addition, current readings can be used not only as a double check for the collision direction, but also for understanding the behavior of the impact. It can indicate if the impact is collision or interaction, continuous or instantaneous[4].

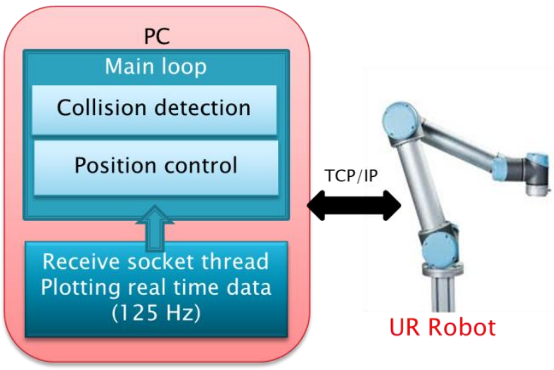

Fig. 5. Interface program architecture

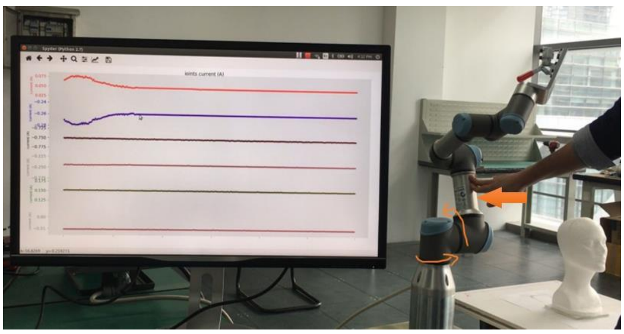

Fig. 6. Monitoring collision impact

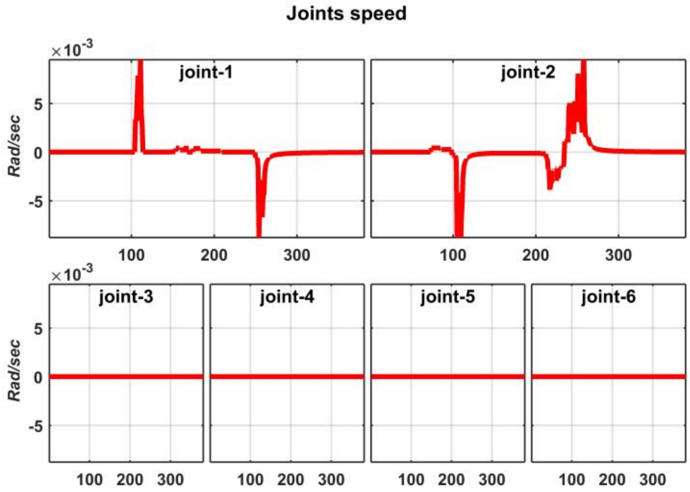

Fig. 7. Joints speed response at collision force applied on link2

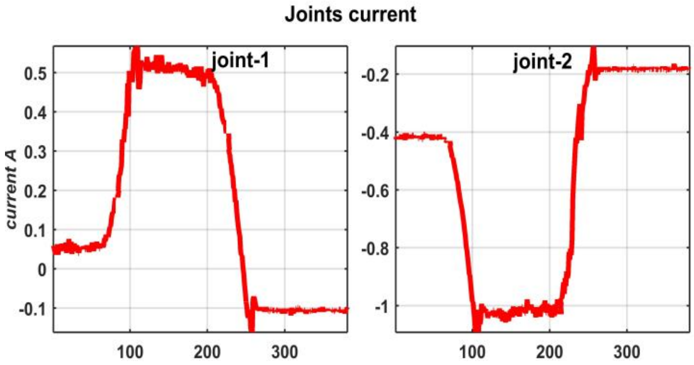

Fig. 8. Joints 1and 2 current response at collision force applied on link2

V. RESULTS

The results of the collision reaction algorithm are presented for two examples as follow; First example is illustrated in Fig. 9, where the robot is in collision in its second link, this collision impacted joint 2. Figure shows the sequence of the robot reaction by moving link 2 down, in the same direction of the collision, to escape the collision impact.

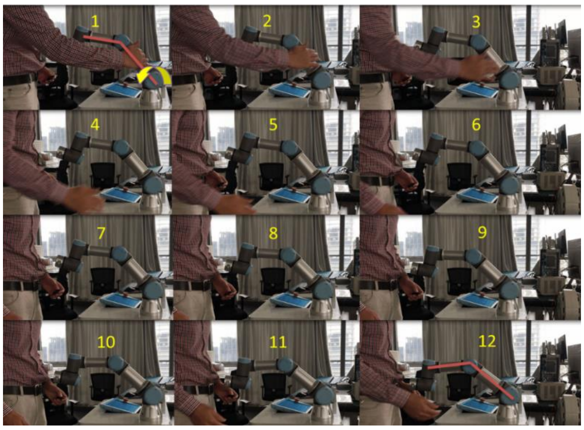

Fig. 9. Collision reaction illustration example 1

Second example is shown in Fig. 10 the robot is in collision the end effector and the highest impact of the collision is affecting joint 2, thus the reaction of the robot is in same direction of the impact by pulling down. More tests were been carried out, but it can't be presented in image format, videos for this work are available upon request

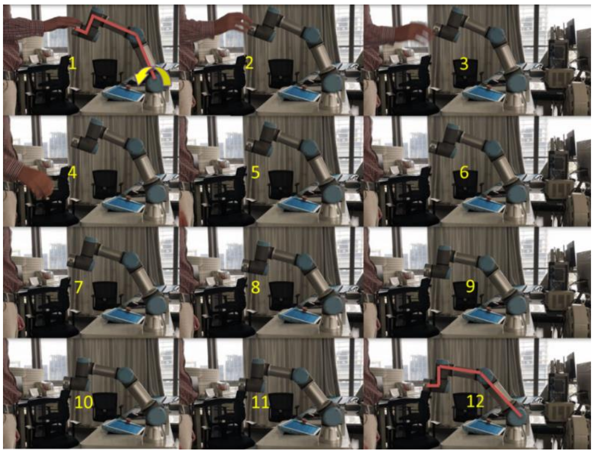

Fig. 10. Collision reaction illustration example 2

CONFLICT OF INTEREST

The authors declared that they have no conflicts of interest to this work

CONCLUSION

The paper presented an experimental setup for recording and plotting real time data from the UR3 interface. This data used for studying the behavior of the joints speed during collision. The experiments were carried out on the robot at static position. The results had shown that during collision there are speeds produced in the joints, and this speeds act in resonant way. This behavior was suggested to be resulting from the harmonic drive. The impacted joints from collision and the collision direction can be detected. This data used for taking a reaction as explained in the paper. The use case in this paper discussing the robot at static position, and the collision detection and reaction was successfully implemented at instantaneous discontinuous collision force.

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