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Joint configuration for physically safe human–robot interaction of serial-chain manipulators

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ABSTRACT

Manipulators with a series of revolute joints usually have more than 6-DoFs from the shoulder to the wrist to conduct miscellaneous tasks for humans. To add physical interaction or safety to manipulators, functions of compliance or safety components are implemented to joints or links of manipulators. However, a physical interaction by a collision may occur anywhere from the base to the end-effector of the manipulators. If a collision occurs at upper link, which has relatively fewer-DoFs joints, an external force may not be transmitted to the respective joints and links properly. Therefore, a study of the overall joint configurations for manipulators is necessary. This paper suggests a simplified methodology for joint configurations of manipulators using two types of revolute joints, rotational (*type R*) or twist (*type T*) joints. When an external force is applied to the link attached to these joints, the characteristics of torque transmission are described. Then, optimal joint configurations at the shoulder joint of 2- or 3-DoFs are described for physical interaction to manipulators. Experimental results followed by the scenario from pre-collision to collision show that joint configurations affect the safety performance of the manipulator.

1. Introduction

When humans and robots coexist, physical interactions including collisions can occur at any time between them. Physical human–robot interaction (pHRI) with collision safety is a challenging issue for robots in an unpredictable environment where they cooperate with humans, contrary to a fixed environment such as an industrial robot system. Research on collision safety focuses on safety components or strategies utilizing several safety standards applicable to field outside robotics.

Several formal or informal safety criteria such as the head injury criteria (HIC), pain and the contact forces of blunt impacts [1], or soft-tissue injury [2] are utilized to verify the safety performance of various safety components. Haddadin conducted experiments and analysis in which several robots of different sizes and weights collide with the dummy at various collision velocities under two kinds of conditions: unconstrained and constrained blunt impacts [3,4].

Based on several safety criteria, manipulators have implemented safety components, which consist of varied parts to implement safety functions, utilizing various electrical, electronic, or mechanical properties in various combinations depending on the safety

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purpose. Safety components of active types generate electrical feedback signals in response to actual or potential contacts from the human or the obstacle; this is accomplished by sensors attached to the inside or outside of the robotic system. The DLR Light-Weight Robot III (LWR-III) has optimized joint modules with highly integrated electronics and sensors, which lead to good safety performance in the event of a collision with a human [5]. The Distribute Macro-Mini (DM^2) approach utilizes mini actuators for safety, while preserving performance by macro-actuators [6]. They adjust the effective inertia of the robot to reduce the impact of the collision.

On the other hand, passive safety components can show reactive motion using mechanical parts of the mass/spring/damper in advance rather than sensing. Pratt and Williamson [7], Morita and Sugano [8], and Wolf and Hirzinger [9] developed serial-type variable stiffness mechanisms where two actuators are connected in series, one to control the stiffness and the other to control the position. The Variable Stiffness Actuator (VSA) [10] and the Variable Stiffness Joint (VSJ) [11] are parallel-type variable stiffness mechanisms where the actuators are connected in parallel, and the stiffness and the position can be adjusted simultaneously. To reduce the effective inertia, control methods that enable rapid adjustment of the stiffness were used. These variable stiffness mechanisms of serial and parallel types require additional actuators, gears, and mechanisms responsible for the stiffness. This leads to an increase in mass and volume from a joint component to the manipulator system and also brings the burden of complex control.

Park proposed simple safety components of safe link and joint mechanisms, which have fixed-stiffness thresholds of nonlinearities with respect to an external force [12,13]. However, a transmitted force or torque on each component is changed by the gravitational effect according to the configurations of a manipulator. Lee et al. developed a safety component, the Spring-clutch which utilizes a CAM profile and has a releasing threshold [14]. A manipulator with this component at each joint, Safe and Speedy Arm 3 (SS-Arm 3), can maintain a consistent response over any transmitted torque by an external force with the help of a gravity compensation mechanism [15]. Choi et al. developed a passively variable threshold torque Spring-clutch (PVSC) which adds the gravity compensation within the Spring-clutch [16]. Seok et al. proposed a new safety component which adds the compliance function to PVSC for soft interaction with humans [17].

These passive safety components have the following advantages: First, the response time for the collision impact is faster than that of the active compliance and the variable stiffness compliance. Second, there is no danger of a malfunction where the failure of the sensor and actuators on the active type lead to an undesired situation, where adjusting the stiffness does not work properly and reducing the effective inertia fails.

The effect of gravity and the torque transmitted to each joint vary depending on the robot configuration. There are restrictions on the consistent responses to the torque by an external force. In addition, there is a certain direction about a contact position of a link in which the corresponding safety component of the passive type functions well. However, a collision does not always occur in such a direction. Therefore, mounting the safety component to each joint cannot ensure the inherent safety of the manipulator. To guarantee the safety from a collision between a human and robot, robots should not only be equipped with the safety components, but also be able to anticipate and avoid situations where the component cannot function well.

Due to the fact that a joint configuration is not suitable for taking action against collisions in particular poses, Chun et al. proposed a strategy which includes an algorithm that avoids obstacles and considers the pose of the manipulator simultaneously with SS-Arm 1, a safe manipulator equipped with VSJ [11] at the shoulder joint and a proximity sensor [18]. Kulic and Croft calculated the danger criterion as the product of the distance factor between the obstacles and each link of the robot, and applied it to the pre-collision strategy [19]. Ikuta et al. classified safety strategies and calculated the defined danger-index to quantitatively evaluate the effectiveness of each strategy [20]. These strategies were focused on collisions but did not pay much attention to several of the joint configurations for which robots can be different. Therefore, a joint configuration strategy of the design of the manipulator is necessary for better use of built-in safety components in preparation for various inevitable collision situations.

In this paper, the types of revolute joints and joint configurations of the serial-chain manipulator for pHRI are described in Section 2. SS-Arm 3, a safe manipulator equipped with a proximity sensor and the Spring-clutch as safety components, is presented in Section 3. Then, Section 4 shows that SS-Arm 3 with a proposed joint configuration is proper associated with physical interaction and collision safety through comparative experiments.

2. Joint configurations for serial-chain manipulators

Robot joints are generally classified into revolute joints and prismatic joints. This study is mainly focused on anthropomorphic manipulators that mimic human arms. These manipulators consist of a serial-chain of revolute joints and links from the base to the end-effector. Most manipulators having shoulder, elbow and wrist joints like a human arm possess six or seven DoF (right side of Fig. 1). In this study, the classification of joint types is reduced from four types in [21] to two types of joints by dividing a link into two parts and adding a relative angle between the two parts. Then, existing manipulators can be generally described using two types of joints.

2.1. Types of revolute joints

The revolute joint of serial-chain manipulators can be classified into two types: Rotational joint (*type R*) and Twist joint (*type T*) as shown in the left side of Fig. 1. These two kinds of joints were classified according to the relation between the joint and the two links adjacent to each corresponding joint. Most elbow joints of the manipulator use *type R* of 1-DoF. The shoulder and wrist joint generally consist of a combination of three kinds of joints of multiple DoF. Let a link i of joint i consists of two parts l_i^- and l_i^+. Let o_i^+ is the node between l_i^- and l_i^+. Then, let link l_{i-1}^+ and l_i^- be two adjacent parts of the input and output link attached to joint i,