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Development and Characterization of a Modular and Reconfigurable Robot

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Abstract: Modular and reconfigurable robots (MRRs) represent the next generation of industrial manipulators that can cope with the rapid changes of product design and manufacturing. This paper introduces a novel MRR mechanical design strategy. The MRR is composed of modular joints and links. Each modular joint has four physical connection ports, so that it can be constructed as either a rotational joint or a pivotal joint. In addition, the proposed MRR provides high position and orientation accuracy. Furthermore, Zero link-offset when used as a pivotal joint increases the robot dexterity, maximizes the reachability, and results in kinematics simplicity. An experimental setup for identifying Harmonic Drive (HD) stiffness and friction coefficients is also presented in this paper. Identification of those parameters will help achieve more accurate control of such MRR systems.

Keywords: modular and reconfigurable robot, harmonic drive, compliance, system identification

1 Introduction

Robot manipulators have served the industry for many years. For a wide range of industrial tasks, conventional fixed-anatomy robots do not satisfy the requirements

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of the next generation of flexible automation plants. To respond to the rapid changes of product design, manufacturers need a more flexible fabrication system. It is common to use programmable robots that are expensive, and limited by hardware constraints. In recent years, modular and reconfigurable robots (MRRs) [Chen 1996] were proposed to fulfil the requirements of the flexible production system. At present, the applications of reconfigurable robots in manufacturing are quite limited. However the technology and research advances are very promising. As an extension of the concept of a modular robot system, the MRR system is referred to the entire manipulator system that includes not only the modular mechanical hardware, but also modular electrical hardware, control algorithms and software [Schmitz, *et al.*, 1988]. In [Chen 1994], an MRR system is defined as a collection of individual link and joint components that can be easily assembled into a variety of configurations and different geometries. The author in [Aspragathos 2005] states that in the near future MRR systems will replace most of the current fixed configuration industrial robots.

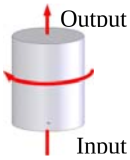
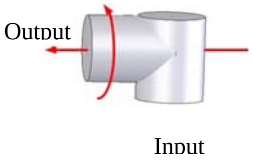
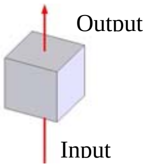
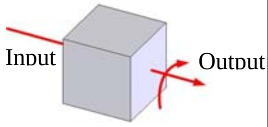
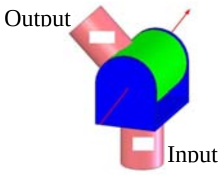
In addition to the advantages of reconfigurability, there are advantages to using lighter manipulators that can handle heavier payloads. To achieve this type of lightweight system, harmonic drives (HD) can be used. They have additional benefits of compact size, zero back-lash, light weight, and high torque transmission [Chen 1996][Schmitz, *et al.* 1988][Hirzinger, *et al.* 2001]. Unfortunately they exhibit drawbacks including flexspline elasticity, and complex meshing mechanisms between the flexspline and circular spline. In this work, we introduce the steps of mechanical design of MRR joint modules with a HD transmission system. In order to accurately model and control such a system, HD compliance and friction must be characterized.

The organization of this paper is as followed: Section 2 describes the mechanical design of the modular joints. Section 3 introduces the dynamic model of the MRR with flexible joints. The HD calibration experimental setup and results are presented in section 4. The conclusion is given in section 5.

2 Mechanical Design

Modular and reconfigurable robots (MRRs) are composed of modular joints and links. Table 1 shows the current commonly deployed joint structures [Paredis, *et al.*,1996; Shi, *et al.*, 2005; Han, *et al.*, 1997; Hirzinger, *et al.*, 2001;Yang, *et al.*, 2001]. The common features of those modules are: 1) one-degree of freedom motion; 2) harmonic drive to transmit power; 3) single input single output (SISO) physical connection port, except for the cubic shape joint module which has multiple connection ports. Therefore, the cubic shape module can be used as either a rotational joint or a pivotal joint, but the link offset “d” is generated when used as a pivotal joint as shown in Fig. 1. The other SISO modules are used together in order to generate a new robot configuration. In this paper, we propose a novel joint module mechanical design as shown in Fig. 2. The key features are summerized as follows: 1) each module has four physical connection ports; 2) the HD is housed for power transmission; 3) parts 1, 2, 3 can be disassembled depending on the configuration to reduce the weight, i.e. rotary or pivotal joint,; 4) links can be precisely positioned onto the joint by four keys/keyways separated 90 deg with respect to each other. This structure not only minimizes the repositioning error, but also provides accurate 90 deg link twist angle; 5) the zero link offset in pivotal rotation increases the robot dexterity, maximizes the reachability, and results in kinematics simplicity. Using the proposed joint and link modules, some typical MRR configurations are shown in Fig. 3.

Table 1. Commonly used MRR joint module

	Rotational Joint	**Pivotal Joint**
Type 1		
Type 2		
Type 3		

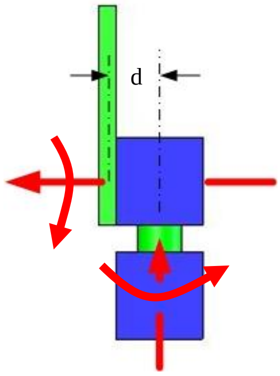


Fig. 1. 2DOF Robot with cubic joint (“d” is the link offset)

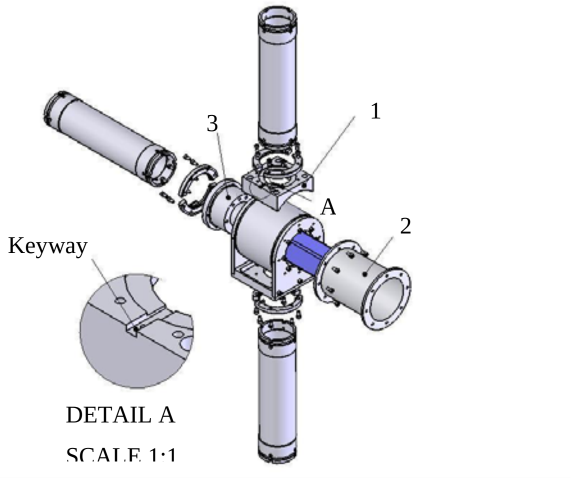


Fig. 2. Proposed joint module with links

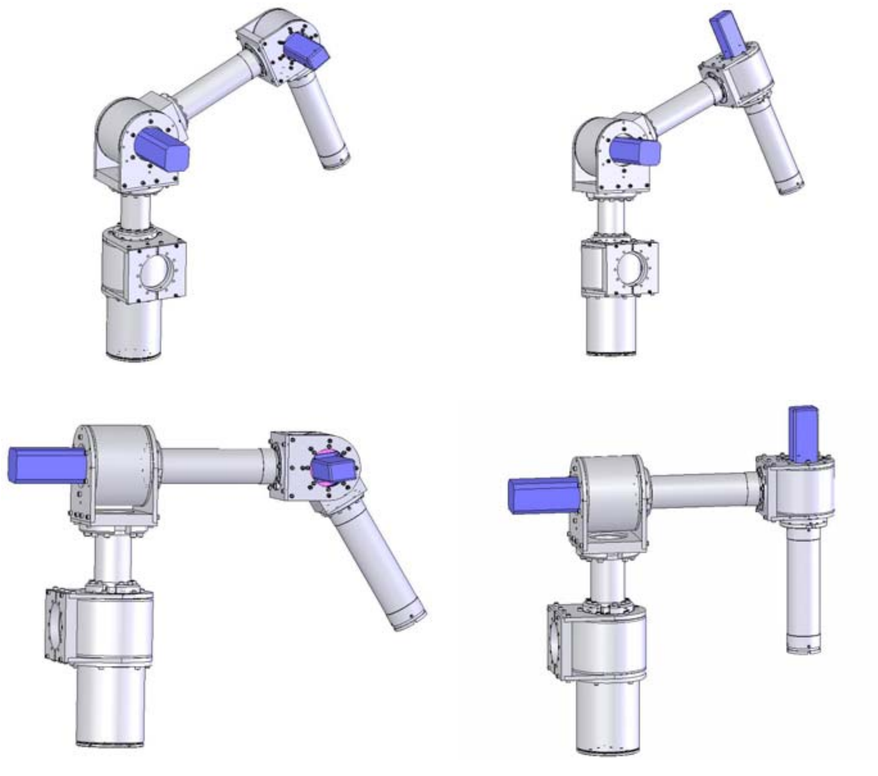


Fig. 3. Four different MRR configurations

3 System Modeling

An n-DOF robot manipulator with flexible joints can be modeled using the following second-order dynamics system [Spoog , *et al.*, 2006]:

$$D(q_1)\ddot{q}_1 + C(q_1,\dot{q}_1)\dot{q}_1 + \tau_f + g(q_1) + \tau_F = 0 \qquad (1)$$

$$J\ddot{q}_2 + \tau_F = u \qquad (2)$$

Where, q_1 and q_2 are the link and motor position, respectively. $D(q_1)$ is the $n \times n$ symmetric, positive definite inertial matrix. The vector $C(q_1, \dot{q}_1)$ contains coriolis and centripetal forces. τ_f and τ_F are the torques due to the friction and the joint elasticity, respectively. $g(q_1)$ is the gravitational torque. J is the $n \times n$ diagonal motor inertial matrix. u is the motor input torque.

Precisely controlling such a system depends on how accurately the system friction and flexible dynamics are represented. For the proposed modular and reconfigurable robot (MRR), viscous and Coulomb friction are considered. A nonlinear cubic function is used to model the joint stiffness. The joint stiffness friction models are represented in the following form [Kircanski, *et al.* 1997]:

$$\tau_f = F_v \dot{q}_1 + F_c(\dot{q}_1) \qquad (3)$$

$$\tau_F = K_{s1}(q_1 - q_2) + K_{s2}(q_1 - q_2)^3 \qquad (4)$$

Where, F_v and F_c are viscous and Coulomb friction coefficients, respectively. K_{s1} and K_{s2} are linear and nonlinear stiffness coefficients, respectively. The MRR control process strategy is beyond the scope of this paper, but the experimental setup and identifying all coefficients in (3) and (4) are described in the following section.

4 System Characterization

Because of its compact size, light weight, high reduction ratio and zero backlash, harmonic drives (HD) have been widely used since their conception in 1955. They are often used as the transmission unit for joints of industrial robotic manipulators. Unfortunately, the elasticity of the flexspline generates robot oscillation. In addition, the complex gear meshing mechanism affects motion control accuracy. Therefore, determining flexspline stiffness coefficients and friction coefficients is necessary for modelling the dynamics. Much work has been done by researchers in modelling HD compliance and friction. In [Tuttle, *et al.* 1993], the HD model developed is composed of three submodels: 1) three terms for friction: velocity-independent, velocity-dependent and friction from resonant vibration; 2) two terms for compliance: linear and non-linear term; 3) a sinusoidal and subsequent harmonics for kinematic error. In [Kircanski, *et al.* 1997], the HD is modeled based on its mechanical components: wave-generator, flexspline and circular spline. A simple friction model is applied, and a similar compliance model is derived by considering the effects of quasi-backlash due to the soft-windup. Detailed HD modeling can also be found in [Tuttle, *et al.* 1996][Taghirad, *et al.* 1998]. The following subsections describe the HD stiffness and friction characterization for the proposed MRR joint module [Kircanski, *et al.* 1997] in Fig. 2.

4.1 Modeling Harmonic Drive Compliance

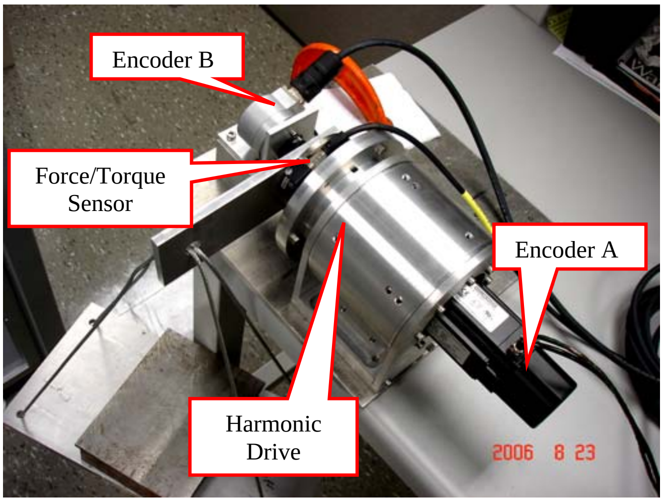


Fig. 4. Experimental setup for HD flexspline compliance calibration

Fig. 4 shows the experimental setup for calibrating HD flexspline compliance. In this experiment, a CSF-32-100 HD is used. A brushless DC motor with an encoder (encoder A) monitoring the motor shaft position is coupled with the HD wave-generator. A Delta type force/torque (F/T) sensor is connected to the HD flexspline to record the applied torque and a high resolution encoder (encoder B) is mounted on the other side of F/T sensor to measure the output side displacement under certain load. The displacement of F/T sensor, provided by the manufacturer, is deducted from the encoder B's reading, and the coupling is assumed to be rigid. During the experiment, the motor is disenergized with the brake holding the motor shaft so the reading from encoder A is zero. Therefore, the flexspline torsion $\Delta\theta$ is the encoder B's reading. The dots in Fig. 5 are the experimentally measured flexspline torsion under a certain applied load, and the solid curve represents the fitted stiffness profile based on (4). The derived stiffness coefficients are:

$$K_{s1} = 4\times10^{4}\ Nm/rad \tag{5}$$

$$K_{s2} = 2.5\times10^{4}\ Nm/rad^{3} \tag{6}$$

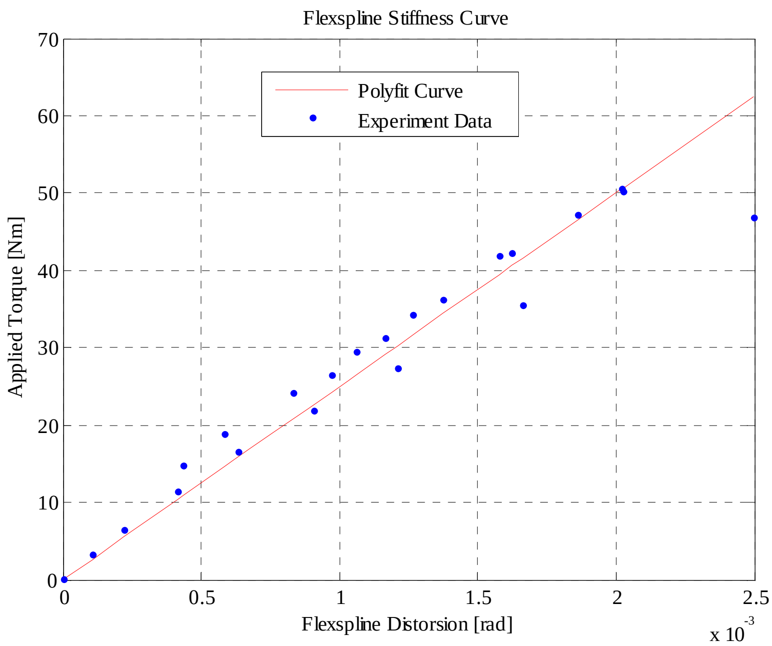


Fig. 5. Flexspline stiffness experiment data and curve fitting

4.2 Modeling Harmonic Drive Friction

The Coulomb and viscous friction can be identified by measuring the torque required to operate the HD at several different constant velocities. Instead of measuring the torque directly, we monitored the current flowing to the motor and multiplied it by the torque constant. The dots and the line in Fig. 6 are observed and fitted friction profile based on (3), respectively. The slope of the line is the velocity-dependent viscous friction coefficient. The velocity-independent Coulomb friction coefficient is the friction torque at zero velocity. From the fitted line, we have:

$$F_v = 0.226 Nm \tag{7}$$

$$F_c = 0.0187 Nm \tag{8}$$

Substituting the experimental results of the stiffness and friction coefficients into (3) and (4), an accurate model can be derived. A decentralized robust controller has been proposed based on the developed model to control the MRR to follow a reference trajectory. This work is beyond the scope of this paper.

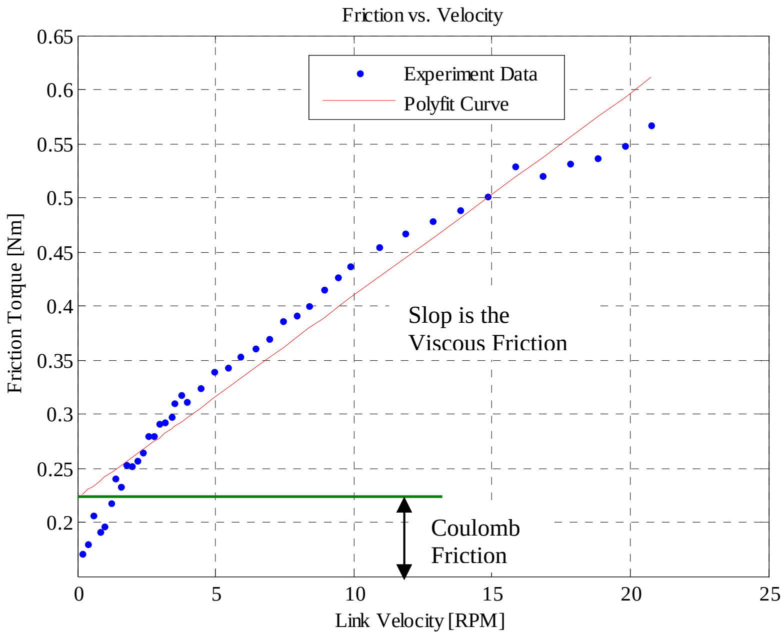


Fig. 6. Harmonic drive friction experimenatal data and curve fitting

5 Conclusion

The mechanical design of a novel modular and reconfigurable robot (MRR) joint is proposed in this paper. Compared with the commonly used joint module in industrial robots, the proposed joint has four connection ports and can be configured either as a rotational joint or pivotal joint. In addition, the zero link offset in pivotal joint increases the robot dexterity and maximizes the reachability. Using the proposed modular joints, different MRR configurations can be easily constructed using rigid links. The proposed MRR system is suitable for flexible automation. The application is quite broad including mechanical assembly, material handling, welding, painting, packaging, etc. Furthermore, due to the accurate link positioning mechanism, the proposed MRR also satisfies the requirements of precision manufacturing applications. One of our test tasks is to install the car back-seat by integrating with an off-the-shelf end tool and an automated screwdriver.

In addition, the dynamics of the robot with flexible joints is given, and the friction and stiffness coefficients' characterization procedure and results are provided. Such coefficients require accurate identification when implementing precise independent joint motion control strategies.

6 References

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