Design of a Passive, Bidirectional Overrunning Clutch for Rotary Joints of Autonomous Robots

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Abstract. Joint design and load transmission are crucial factors when building autonomous robots. On the one hand, heavy torques are often needed which result in multi-stage gearboxes, on the other hand the latter exhibit massive friction which gets in the way of energy-efficient actuation systems. Furthermore, the immense impact forces of a tumbling robot can easily break its joints, gears, and motors. This holds especially true for tall humanoid robots. In this paper we present a novel clutch for rotary joints which is able to resolve the aforementioned dilemma.

Keywords: overrunning clutch; frictionless decoupling; energy-efficient actuation; compliant parallel actuation.

1 Introduction

Joint design and load transmission are crucial factors when building autonomous robots, especially humanoid robots. On the one hand, heavy torques are often needed, e. g. at the knee and ankle joints of a humanoid robot. As a consequence, this normally results in multi-stage gearboxes which exhibit massive friction. On the other hand, an equally important goal of robot design is energy-efficiency. Obviously, the friction of multi-stage gearboxes gets in the way of energy-efficient actuation systems. Furthermore, the immense impact forces of a tumbling robot can easily break its joints, gears, and motors. This holds especially true for tall humanoid robots.

In order to resolve the aforementioned dilemma, we present a novel overrunning clutch for rotary joints which is able to automatically connect the geared motor to the limb of an autonomous robot, e. g. an arm, whenever the motor applies torque – and to disconnect the limb during energy preserving phases of a motion. This way, a multi-stage gearbox can be used to deliver the necessary torque for the robot to lift its arm including heavy weights, but the robot is also able to let the arm swing freely, e. g. during walking.

Clutches which couple or decouple a drive shaft from a driven shaft are well-known and used in a wide field of applications. An exhaustive overview is, e. g., given in [8]. The unique and novel property of the overrunning clutch presented in the paper at hand, is that the clutch works both passively and bidirectional, i. e., no additional active actuation is needed for coupling and decoupling, independent of the rotational direction. In the rest of the paper, we first reference existing clutch designs, then describe in detail the construction and operating modes of our clutch design, and finally present first experimental data which verifies the successful operation of the clutch.

2 Construction and Functional Principle

There exist various design principles for unidirectional overrunning clutches, namely the spring clutch, roller or ball clutch, sprag clutch, and ratchet and ball clutch – just to list the most common types [11]. More sophisticated designs make use of electro-rheological fluids [7, 9] or exhibit special non-linear dynamics [12, 13]. Clutches which are used for autonomous robots need to work bidirectional. Existing approaches control the coupling [4] and thus need additional actuation, e. g. an electromagnetic mechanism to engage the clutch [5]. In contrast, our clutch uses a special mechanism which works fully passively. Often, series elasticities are used [10] to combine several actuators at the same joint. Our clutch already exhibits a small amount of serial elasticity which may be used for multi-actuated joints. Using such techniques, one may eventually reach the power of pneumatic or hydraulic actuators without the need for compressors, which is always difficult to achieve on autonomous robots, although some robots of this kind do exist [1, 2].

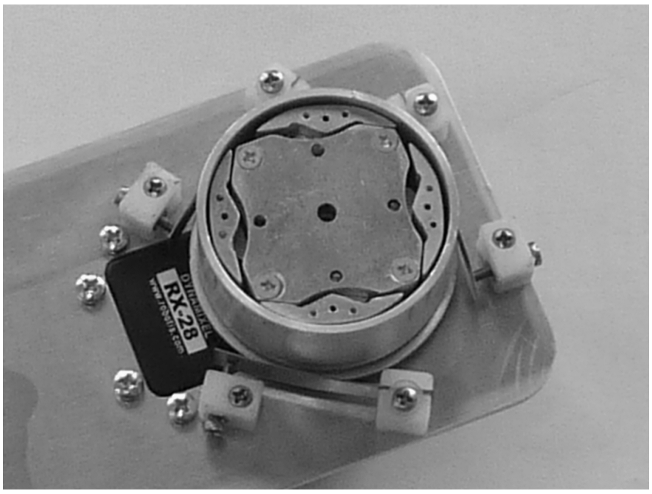

Fig. 1. Picture of the bidirectional overrunning clutch.

2.1 Overview

Overall, the bidirectional overrunning clutch (see Figure 1) is 22 mm long, has an outer diameter of 40 mm and weighs approximately 50 g. All parts consist of aluminium and ABS plastic. A traction principle is used to tranmit the torque from input and output. Furthermore, the clutch works in a passive manner, i. e., no additional actuation is needed to connect or disconnect the actuator from the driven shaft. The mechanism only depends on the relative position between the internal drive shaft, the driven hub, and the case inside which the actuator is mounted (see Figure 2).

2.2 Basic Components

The functional parts of the clutch are shown in Figure 2. Part 2 is the drive shaft of the clutch that is directly connected to the actuator (part 5). It transfers the actuator's torque to the interior of the clutch. Within the drive shaft, four clamping wedges (parts 4) are pivoted radially symmetrical. They are connected to the mechanical grounding (part 1). The internal structure of the clutch is enclosed by the driven hub (part 3). Depending on the current operational mode, the driven hub either rotates freely or transmits the actuator's torque to the hub. The inner cylindrical surface of the driven hub is rubber-coated in the area where the wedges operate. For actuation, a servo motor of the type Dynamixel RX-28 (Robotis, Inc.) is used (part 5).

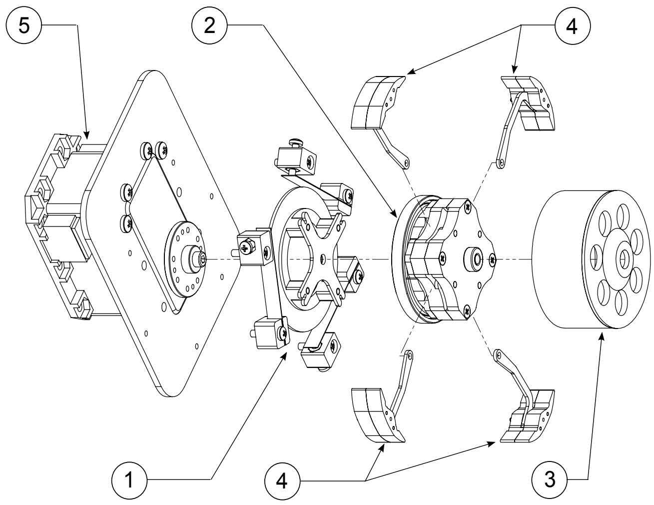

Fig. 2. Exploded view exposing the main components: mechanical grounding (1), drive shaft (2), driven hub (3), wedges (4), and actuator (5).

2.3 Description of the Internal Structure

We now detail the internal construction. Figure 3 illustrates step by step how the basic parts are mounted: the top side of the drive shaft (2), the driven hub (3), and one of the four wedges (4) are shown in section A. Drive shaft and driven hub rotate around the main axis a. The wedge is mounted to the drive shaft and rotates around axis b until the wedge touches the outer surface of the drive shaft. As can be seen in Figure 3 B, all four wedges are mounted radially symmetrical to the drive shaft and rotate as explained before. All four wedges are covered by the bottom of the drive shaft (see Figure 3 C). Both parts of the drive shaft have the same thickness, therefore opposite wedges are mounted symmetrically to the middle of the drive shaft. This reduces backlash between parts 2, 3, and 4, leading to a reliable function of the overall clutch. Figure 3 D shows a synchronization (grounding) cross mounted to the bottom of the drive shaft. This synchronization cross rotates around the main axis a and is connected to all wedges by small guidances. Each of these guidances consists of a 1 mm pin on the bottom of each wedge and a corresponding slot at one the four ends of the synchronization cross.

2.4 Mechanical Grounding

For reliable operation, a frictional engagement between the wedges and the gearbox housing is crucial. This traction is referred to as the mechanical grounding (see part 1 in Figure 2) and serves the following two purposes:

1. Creation of friction torque between wedges and gear housing to avoid random connections of the clutch.
2. Radially symmetrical alignment of the clamping wedges.

The friction torque τ can be fine-tuned using adjustment screws, as shown in Figure 4). A modified pretension of the flat springs results in an alteration of the contact force F. The friction torque of rigid bodies is $\tau = 3\mu rF$, wherein μ is the coefficient of friction and r the radius of the friction washer. The coefficient of friction is an empirical property of the contacting materials, i. e., the type of metal of both the flat springs and the friction washer. With respect to the materials used in our clutch, we have $\mu = 0.19$. The friction torque is necessary for the stable operation of the clutch. However, it is small in comparison to the driven torque of the actuator. Energy waste due to traction is thus negligible.

2.5 Operational Modes and Coupling Sequences

In the following, we will explain the functional sequences of coupling in clockwise rotation and subsequent decoupling. The coupling sequence starts with the clutch in the neutral position as shown in the middle of Figure 5. In this position, the driven hub can freely rotate in both directions.

First, we assume that the drive shaft is directly driven clockwise by the actuator. Due to the mechanical grounding, the wedges do not rotate around the main axis, but instead stay in place. Relative to the drive shaft, they actually rotate counter-clockwise around axis b (review Figure 3). As soon as the clamping wedges achieve a rotation of three degrees relative to the drive shaft, they start to touch the inner rubberized surface of the driven hub. Immediately after that, the clamping wedges also touch the outside of the drive shaft, whereby the clamping wedges are pushed further outwards against the inside of the driven hub (see Figure 5). As a result of the entrapment of the clamping wedges between drive shaft and drive hub, the actuator's torque is fully transmitted to the driven hub. If the actuator rotates further clockwise, then the synchronization cross also starts to rotate into the same direction.

In case of an externally acting torque which turns the driven hub into clockwise direction, the wedges will be released from their clamping positions, so the driven hub can overrun the internal movement. Traction will be released due

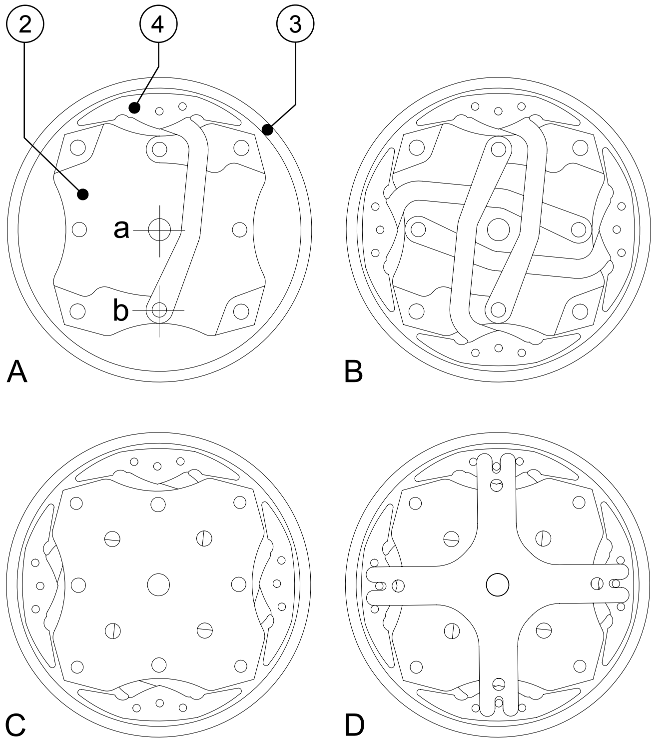

Fig. 3. Internal structure of the clutch. Drawing. A shows the basic components, incorporating the drive shaft (2), the driven hub (3) and a wedge (4), as well as the main axis a of the clutch and the axis b around which the wedge rotates. All clamping wedges are shown exposed in drawing. B and covered in drawing. C, respectively. Drawing. D displays the synchronization cross which synchronizes the four wedges and connects them to the actuator's chassis (grounding).

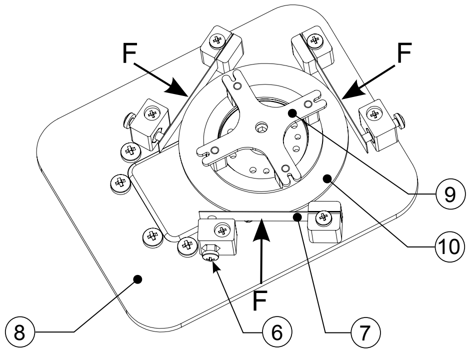

Fig. 4. Overview of the components which generate the friction forces as needed for the mechanical grounding: adjustment screw (6), flat spring (7), gearbox (8), synchronization cross (9), and friction washer (10).

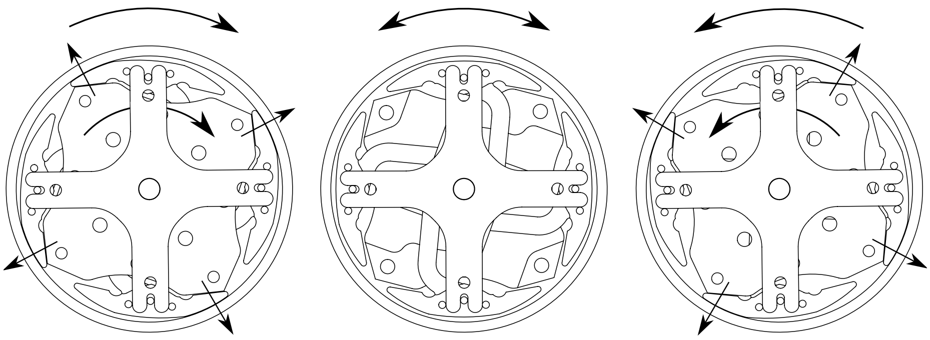

Fig. 5. Operational modes of the clutch. Left: Frictional engagement between drive shaft and driven hub for clockwise rotation. Middle: Uncoupled (neutral) position of the clamping wedges. Consequently, the driven hub can rotate freely. Right: Friction between drive shaft and driven hub for counter-clockwise rotation.

to a *resetting movement* until the wedges reached their neutral position. The coupling sequence counter-clockwise is analogous to the clockwise one.

3 Experimental Validation

Using a straightforward adaption of the measurement apparatuses in [3] and [6], we experimentally verified the proper operation of the described clutch. The setup is shown in Figure 6, along with the corresponding schematic diagram. A pendulum has been lifted and released, using either the clutch or instead a simple metal rod for torque transmission. The results can be seen in Figure 7. In the control condition with the simple metal rod, almost no torsion takes place.

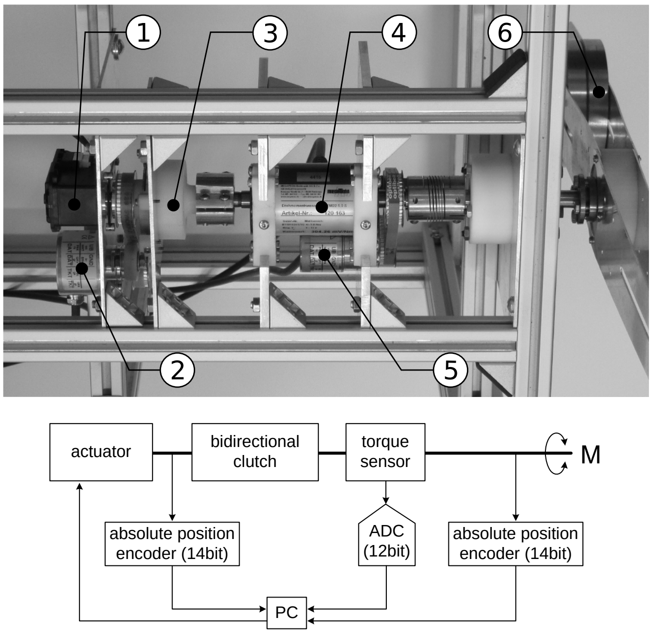

Fig. 6. Picture and schematic diagram of the measurement apparatus. The main components are as follows: Actuator RX-28 (1), angle sensor for the drive shaft (2), bidirectional overrunning clutch (3), torque sensor (4), angle sensor for the driven hub (5), pendulum (6).

The actuator's torque is transmitted directly from the actuator to the pendulum. The expected linear relationship between torque and torsion can be observed.

Using the clutch, this changes significantly. After three degrees of rotational displacement the clutch starts to couple and transmits the actuator's torque up to a specific limit (approx. 1.2 Nm, depending on the rubber coating used). The clutch exhibits a certain amount of series elasticity which can be useful when designing multi-actuator driven joints for autonomous robots. After reversal of the rotational direction, first the torque decreases, then the clutch decouples (see arrows in Figure 7).

Besides the rather slow decoupling process, the clutch can also be decoupled within milliseconds but just switching the motor to free-run operation. As can be seen in Figure 8, the pendulum then immediately swings freely and (almost) frictionless after decoupling, since the gear's friction does not disturb the pendulum's motion.

4 Conclusion and Outlook

We have presented the design of a passive bidirectional overrunning clutch which can be used for the design of rotary joints of autonomous robots. Although fur-

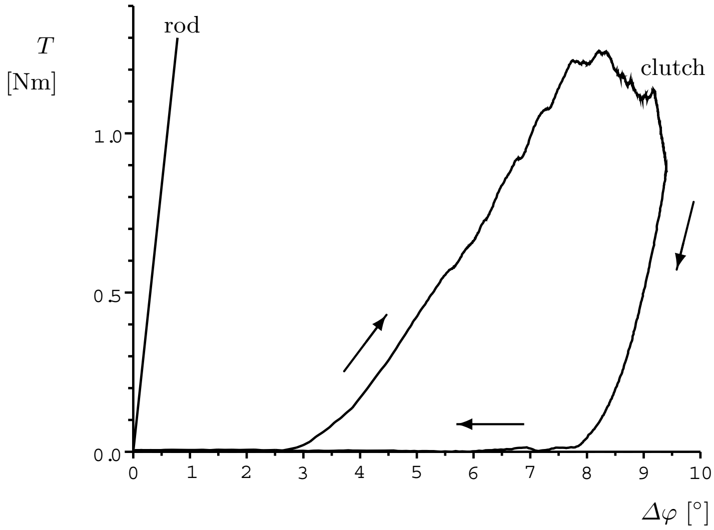

Fig. 7. Torque transmission over degrees of torsion. Compared to the linear direct coupling of a metal rod, the clutch begins to transmit torque after three degrees of angular displacement. There is an upper transmission limit of approx. 1.2 Nm where a stick-slip effect is observable. Sensitive fade-in of torque is eased by the clutch's serial elasticity, whereas decoupling happens more quickly. These properties can be utilized within the mechanical design of angular joints of autonomous robots.

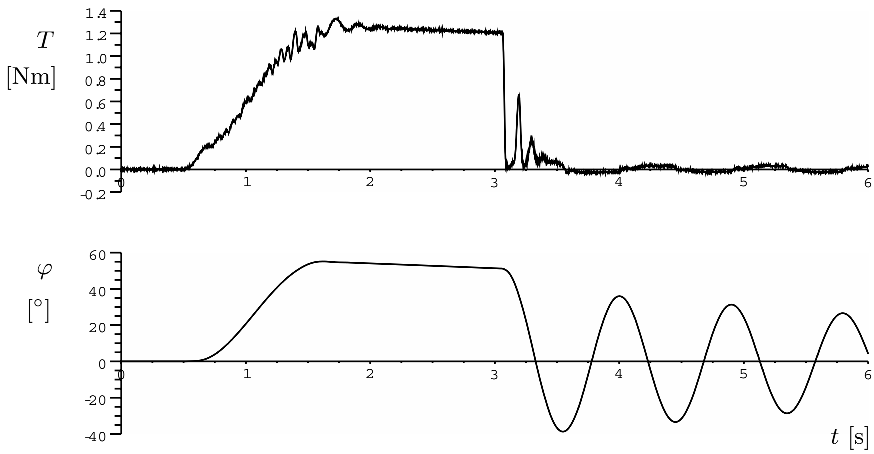

Fig. 8. Coupling and decoupling sequence of the clutch over time. After 0.5 s the actuator increases torque up to approx. 1.2 Nm at 1.5 s. A stick-slip effect can be observed for high torque values. During the 1 s steady-state phase there is no stick-slip effect, but the torque transmission ratio declines slightly due to the rubber coating. Decoupling can either be achieved by slowly decreasing the actuators torque into the opposite turning direction (not shown here, see Figure 7), or by abruptly switching the motor to free-run operation. As can be seen, the pendulum immediately starts to swing freely – the gear's friction is irrelevant.

ther tests are needed, we could demonstrate that the clutch works as supposed. The clutch's series elasticity, bounded torque transmission, and frictionless mode are useful within the mechanical design of robots, since they ease the construction of multi-actuator driven joints and protect the gears and motors from external forces like impacts. Currently, different rubber coatings and morphological design variations are investigated. In parallel, the clutch is used within sensorimotor loops so that control paradigms can be evaluated and extended as to include the quick decoupling mechanism, e. g. in the case of an impending impact during a downfall.

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