Mechanism and Machine Theory 45 (2010) 1395–1406

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

Miniaturized non-back-drivable mechanism for robotic applications

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ARTICLE INFO

Article history:
Received 6 November 2009
Received in revised form 19 May 2010
Accepted 20 May 2010
Available online 8 July 2010

Keyword:
Micro-mechanisms
Clutch
Non-back-drivability
Robotics

ABSTRACT

Small actuators and high efficiency transmissions are essential components in mechatronic and robotic systems, since their performances affect overall volume, weight and power consumption. An innovative miniaturized, low cost, clutching mechanism for robot applications, based on wedge phenomenon in eccentric non-eccentric cam coupling has been designed, developed and evaluated. It is embedded into a human-size, robot hand prosthesis, allowing it to efficiently produce powerful grasps, but it could be employed in all those applications where strict power and weight-size constraints exist and a self-braking mechanism is required. High efficiency, compared to conventional non-back-drivable mechanisms based on screw lead-screw coupling, is achieved by means of roll cylinders inside the clutch. The system has been integrated with a DC motor and a capstan on which a tendon is wound, and then finally connected to the hand fingers. Detailed kinematics, static and dynamic analysis are presented as well as finite-element-method simulations and experimental measurements showing successful fulfilment of requirements. Maximum efficiency is about 0.95 in a large load range, the critical torque at which the mechanism unlocks is about 1 Nm.

1. Introduction

The development of high energy storage capacity actuators and efficient transmission architectures is one of the key issues for the successful achievement of lightweight, efficient, and therefore functional robots. These features become more important in battery-powered systems, where energy-saving and harvesting convert into a longer working autonomy. Within this framework, one of the most representative and challenging unresolved scientific problems is grasping and manipulation with robotic dexterous hands, prostheses and grippers, for which the actuator has been identified as the most serious long term impediment [1]. The idea of having dexterous manipulative, non task-specific robotic tools has been behind the interest shown by a number of research groups worldwide. The covered areas range from kinematics to actuation, to dynamic control of grasping and manipulation including design considerations [1]. When considering prosthetic applications, the multi-functionality of the prosthesis strongly depends on the performance of the actuator unit, since it will determine to a large extent the *autonomy* of the entire system, the available *grasping force*, the *weight* and *size*, and *aesthetic* issues like *noise* [1]. One of these properties is non-back-drivability: a transmission mechanism is defined as *non-back-drivable* when motion can be transmitted only from the input to the output axis and not vice-versa. Such property enables the actuator to deliver a stall torque without energy consumption, therefore the possibility to switch off the power, once a desired position of the hand or grasp stability has been achieved. Generally, in grippers and artificial hands, e.g. employed as end effectors for humanoid robots [2,3], non-back-drivability is important for safety reasons; electrical supply or battery failures should not cause the (potentially dangerous) release of grasped objects or tools due to back-drivable transmissions. Moreover in grippers with high level of underactuation, the presence of a minimum number of non-back-drivable mechanisms is mandatory in order to produce first order form closure grasps [4].

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doi:10.1016/j.mechmachtheory.2010.05.008

Many non-back-drivable mechanisms and mechanical clutches have been developed in the past, and some have been miniaturized for robotic applications where constraints of weight and dimension do exist. In particular *lead-screw* (cf. Fig. 1a), and *worm gear* pairs (cf. Fig. 1b) have been employed. In these non-back-drivability is obtained due to shear friction involved during operation, and therefore their efficiency is very low. The mechanical efficiency of the backward motion ξ, in a common screw/lead screw or worm gear pair is defined as:

$$\xi \approx \frac{2\eta - 1}{\eta} \tag{1}$$

With η the mechanical efficiency of the direct motion. The non-back-drivable condition of $\xi < 0$ is assured with low direct efficiency $\eta \leq 0.5$ [5]. Even though, these mechanisms are easy to build and assemble, and have been successfully employed in several advanced prototypes like the Southampton hand [6], CyberHand [7], RTR II [8], TBM [9] and the recently (since 2007) commercially available i-Limb [10].

Non-back-drivability may also be achieved by means of *high reduction ratio* transmissions, where a large rotation of the motor is transformed into a small displacement of the end-effector. This in turn means that when a large force is applied to the end-effector it corresponds to a small torque on the motor, due to the principle of virtual work. Such a concept has been employed in prosthetic hand prototypes, e.g. in the Oxford [11], the MARCUS [12] and the MANUS [1] hands. The main drawbacks are the high backlash, and consequent controllability problems, resulting from the number of gears and components involved in the transmission chain, and the necessity of finding a trade-off for obtaining suitable speed-torque performances. In order to obtain good performances, bulky motors could be required, resulting in a less dexterous hand, because of the unavailability of high power density commercial actuators.

Besides previous concepts, other kinds of non-back-drivable mechanisms not governed by Eq. (1) are present in literature [13]: these include *brakes* and mechanisms based on *wedge phenomena*. Brakes, commonly employed in automotive, vehicular, and mobile robotic applications, are based on slip friction maximization between mobile surfaces connected to the transmission and finally to the load, and fixed surfaces rigidly fixed to the frame. The main drawback for their employment in robotic hands, grippers, or prostheses, is the requirement of extra energy for connecting (or disconnecting) the braking system. The *free wheel* shown in Fig. 1c (employed for example in bicycle transmission or fishing reels) is a basic mechanism based on the coupling between a cam and rolling elements (spheres, cylinders, etc.), in which wedge phenomena are involved during the operation in one direction, stopping the torque transmission from the output to the input shaft. A conventional cam-ball clutch consists of an inner member, outer member, and rolling elements. The inner driving member has cam surfaces on opposite sides and carries spheres to either wedge or unwedge them. During the counter-clockwise rotation of the inner member, self-energizing friction forces the balls to tightly wedge between the inner and outer members. As a result, the outer and inner members are driven in the same direction. Conversely, if the inner member rotates clockwise or the outer member attempts to run ahead of the inner member, the balls move out of the tightly wedged position. Consequently the connection between the inner and outer members is broken. A system based on this mechanism has been recently employed in the KNU hand [14]. More complex systems based on wedge phenomena may be found in prosthetics: Ottobock Sensor-Hand (the market leader myoelectric prosthesis) [15] embeds a patented system integrated with the motor axis [16] combining a clutch with a two speed automatic transmission. The system automatically increases the pinch force (by increasing the transmission ratio) when high torque is required while grasping, and locks the fingers (thus maintaining the grasp) when the power is switched-off. Such a smart device represents a benchmark for engineers working in the field. Nevertheless, being so sophisticated, and integrated on its motor axis, as well as patented, preclude researchers for exploiting it in other designs or even to replicate it. Moreover, it must be noted that it is composed of approximately 100 sub-parts, including elastic and rolling elements, therefore it cannot be defined as a simple, cheap device.

The objective of this work is the development of an innovative, (i) miniaturized, (ii) low-cost, (iii) high efficiency, (iv) easy to manufacture and assemble, non-back-drivable mechanism with (v) high efficiency. Such a system is currently embedded into a human-size, robot hand prosthesis, named SmartHand [17], allowing it to efficiently produce powerful grasps, but it could be

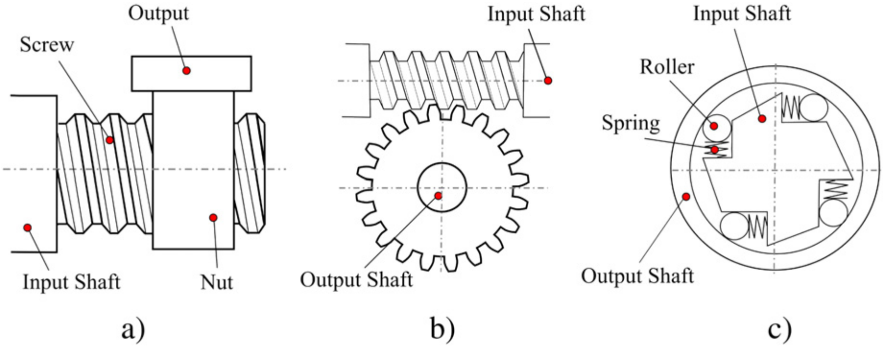

Fig. 1. a) Lead screw pair. b) Worm gear. c) Conventional free wheel.