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Mechanical adaptability analysis of underactuated mechanisms

Wenrui Chen[a], Caihua Xiong[b,*], Wenbin Chen[b], Shigang Yue[c]

[a] School of Robotics, Hunan University, Changsha, Hunan 410082, China
[b] State Key Laboratory of Digital Manufacturing and Equipment Technology, School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan, Hubei 430074, China
[c] School of Computer Science, University of Lincoln, Lincoln, LN6 7TS, UK

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ABSTRACT

Underactuated mechanisms have been implemented in a good number of automation mechanical systems due to their adaptability. There are few measures to quantitatively analyze the mechanical adaptability, although it has been mentioned repeatedly as one of the highlights of underactuated mechanisms in literatures. This paper presents a quantitative analysis methodology for the mechanical adaptability of underactuated mechanisms. Different from compliance, namely the reciprocal of stiffness, the adaptability is presented as an ability of mechanical motion under environment constraint. To quantitatively analyze the adaptive behavior of underactuated mechanisms, a measure based on the relation of force and motion is proposed. The measure is used for the prediction of underactuated grasping process and the evaluation of mechanical adaptability. Meanwhile, we apply this measure to compare the inherent adaptability of three typical compliant underactuated mechanisms, and to analyze the adaptive behavior of other underactuated mechanisms in different structure types.

1. Introduction

In an underactuated mechanism where the number of actuators is less than the degree of freedom, there exist uncontrollable movements and forces so that it interacts passively with the physical environment, such as complying onto the shape of grasped objects with robotic hands [1] and adapting to complex road conditions with walking robots [2]. These behaviors highlight intensively an ability of the underactuated mechanisms to adapt passively to real environment constraints, also called mechanical adaptability. Underactuated mechanisms has been widely utilized in design of robots such as walking robots [3–5], flapping-wing aerial robots [6,7] and rehabilitation robots [8,9], particularly in the design of robotic hands [10–16]. To adaptively grasp an object is to comply onto the shape of the object. In contrast to fully-driven dexterous hands, the underactuated mechanisms provide a simple way to envelop an object with low-quality sensory information and easer control strategy because of their adaptability [17]. Besides a high-level adaptability helpful for enveloping grasp, the mechanical adaptability is also interesting for a second reason: a low-level adaptability is beneficial for precision grasp. An infinite adaptability means that the hands could not exert contact force upon the object but move, while no adaptability means that the hand cannot be driven to move but the contact force changes as active control of actuators. Appropriate adaptability is crucial in a specific task. It is on how to quantitatively evaluate and regulate the mechanical adaptability of underactuated mechanisms, that we set the focus of this paper.

Mechanical adaptability, as a terminology, is used by humans as old as the invention of differential underactuated mechanism [1], if not older. A ubiquitous example about mechanical adaptability in modern times is the automobile differential, where a differential mechanism operates on torques of two wheels so that the wheels can rotate along complex relative trajectory, adapting the uneven territory so that maintaining traction on the bumpy ground without closed loop active control. Mechanical adaptability was presented in robotic grasp for the first time by Hirose and Umetani [18], where a prototype of tendon-driven gripper is developed via differential mechanism for softly and gently adapting to objects of any shape and holding them with uniform pressure. Inspired by the research of neuroscience [19,20], human hand movements were decomposed into primary motion and secondary motion: primary motion achieved via actuators [21,22] and secondary motion implemented with mechanical compliance [23,24]. Upon to now, the research has been attempting to solve the problem of mechanically replicating the high-order information of human hand synergies [25], which depends directly on the adaptability.

This paper presents a measurement to quantitatively analyze the mechanical adaptability of underactuated mechanisms. To the best of our knowledge, the closest work to this paper is in [26] about passively adapting to environmental constraints under possible contact sequences

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[*] Corresponding author.
E-mail address: chxiong@hust.edu.cn (C. Xiong).

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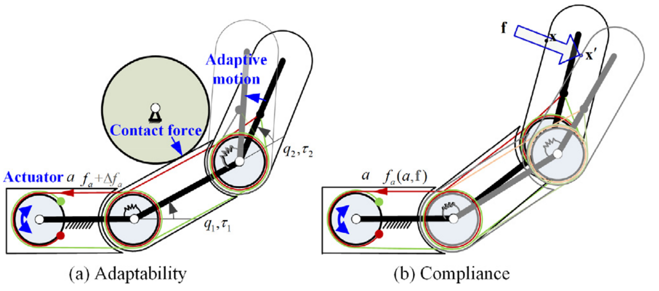

Fig. 1. Difference between adaptability and compliance.

with underactuated mechanisms along a line. The main contribution of our work is the first to quantitate mechanical adaptability of underactuated mechanisms. Examining underactuated mechanisms from the perspective of the adaptability measure presented, some important conclusions and suggestions, which are helpful to improve the performance of underactuated mechanisms, are obtained.

This paper is organized as follows. A measure of the adaptability is proposed in Section 2. Section 3 investigates the grasping processes of enveloping grasp and fingertip grasp with an underactuated gripper. The inherent adaptability of underactuated mechanism is established in Section 4. Section 5 analyzes and compares three typical compliant underactuated mechanisms with the measure of inherent adaptability. The inherent adaptability in other five designs of underactuated mechanisms is displayed in Section 6. Finally, discussions are given in Section 7.

2. Adaptability measure

Adaptability is usually performed along with compliance in underactuated mechanism. Consider an object fixed in the space as shown in Fig. 1(a). An underactuated finger grasps the object with the continuous motion of an actuator. $\tau_i (i = 1, 2)$ is contact force expressed in joint space and $\Delta q_i (i = 1, 2)$ is joint motion of the 2-joint finger. Ignoring frictional force on contact between the finger and the object, the following equation is true during grasping

$$\tau_1 \Delta q_1 + \tau_2 \Delta q_2 = \tau_1 \times 0 + 0 \times \Delta q_2 = 0$$

which means that the contact force is not doing any work. Fig. 1(b) shows the compliant behavior of an underactuated finger (the compliance is measured with the ratio of the deformation to the change of external force). Once an external force acts on the fingertip at a point $\mathbf{x}$, the finger occurs deformation to withstand the external force. It means that the external force does work. The examples in Fig. 1 indicate that the adaptability is different from compliance.

From the hand's point of view, the profile of a grasped object restricts the motion of the hand after the hand contacts with the object. The geometrical profile of the grasped object forms a constraint on the movement of the hand, which is referred to as external constraint, or environment constraint. The robotic hand moves along the geometrical profile of the grasped object. Thus, the mechanical adaptability of underactuated mechanisms is the mechanical motion ability under the environment constraint. It is different from the grasp stability [27] and the grasp capability against the external force [28].

Given a underactuated mechanism, the vector of joint angles is denoted as $\boldsymbol{q}$, and the contact force with the environment constraint is expressed in joint space as $\boldsymbol{\tau}$. Driven by actuators, the changes of the mechanism's posture and contact force, i.e. $\delta_{\boldsymbol{q}}$ and $\delta\boldsymbol{\tau}$, reflect the mechanical adaptability in a specific tasking scenario. To analyze the mechanical adaptability in more detail, the following quantitative measure of adaptability is proposed:

Definition 1. A scalar value Ad given by

$$Ad = \frac{\|\delta \boldsymbol{q}\|}{\|\delta \boldsymbol{\tau}\|} \tag{1}$$

is called the *adaptability* measure at the state $\boldsymbol{q}$ with respect to the external constraints.

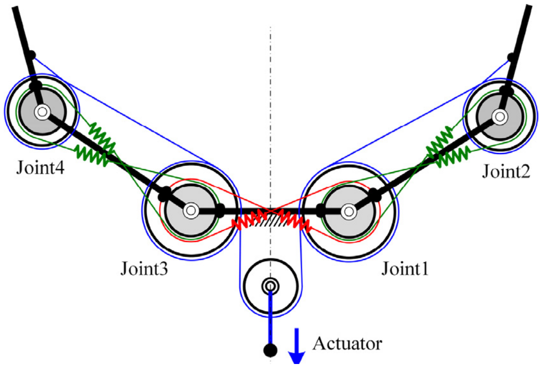

Fig. 2. A gripper with four joints, including one actuator and three groups of elastic constraints.

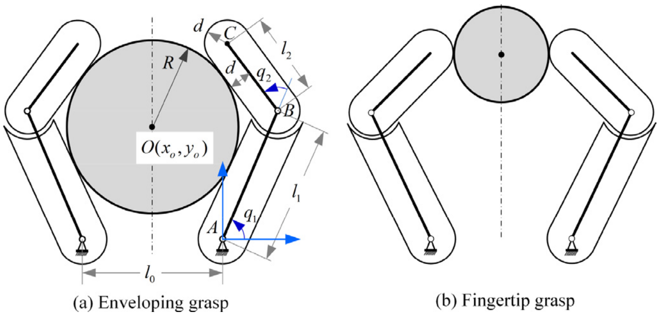

Fig. 3. Two patterns of grasp with a two-fingers gripper.

Ad shares the same dimension as compliance, but has different physical meaning. When the joint motion $\delta_{\boldsymbol{q}}$ is given, the adaptability is inversely proportional to the magnitude of the contact force. From the other side, given the contact force, the adaptability is proportional to the value of the joint motion. So, for a specific task, the higher the value of Ad is, the greater the movement ability of underactuated mechanism on environment constraints is. Extremely, $Ad = 0$ means the mechanism could not be driven by actuators while the contact force is changed. When $Ad = \infty$, the mechanism adapt to the external constraint and do not increase the squeezing impact on the object.

According to the measure Ad, in fully-actuated mechanisms whose number of actuators equals to the degree of freedom, the adaptability can be actively adjustable. With the aid of sensitive sensors, a fully-actuated mechanism cannot only withstand the external constraint through applying force to the constraint, but also comply with the external constraint through driving the joint motion actively. In other words, theoretically, the fully-actuated mechanisms have arbitrary adjustable adaptability. However, the adaptability in underactuated mechanisms seems not obvious. We will display the adaptability of underactuated mechanisms in next section.

3. Grasp analysis of underactuated hand

Consider a simple gripper with two identical fingers (Fig. 2) to grasp cylinders by two typical modes, namely enveloping grasp and fingertip grasp as shown in Fig. 3. The gripper is driven by one actuator via differential transmission. The coupling motion among joints is constrained by 3 groups of springs among 4 joints. The grasped object is placed within the scope of grasping and can be moved freely in the (x, y)-plane. Since both gripper and the grasped object are symmetric, these two fingers have the same motion during grasping process and the force on the springs coupling the two fingers is zero. Hence, we can only analyze