Vibration-based Full State In-Hand Manipulation of Thin Objects

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***Abstract*— Robotic hands offer advanced manipulation capabilities, while their complexity and cost often limit their real-world applications. In contrast, simple parallel grippers, though affordable, are restricted to basic tasks like pick-and-place. Recently, a vibration-based mechanism was proposed to augment parallel grippers and enable in-hand manipulation capabilities for thin objects. By utilizing the stick-slip phenomenon, a simple controller was able to drive a grasped object to a desired position. However, due to the underactuated nature of the mechanism, direct control of the object's orientation was not possible. In this letter, we address the challenge of manipulating the entire state of the object. Hence, we present the excitation of a cyclic phenomenon where the object's center-of-mass rotates in a constant radius about the grasping point. With this cyclic motion, we propose an algorithm for manipulating the object to desired states. In addition to a full analytical analysis of the cyclic phenomenon, we propose the use of duty cycle modulation in operating the vibration actuator to provide more accurate manipulation. Finite element analysis, experiments and task demonstrations validate the proposed algorithm.**

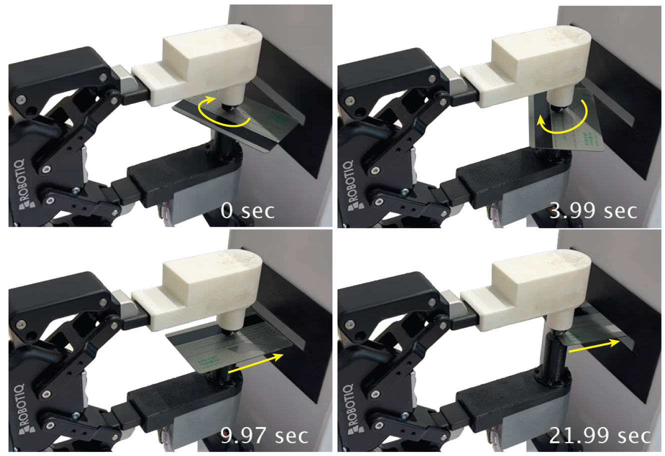

Fig. 1. A parallel gripper equipped with the Vibration Finger Manipulator (VFM) demonstrates the manipulation of a credit card into an ATM-like slot. Using only vibration, the card is first aligned with the slot through rotational motion, followed by linear motion into the slot.

I. Introduction

In-hand manipulation typically requires either a dexterous robotic hand with multiple degrees of freedom (DOF) [1] or complex manipulation strategies involving dynamic interactions with the environment [2], [3] or environmental engagement [4], [5]. However, these approaches often demand sophisticated sensing and control systems [6], leading to increased complexity and cost. Such factors can hinder the practicality of these methods in applications like assembly lines or medical procedures.

Parallel jaw grippers are a class of low DOF end-effectors that are unable to perform intrinsic in-hand manipulations. They are inherently limited to a single DOF, restricting their ability to manipulate objects within their grasp. Nevertheless, they are renowned for their simplicity, durability and affordability. These are widely adopted in industrial applications. Their versatility allows for precise grasping of various objects, making them indispensable in material handling tasks [7]. The prevalent manipulation strategy for these grippers involves a pick-and-place approach, where objects are placed on some surface and re-picked with a different grasp configuration [8]. However, this method can be time-consuming and requires ample workspace, limiting its applicability in certain scenarios. Several mechanisms have been proposed to augment the capabilities of parallel jaw grippers such as an active conveyor surface [9] and pneumatic braking mechanism [10]. However, these additions often introduce complexity and may be limited to specific manipulation tasks [11]–[13].

Vibration has been employed as a mechanism for object manipulation since the pioneering work of Chladni with horizontally vibrating plates [14] and the establishment of vibrating conveyor belts in industrial part management [15]. These have contributed to the existing technology of vibrating systems often based on acoustic [16], [17] or mechanical excitation [18]–[23]. A fundamental aspect of vibration-based manipulation is the *Stick-Slip* effect [24]. This phenomenon involves alternating between static friction (no relative motion) and kinetic friction (sliding motion) at the contact interface between two surfaces. More focused toward robotic applications, the Stick-Slip effect was harnessed to design simple, low-cost micro-robots. A notable example is the use of two collinear vibration motors, as proposed in [25], to achieve effective locomotion. This approach inspired the development of the Kilobot platform, a widely used tool in swarm robotics research [26], [27].

Vibration has been primarily used in robotic hands to control slippage, without additional manipulation capabilities [28]–[31]. Recently, vibration was introduced to in-hand manipulation by parallel jaw grippers [32]. A novel mechanism termed the *Vibratory Finger Manipulator* (VFM) was proposed where an off-the-shelve vibration motor within one jaw manipulates a grasped object. A simple rotary actuator allows for precise control of the vibration direction, enabling precise position manipulation of the grasped object. While the proposed controller demonstrated partial stability

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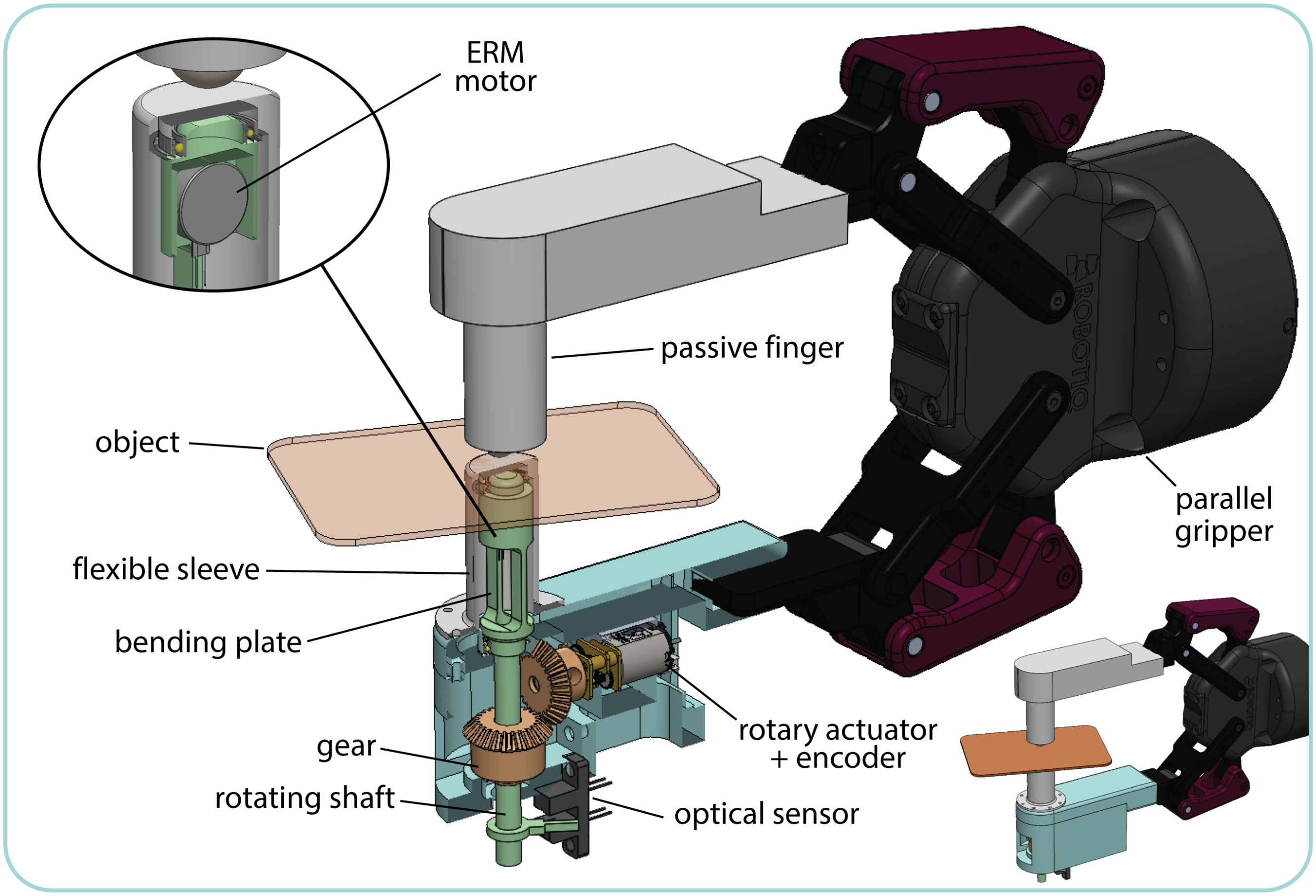

Fig. 2. Design of the Vibratory Finger Manipulator (VFM) and its mount on a parallel jaw gripper.

[33] with accurate position control, it was unable to control the object's orientation. Furthermore, the effect of vibration frequency on the control's performance was not considered.

In this letter, we address the manipulation challenge of a thin object over its full state using a VFM-based parallel gripper. The VFM-object system is underactuated and does not enable direct control over the entire state and, particularly, the orientation. Hence, we decouple the position and orientation components of the manipulation task and propose a manipulation algorithm. Through rigorous analysis of the VFM-object system, we devise an approach to exert cyclic motion of the object to reach the desired orientation. Then, linear motion through the object's center-of-mass will enable rotation-free motion to the desired position. In addition, we explore the use of duty cycle modulation to operate the vibration motor over the simple application of a constant voltage. We show that the duty cycle better maintains the orientation of the object, yielding increased accuracy. The proposed mechanism and vibration-based control have potential applications in fields such as medical procedures, requiring precise manipulation of delicate instruments like surgical knives. Additionally, it could be utilized for tasks like textile and tissue handling, plastic card (e.g., security and ATM cards) insertion as demonstrated in Figure 1 or manipulating keys.

II. System & Method

A. Design

The Vibration Force Module (VFM) was proposed by Nahum and Sintov [32] for in-hand object manipulation of thin objects within a parallel gripper. We briefly present its design mechanism seen in Figure 2. The VFM comprises an Eccentric Rotating Mass (ERM) motor and a rotary actuator. The ERM motor, housed within a 3D-printed shaft, generates vibrations perpendicular to the shaft axis. The shaft, made with Polylactic-Acid (PLA) filament, is supported by three bearings to ensure concentric rotation with minimal friction. The shaft also includes a thin bending plate that amplifies the vibrations by having its normal perpendicular to the ERM axis and, thus, minimizing energy loss. The entire assembly is encased in a flexible Thermoplastic polyurethane (TPU) sleeve to enhance vibration transmission and protect internal components.

The rotary actuator, equipped with an encoder, controls the shaft's orientation, enabling directional vibration control. An optical sensor enables the calibration of the encoder and rotating shaft. In addition, a passive finger equipped with a roller ball bearing opposes the vibrating finger, creating an