Wearable Roller Rings to Augment In-Hand Manipulation through Active Surfaces

Hayden M. Webb[1], Podshara Chanrungmaneekul[1], Shenli Yuan, and Kaiyu Hang[1]

***Abstract*— In-hand manipulation is a crucial ability for reorienting and repositioning objects within grasps. The main challenges in this are not only the complexity of the computational models, but also the risks of grasp instability caused by active finger motions, such as rolling, sliding, breaking, and remaking contacts. This paper presents the development of the Roller Ring (RR), a modular robotic attachment with active surfaces that is wearable by both robot and human hands to manipulate without *lifting a finger*. By installing the angled RRs on hands, such that their spatial motions are not colinear, we derive a general differential motion model for manipulating objects. Our motion model shows that complete in-hand manipulation skill sets can be provided by as few as only 2 RRs through non-holonomic object motions, while more RRs can enable enhanced manipulation dexterity with fewer motion constraints. Through extensive experiments, we test the RRs on both a robot hand and a human hand to evaluate their manipulation capabilities. We show that the RRs can be employed to manipulate arbitrary object shapes to provide dexterous in-hand manipulation.**

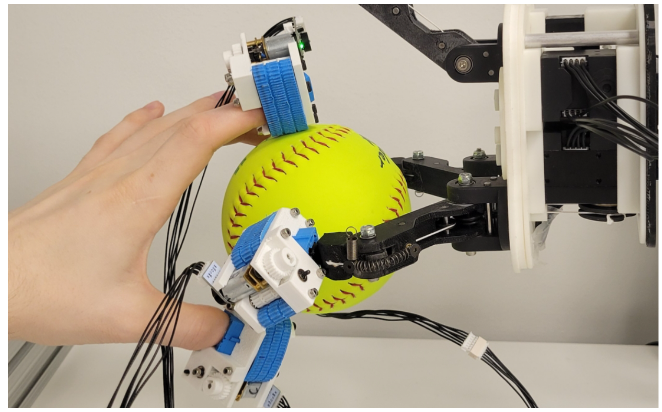

Fig. 1. Four Roller Rings, affixed on both a robot hand and a human hand, that are co-grasping a softball. Configurations like these can enable in-hand human-robot co-manipulation for grasped objects.

I. Introduction

To physically engage robots with our daily tasks, evolving new modalities of in-hand manipulation skills is crucial for addressing problems associated with the traditional manipulation paradigms. In the past decades, extensive studies have worked towards improving in-hand manipulation by developing new hand designs, computational models, and more integrated systems. These not only mechanically provide better options, but also computationally and perceptually enhance their manipulation capabilities [1]–[3].

Typically, in-hand manipulation is performed using precision grasps due to its robust dexterity. However, such hand-object configurations come at the cost of stability and strength due to the small fingertip contacts. Moreover, due to the high degrees of freedom, precision grasp manipulation often relies on computationally complex, small-scale, and vulnerable non-holonomic movements. In contrast, using power grasps is more stable, but typically lacks the capability to perform relative motions between the object and hand. While in-hand manipulation, in essence, is about stably maintaining and moving contacts with the manipulated object, most traditional approaches fail to encompass these values.

To this end, a number of novel hands have been developed to fill in the aforementioned gaps. Underactuated hands have been designed to enable passive stability maintenance, while requiring significantly fewer degrees of control to be regulated for in-hand manipulation [4]. Yet, such designs are limited to very small-scaled manipulation when utilizing manipulation techniques, such as finger-gaiting [5], due to their high complexity and lack of stability. Alternatively, compliant palm support-based manipulation has been explored to greatly expand manipulation ranges [6]–[8], however, without much consideration for their manipulation precision. Moreover, techniques and hands such as these require non-holonomic movements in their planning. This is due to the potential for unstable grasps or collisions along the direct manipulation path between arbitrary positions, or the lack of guarantees for orthogonal axes of rotations (Further discussion of this can be found in Sec. IV). This necessitates detours to ensure stability and movement while guaranteeing a full manipulation solution. Despite this, these hands and techniques do guarantee full movement solutions for almost all in-hand manipulation.

Alternatively, the concept of active surfaces [9], which actively moves a grasp contact by directly translating the contact on the hand, has created a new modality for in-hand manipulation. Hands developed with active surfaces are capable of performing dexterous manipulation *without lifting a finger* and, in theory, can translate the contacts without limitations. However, this has not proven to be the case for previous designs utilizing active surfaces. For rigid hands, motions actuated by active surfaces need to be precisely controlled to maintain the grasp stability [10]–[12]. The BACH hand further combined mechanical compliance and active surfaces into a hand design [13], enabling unprecedented in-hand manipulation without requiring complex computational models or control schemes while still garnering precision grasp robustness and power grasp stability. However, a major

[1]Department of Computer Science, Rice University, Houston, TX 77005, USA. This work was supported by US National Science Foundation award FRR-2240040.

limitation of the BACH and other similar systems is that the benefits from active surfaces cannot be directly transferred to other hands. Likewise, algorithms for these designs are integrated into the system's design directly rather than being generally integratable across designs. Thus, these designs and their solutions only exist in an *ad hoc* manner and cannot be transferred to other existing hands.

To this end, we, in this work, propose the design of the Roller Rings (RR) (exemplified in Fig. 1) – a new form of wearable devices that can enable and augment active surface-based in-hand manipulation for *any hand* due to its modularity. In brief, this work provides:

1) The world's first wearable device for manipulation augmentation that is low-cost and easy to fabricate;
2) A complete manipulation solution through differential manipulation motions (Sec. IV);
3) A manipulation device attachable to any robot and human hand while not changing the existing capability of the original hands.

We discuss related research in Sec. II, then describe the design principles for the Roller Rings in Sec. III. In Sec. IV, we derive the differential motion model for the RR-based in-hand manipulation. Real-world experiments with both robot and human hands are discussed in Sec. V. Finally, Sec. VI concludes and discusses the future work.

II. Related Work

In the past decades, a myriad of robot hands have been developed to carry out dexterous manipulation [3]. The Stanford/JPL hand [14] and the Utah/MIT hand [15], for example, are among the earliest hands with in-hand manipulation capabilities. Because a number of robot hands are inspired by human hands, common biomimetic manipulation techniques such as finger-gaiting became a natural choice for robot manipulation [5], [16]–[18]. During finger-gaiting, robot fingertips will sequentially break and remake contacts, allowing fingers to "walk" along the grasped object to perform manipulation. However, fingertip movements are limited by grasp stability and small motion scales. Differing from finger-gaiting approach, rolling manipulation [19]–[21] allows the grasped object to be moved in-hand without breaking contacts, enabling simpler controls and more stable manipulation. However, this approach is still challenged by the small scale of in-hand object motion ranges. Moreso, these approaches are similar in that their respective movement schemes are nominally non-holonomic.

A. Rolling Manipulation and Active Surfaces

Robot grippers with active surfaces [10]–[13], [22]–[24] are specifically designed to perform rolling manipulation. These grippers have shown their unique abilities in various in-hand manipulation tasks, as they allow the grasped object to be manipulated without the need to lift fingers during manipulation. The velvet finger [22], for example, utilizes a set of actuated fingers inlaid with active surfaces to perform both rotational and translational manipulation. Additionally, the Roller Graspers [10]–[12] have active surfaces designed into their fingertips to dexterously grasp and manipulate objects with the combination of roll and pitch movements. A more recent work [13] demonstrated that active surfaces and mechanically compliant grasps can be used to dexterously manipulate objects without any complex computational models or control schemes non-holonomically. However, these designs do not generalize to, or enhance, the capabilities of any existing hand designs. Thus, existing hands cannot benefit manipulation-wise without modifying their existing capabilities or completely redesigning the system. In this work, we address these issues by creating an active surface-based manipulator that can be easily affixed to existing systems to provide these capabilities (See Sec.III) without compromising the existing system.

B. Algorithmic Approaches to Active Surfaces

Computational models have been derived to search for the optimal combinations of active surface motions to enable in-hand manipulation. For example, [25] samples certain grasps using object mesh models to generate object rotations. Using this approach, the sum of combinations of angular velocities is standardized to actuate the in-hand motions of the grasped object. [26], [27] used a vision-based control system to determine the geometric information of an object in the next frame and calculated the necessary control commands of the active surface motions to achieve it. Additionally, employing control over both the belts and fingers greatly increases the flexibility of the active surface-based manipulation, while at the cost of more complex hand-object models [11]. However, these existing algorithms are all designed in an *ad hoc* manner to only work for their respective designs. Therefore, existing hands are not able to directly benefit from these approaches. To this end, this work presents a generalized Motion Model (See Sec. IV) to remediate this discrepancy.

C. Human Augmentation

Numerous augmentation devices have been designed utilizing the same concepts as robotic hands to mitigate the gap in in-hand manipulation for users [28]–[30]. Thus, these approaches are nominally focused on recreating power and precision grasps in their designs. The Yale Multigrasp Hand [31], for example, uses a series of body-powered cables to recreate different forms of grasps to facilitate manipulation. Likewise, myoelectric augmenters, like in [32], utilize a set of actuated cables that drive underactuated fingers through signals sent by the body. Both devices' fingers can be used in conjunction to manipulate a grasped object. However, because these designs utilize biomimetic power and precision grasps, augmentations like these are naturally lackluster at performing complex in-hand manipulation tasks. Moreso, as often seen in nature, these manipulation paths are non-holonomic and often require detours during manipulation due to the lack of stable direct control in this grasp formation. Thus, this work provides the framework for a manipulation device that can be affixed to any biomimetic hand to augment their in-hand manipulation capabilities (See Sec. V).