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Design and development of a novel micro-clasp gripper for micromanipulation of complex-shaped objects

Sandeep Krishnan, Laxman Saggere*

Department of Mechanical and Industrial Engineering, University of Illinois at Chicago, Chicago, IL 60607, USA

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ABSTRACT

This paper presents the design and development of a novel tool, called the micro-clasp gripper, for accomplishing firm and stable gripping and manipulation of complex-shaped micro-scale objects in any orientation using a single rectilinear actuator. The micro-clasp gripper is a compliant mechanism comprised of an endeffector with a closed-loop boundary that can be folded and unfolded in a plane by the action of the rectilinear actuator. Upon actuation, the endeffector of the micro-clasp gripper clasps an object by first encircling the object, and then, folding in on the object to accomplish multi-point contact with the object. This clasping of the micro-object with multi-point contact ensures a stable grip on the object regardless of its shape and initial orientation, even in presence of ambient disturbances the transport of the object or complex micromanipulation and microassembly tasks. The design of the micro-clasp gripper is obtained through a systematic modeling and topology optimization techniques, and a proof-of-principle device is microfabricated using conventional micromachining techniques. The device design is validated through experiment-model correlation studies on the input-output characteristic of the micromachined prototype, and practical feasibility of the clasping functionality of the gripper is demonstrated through experiments involving grasping and repositioning of irregularly shaped micro-particles on a glass substrate.

1. Introduction

Micromanipulation – the task of grasping, moving, reorienting and repositioning of micro-scale objects – is central to assembly and manufacturing of micromachines [1–3]. Micromanipulation of objects in applications such as complex 3D microassembly involves grasping and repositioning of objects that are irregularly shaped and/or subject to ambient disturbances such as mechanical vibrations or airflow. Achieving stable grasps of objects in such manipulation tasks is particularly challenging, and grippers for accomplishing stable grasps reliably are lacking.

Over the last decade, researchers have demonstrated a variety of techniques for mechanical manipulation of objects at micro- and nano-scales. Most currently available micro-grippers are compliant (flexible) devices, typically comprised of two legs that open and close, to grasp a micro-object at two contact locations. Some examples of these devices include SMA (Shape Memory Alloy) actuated micro-grippers [4–6], electrostatically driven micro-grippers [7,8], a hybrid microgripper that uses both electrostatic actuation and vacuum principles to accomplish grasp and release [9], passive micro-grippers that purely rely on compliance to grip micro-objects [10,11], electrothermally actuated micro-grippers [12–14], piezoelectrically actuated micro-grippers [15–17], a superelastic alloy micro-gripper with embedded electromagnetic actuators [18], and multi-finger micromanipulators on chip [19,20]. However, currently available gripper devices are not ideal for grasping complex or irregularly shaped objects mainly because it is difficult or tedious to ensure stable grasps on such objects with a two-point contact.

Grasping of objects of any shape can be achieved more easily if the endeffector of the gripper could establish contact at multiple (three or more) points on the object. One possible way of accomplishing multi-point contact with the object to be manipulated is to employ a gripper or endeffector with multiple fingers. However, such a manipulation using a gripper with multiple fingers would entail a spatial mechanism that is difficult to build and/or require multiple actuators at micro-scale. Moreover, such a multipoint contact manipulation using a multifinger gripper would also involve determination of ideal contact locations on the irregularly shaped object to achieve a stable grasp a priori before every grasping event. Therefore, an ideal gripper for accomplishing multipoint contact manipulation of micro-scale objects of any shape should have the following attributes: (i) it should be a planar mechanism so that it is amenable to microfabrication constraints, (ii) it should utilize minimal number (ideally one) of micro-scale actuators, and (iii) it should not involve determination of grasp contact points on the object a priori for achieving stable grasps. The main research

* Corresponding author. Tel.: +1 312 413 1031; fax: +1 312 413 0447.
E-mail address: saggere@uic.edu (L. Saggere).

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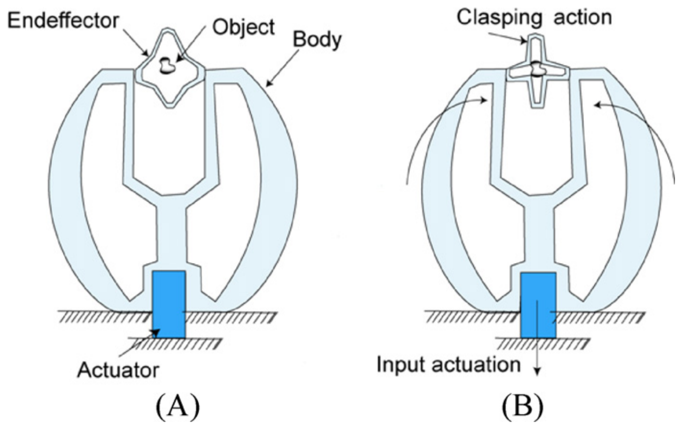

Fig. 1. Conceptual diagram of the micro-clasp gripper: (A) initial open (unfoled) configuration before the input actuation and clasping of the object, and (B) final closed (folded) configuration after the actuation and clasping of the micro-object.

issue in the synthesis of such a planar gripper mechanism is to identify an innovative manipulation scheme and topological design of the endeffector beyond the traditional microgrippers.

Motivated by the need for a planar microgripper mechanism capable of accomplishing multipoint grasp of irregularly shaped micro-objects without the knowledge of ideal contact points for stable grasps, this paper presents a novel chip-scale gripper, called the micro-clasp gripper, for accomplishing firm and stable gripping of micro-scale objects of arbitrary shapes and orientations using a single rectilinear actuator. The concept of the micro-clasp gripper (first introduced by the authors in [21]) followed by design, modeling, fabrication, and experimental characterization of the gripper's performance including demonstration of manipulation of an irregularly shaped particle, are detailed in order in the following sections.

2. Micro-clasp gripper concept

The micro-clasp gripper, conceptually illustrated in Fig. 1, is a planar mechanism comprised of two main components: an endeffector that can be lowered down from top and folded and unfolded around an object by the action of a rectilinear actuator and a compliant mechanism body that transforms the force and displacements from the actuator to the endeffector. The endeffector is a closed-loop structure with a hollow interior; the folding and unfolding actions of the endeffector structure around an object lying within the structure boundaries causes "clasping" and "unclasping" of the object. The body of the micro-clasp is a monolithic compliant structure that has symmetry about a vertical axis and features one input point on the vertical axis and two output points symmetrically about the vertical axis. The body is connected to a linear actuator at the input point and to the endeffector at its two output points.

The topology of the body is such that it transforms a single rectilinear input displacement imparted along the longitudinal direction into amplified output displacements along transverse directions at its two output points, which in turn serve as the input displacements to the endeffector. Upon actuation by these two input displacements in the transverse direction, the endeffector structure that is initially in an open configuration, folds into a closed configuration and folds in on an object lying within the clasp area. As the endeffector structure makes contact with the object at various locations, the object will reorient and self-equilibrate regardless of its initial orientation until the structure is firmly wrapped on the object and a stable grasp is formed. When the input displacement to the body is removed, the micro-clasp returns to its normal open configuration and the object is released from its clasp.

The synthesis of the gripper with the above conceptualized functionality involves obtaining a suitable topology and dimensions of its two main components, viz. the body and the endeffector. The topologies should allow for the entire gripper to be fabricated as a monolithic structure on a silicon (or other suitable) substrate using the standard micromachining techniques. In addition, the topology of the body should allow for integration of a suitable miniaturized actuator or access for a mechanical probe tip to provide the necessary input displacement and force to operate the endeffector. An ideal actuator for supplying the necessary input force to the gripper for precise repeated operations and/or transport of the gripped object over certain distances would be a miniaturized stack piezoelectric actuator due to its relatively large force per stroke capability. Alternatively, for operation of the endeffector at a fixed location of the gripper, the actuation can be provided by a simple mechanical probe that can rectilinearly push/pull at the input actuation point of the mechanism body.

3. Design

Considering that the endeffector and the body components of the monolithic gripper have uniquely different input–output characteristics, the complete gripper design is conveniently accomplished by designing each component separately, treating each component as a free-body in static equilibrium. From the free-body equilibrium principle, the force/moment that the body applies on the endeffector will be equal and opposite to the reaction force/moment that the endeffector applies on the body and the displacements/rotations at the interconnection points on two components will be compatible. The entire design approach involves the following four stages: (i) design of a suitable topology and dimensions for the endeffector, (ii) derivation of closed-form analytical expressions for necessary input force and moment on the endeffector as functions of displacements and rotations at the input points to the endeffector, (iii) design of an optimal topology and dimensions of the compliant mechanism body, and (iv) integration of the body and the endeffector components to obtain the complete design of the gripper. Accordingly, each of these design stages is described separately in the following subsections.

3.1. Endeffector design

As described in Section 2, the conceptual design of the endeffector requires that a contiguous boundary be morphed from an open (unfolded) configuration into a closed (folded) configuration, thus significantly reducing its initial area of enclosure, when actuated by two inward transverse displacements and rotations (accompanied by forces and moments) at the interconnection points with the body. This type of mechanical action in the endeffector requires a topology that allows large displacements and rotations of sections that comprise interior boundary. A simple kinematic model of the topology conceived for the endeffector to accomplish the desired folding/unfolding action is shown in Fig. 2. The kinematic model is comprised of multiple rigid links that are connected in a closed loop by means of rotary (pin) joints, some of which are constrained by weak torsional springs, to allow for large rotations of the rigid links. When the displacements and rotations (or equivalently force, P, and moment, M) are applied transversely on the two sides of the endeffector as schematically illustrated in Fig. 2, the rigid links fold inwards at the rotary joint locations (and thereby decrease the area enclosed by the links).

The endeffector design task involves transforming the kinematic model of the mechanism comprised of rigid links and lumped compliant joints in Fig. 2 into a distributed compliant mechanism and determining its topology and dimensions in such a way