Robotics and Autonomous Systems 74 (2015) 166–174

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

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

Automated dual-arm micromanipulation with path planning for micro-object handling

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HIGHLIGHTS

- Micro-object handling through an automated dual-arm micromanipulation system.
- Image processing to detect the targeted object and other obstacles.
- Generation of collision-free paths for the two probes via artificial potential field.
- Probe reconfiguration scheme to minimize the adhesion for object release.

ARTICLE INFO

Article history:
Received 15 June 2014
Received in revised form
30 December 2014
Accepted 12 July 2015
Available online 29 July 2015

Keywords:
Automation
Computer vision
Dual-arm micromanipulation
Path planning
Robot control

ABSTRACT

Object handling has been a challenging operation at the microscale level. In order to manipulate these micro-objects within a confined workspace, it is inevitably imperative for the handling tool to be manipulated along an unobstructed trajectory or path. In addition, the presence of undesirable adhesion force can cause the object to adhere to the tool, making the release process problematic. This work presents the development of an automated dual-arm micromanipulation process to overcome these challenges in micro-object handling. The two probes of the dual-arm micromanipulation system were individually controlled to manipulate a micro-sphere lying on top of a glass substrate. A potential field path-planning algorithm was employed to evaluate the paths for positioning of the two probes and prevent the probes from undergoing collisions. To release the grasped micro-sphere after manipulation with minimal adhesion force, the orientations of two probes were reconfigured to reduce the contact area with the sphere. Vision images obtained from a top-view CCD camera were utilized to evaluate the contour of the sphere for automatic reconfiguration of the two probes. Experimental results confirmed that the two probes can be manipulated to grasp the targeted micro-sphere from arbitrary positions and the incorporation of the probe reconfiguration scheme yields a higher success rate for sphere release.

1. Introduction

Over the past few decades, robotic manipulators have been utilized extensively in a variety of manufacturing operations. The use of manipulators helps reduce human effort in accomplishing these operations and maintains the quality standards of the products. Recently, the applications of robotic manipulators have been extended to the microscopic domain. Through the utilization of various microscale handling tools, robotic manipulators are capable of performing many delicate operations, for example, the manipulation of micro-objects or tissue cell specimens, which are difficult to perform solely by the hands of humans [1–4].

When a robotic manipulator is utilized to manipulate micro-sized objects, the influence from adhesion force becomes more prominent. The adhesion force can cause the objects being manipulated to adhere to the tool, making the release process problematic. To overcome this issue, researchers have investigated different strategies to ease detaching the adhered objects from the tool. For instance, the tool can be equipped with actuators to induce vibration [3] or electrostatic force [5] for the detachment. Another stream of strategies involves the use of multi-tool manipulator for micro-object handling. Tools and probes are arranged in a gripper [6,7] or cage [8,9] configuration and the object release process is performed through coordinating the movements between two or more probes.

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http://dx.doi.org/10.1016/j.robot.2015.07.012
0921-8890/

In our previous research [10], our group reported the development of a dual-arm micromanipulation system to manipulate a polymer micro-sphere via the two individually-controlled probes. By monitoring the images displayed on the computer screen, operators can perform different tasks such as grasping and manipulation of the micro-sphere by specifying the initial and the final positions of the two probes on the screen manually using the mouse cursor. Through this developed control interface, a probe reconfiguration process for object release was also proposed and was found to be effective in minimizing the adhesion issue. However, the entire process involves intensive human effort and the repeatability in positioning the two probes for object grasping varies from one operator to the other. In order to enhance the performance of the process, the manipulation of the two probes can be automated via visual feedback.

When the two probes of the system are manipulated simultaneously to their desired positions for object grasping, there is a possibility that the two probes could collide with each other. Hence, the movements of these probes must be coordinated and planned in advance to avoid damages to the probes after collision. Path planning in the microscopic domain has received much attention in recent years. Algorithms that have been utilized for path planning include the potential field approach [11–14], the rapidly-exploring random trees (RRT) approach [15], the fuzzy-logic approach [16], and the reinforcement learning approach [17]. Classical path planning algorithms, such as different graphic-based and grid-based search methods [18,19] could also be considered for microscopic applications. Among these approaches, the potential field approach is widely adopted due to its elegance and simplicity [20] and further, this approach continues to be used for various microscale applications. This approach was first proposed by Khatibet al. [21] for real-time obstacle avoidance. Utilizing this approach, Balch et al. [22] later developed a new methodology that was capable of avoiding local minima of the field. Other techniques such as numerical approach [23] and simulated annealing [24] had also been reported to resolve the local minima issues during the path planning process.

In this paper, the micro-object handling operation as described in [10] was automated through the incorporation of different algorithms into the dual-arm micromanipulation system. In contrast to many research studies, two probes of the system can be placed arbitrarily at any two positions at the beginning of the experiment, which significantly enhances the manufacturing flexibility of the entire micromanipulation process. To coordinate the movements of the two probes, an artificial potential field algorithm was first employed to evaluate the collision-free path for positioning the two probes for sphere grasping. Next, the grasped micro-sphere was manipulated to a new location and the two probes automatically reconfigured themselves to reduce the adhesion force between the probe and the micro-sphere. A vision-based algorithm was developed to automatically extract the contour of the grasped micro-sphere from the images and compute the repositioning path of the two probes for object release. Hence, the process can be performed with high repeatability in order to identify the optimal parameters for object release. Experiments were conducted to evaluate the performance of the proposed automatic path planning and probe reconfiguration algorithms.

2. Background

2.1. Dual-arm micromanipulation process

The micromanipulation system used for the experiment consists of two micromanipulators and a vision system. Each micromanipulator provides three independent translational motions (x, y, z) to the attached tungsten probe with a resolution of 20 nm. The two tungsten probes, each with a tip radius of 1 μm, are utilized to perform the manipulation experiments of polymer micro-spheres, Bio-Gel P-6 DG. The micro-spheres have a mean diameter of approximately 90 μm, which is comparable to the size of a human embryo or a bone marrow cell commonly used in biological studies. To securely grasp a micro-sphere, the probes must provide sufficient contact area at the point in contact with the sphere. In this work, the micro-sphere will be grasped by two conical probes at a position at which the probe diameter at the point of contact is approximately 15 μm, providing a 6:1 diameter ratio for proper object handling. The vision system has a 2048-by-1536 pixel resolution. Combined with a 10× (N.A. 0.25) objective lens, the pixel pitch of the vision system is 0.32 micron/pixel while the optical resolution is approximately 1.3 μm. A complete description of the system can also be found in [10].

Before the experiment, the entire system was pre-calibrated by first manipulating two tungsten probes along the z-direction to gently touch the substrate surface. Then, the two probes were lifted upwards 45 μm above the substrate surface, which was approximately half of the height of the sphere. After this calibration, the two probes were adjusted to the same height level so that an equal but opposite force can be applied from each probe when grasping and manipulating the sphere. The focal plane of the vision system was adjusted to focus at the probe tips throughout the entire experiment to prevent possible interference to the experimental setup. The two probes, initially located at two arbitrary positions, were manipulated (in the x–y plane) to the two sides of the targeted micro-sphere for grasping and the entire process was monitored through the vision system. Due to the limited depth of field of the vision system, manipulating the probes further upwards in the z-direction could result the two probes to become out-of-focus, making them impossible for tracking and position evaluation. Hence, collision-free paths for manipulating the two probes towards the center of the sphere for grasping were generated to avoid collisions between the probes and other objects. After the sphere was grasped, the probes lifted the sphere upwards in the z-direction and then manipulated it to the desired location. Afterward, the two probes were lowered back to the focal plane and reconfigured their orientation to release the sphere. In this work, the two crucial processes, the initial positioning of the two probes for object grasping, as well as the path estimation for probe reconfiguration, were automated via vision images. Details of the algorithms are presented in the next two sections.

2.2. Adhesion minimization through probe reconfiguration

The influence of adhesion forces has been a known issue during the release of a micro-object [3,25]. After an object is grasped by a handling tool, the adhesion force may prevent the object from falling out of the tool. In general, the three major components that make up the unwanted adhesion force are the van der Waals force, the electrostatic force, and the capillary force. The van der Waals force is the interaction force between two bodies and the strength of this force is dependent on the geometries of the bodies as well as the interaction distance. For a plane–sphere contact between the handling tool and the micro-object, the van der Waals force, F_{vdw}, can be evaluated as [26]:

$$F_{vdw} = \frac{S_A R}{6D^2} \tag{1}$$

where S_A is the area of contact
R is the sphere radius
D is the separation distance.

The capillary force is the surface tension force caused by water condensation on the surfaces of the two bodies, leading