Development of a Tactile Low-Cost Microgripper with integrated Force Sensor

Markus Kemper

Abstract— This paper describes recent results of the development of a novel tactile force-sensing microgripper based on a flexure hinge fabricated in stainless steel by wired Electro Discharge Machining (EDM). The gripper was equipped with a commercial semiconductor strain-gauge and a piezo stack.

The microgripper is an end-effector of a microrobot developed to grasp and manipulate tiny objects. Acquiring force-information with the microgripper is of fundamental importance in order to achieve the dexterity and sensing capabilities required to perform micromanipulation or assembly tasks.

I. INTRODUCTION

Assembling parts of micrometer-size is important for the fabrication of microsystems and of micromachines [1]. Hence, it is particularly useful to grasp and manipulate 'hybrid' parts, i.e. objects made out of different materials (silicon, metals, polymers) and for different functions (structural, actuation, sensing, processing). These components can be assembled automatically for mass manufacturing, or manually for small-scale manufacturing or for prototyping [2][3]. Robotic assembly lines have been developed and are extensively used in the industry (e.g. the watch industry). Automated assembly lines are currently investigated for the manufacturing of microsystems. The assembly of prototypes or products to be manufactured on small scales (e.g. high-quality, expensive devices such as medical endoscopes) is still performed manually by skilled operators.

Due to the increasing workplace miniaturisation, it is difficult to use conventional manipulation robots for the assembling of microsystems. The manipulation accuracy of conventional robots is mechanically limited, due to the fact that disturbing influences, such as fabrication defects,

friction or thermal expansion are not negligible in the micro-world. Further on, the positioning accuracy and the tolerances of the micro-components lie in the range of nanometers, a few magnitudes smaller than in conventional assembly. These accuracy requirements can be obtained with micro-robots having highly precise direct drives and advanced closed-loop control. A micro-robot-based desktop station may offer the desired features and versatility [4][5][6][7].

Special micromanipulators are needed to manipulate very small objects. Most micromanipulators are specialised to perform a task they are designed for, but are too inflexible to adapt to other problems. Therefore, in our division we are developing flexible mobile microrobots with precision in the sub-micrometer range while offering a macroscopic workspace [8]. A manipulation unit, mounted on top of the mobile platform, is necessary to carry out manipulation tasks with the required degrees of freedom, cp Fig. 1. These mobile robots perform operations with a precision of approximately 110 nm and transport the objects at speeds of up to a few mm/s [9].

Fig. 1: RollBot IV, 6-DOF Microrobot

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M. Kemper is scientific researcher at the Division Microrobotics and Control Engineering, University of Oldenburg, 26111 Oldenburg, Germany (phone: +49 441-798-4352; fax: +49 441-798-4267; e-mail: kemper@informatik.uni-oldenburg.de).

The endeffector is the core component of the mobile microrobot and it requires special efforts for the designing and for the fabricating purposes of micro-systems. In this paper we present the design, functional principle and

preliminary testing of a microgripper fabricated in our division.

II. DESIGN OF THE TACTILE MICROGRIPPER

The novel tactile force-sensing microgripper is based on a flexure hinge fabricated in stainless steel by wired Electro Discharge Machining (EDM), cp. Fig. 3. A piezo stack which generates a linear force proportional to a input voltage, is used in the microgripper. The gripper consists of a passive and an active gripper arm. The active gripper side is pre-stressed via a torsional moment M of the flexure hinge, so that the gripper is closed, in case no voltage is applied to the piezo stack, cf. Fig. 2.

Fig. 2: Principle of the novel microgripper

The gap d of the gripper is proportional to the linear motion x of the piezo stack and to the length l of the active gripper arm. In consideration of the geometrical conditions ($l \sim 35$ mm, $x_{max} \sim 9$ μ m at 150 V) and the point of load incidence of the piezo stack, the maximum gap d_{max} is approximately 150 μ m.

Fig. 3: The microgripper (stainless steel)

The microgripper can be opened, due to the linear expansion and the generated force of the piezo stack

(opening moment). It closes as a result of a torsional moment of the flexure hinge (closing moment). The motion of the active gripper arm can be controlled by the voltage of the piezo stack and by the signal of a commercial semiconductor strain-gauge mounted at the flexure hinge. The dynamics of the gripper depends on the velocity by which the piezo stack is expanded. Fig. 2 shows the principle of the novel microgripper.

III. TACTILE FORCE SENSING

The novel microgripper shows mostly linear characteristics within the operational range. The flexure hinge operates like a torsion spring. Hence, the torsional moment M is proportional to d/l and the force F of the microgripper is proportional to d/l^2 . In consideration of the input voltage U of the piezo stack and the resistance R of the strain-gauge it can be written:

$$d \sim R \quad (1)$$

$$U \sim d \quad (2)$$

From the equations 1 and 2 can be obtained that:

$$R \sim U. \quad (3)$$

Thus, a linear reference curve of the microgripper (without any object gripped) can be recorded.

If the gripper grasps an object this can be detected by deviation of the gradient of the grasping curve from the reference curve in place of X , see Fig. 4. The deviation of the first derivative provides information whether an object was gripped and provides conclusion about the elasticity of this object.

So far, the interrelationships mentioned show that the gripping force is proportional to the resistance:

$$F \sim R. \quad (4)$$

Hence, the variation of the grasping curve and the reference curve in Fig. 4 provides information of the gripping force, $\Delta F \sim \Delta R_{grasp}$. The force ΔF is very small in the area of X and it is increasing with decreasing voltage U . Further, the sensitivity and the gripping force of the microgripper depend on the stiffness K of the flexible hinge:

$$K \sim \frac{EI}{l^3}, \quad (5)$$

with E as the Young's modulus and I as the inertia. Thus, the choice of the material and of the shape of the flexible hinge effects the application area of the microgripper considerably.

Fig. 4: Reference and grasping curve (theory)

IV. CALIBRATION

The microgripper has been calibrated by varying attached weights. Fig. 5 presents the linear calibrating curve, cp. equation 4, $F \sim R$. The function shown in this figure is described by

$$\Delta R_{grasp} [\Omega] = 49,617 \cdot F [N] - 0,0996. \quad (6)$$

The resistance has been measured directly from the strain gauge. The resolution of this sensor system constitutes 0.002 N which is sufficient for most of the micromanipulation tasks.

Fig. 5: Force calibrating curve

To enhance the sensor's resolution, the stiffness can be reduced, cp. Equation 5, or an optimal analysis circuit can be applied, e.g. precise comparison of resistances (Wheatstone bridge).

In a next step, the sensor system has been investigated in a scanning electron microscope (SEM) with integrated measuring function. The gap d has been calibrated by recording the resistance of the strain gauge and the voltage of the piezo stack. Fig. 6 shows the tip of the microgripper in the SEM while measuring the gap.

As already mentioned in chapter 3, equation 1 and 2, it can be written that $d \sim R$ and $U \sim d$.

Fig. 7 and Fig. 8 show the almost linear curves. The problem in the acquisition of the gap is the manual positioning of the measuring line, so that deviations may be caused. The average resolution is about 0.15 μm .

Fig. 6: SEM image of the microgripper

The function shown in Fig. 7 can be written as

$$\Delta R [\Omega] = -0,5109 \cdot d [\mu m] + 61,219, \quad (7)$$

and the function presented in Fig. 8 is described by:

$$U [V] = 1,2423 \cdot d [\mu m] - 25,487. \quad (8)$$

From the illustrations in Fig. 5 and Fig. 7 can be obtained that the gripping force F depends on the gap d , $F \sim d$. By using the equations 6 and 7 it can be obtained that:

$$F [N] = \frac{1}{49,617} (-0,5109 \cdot d [\mu m] + 61,3186). \quad (9)$$

Thus, in order to calculate the gripping force, it is necessary to determine a gap d which is proportional to the variation in resistance.

Fig. 7: Gap calibration curve: resistance vs. gap

Fig. 8: Gap calibration curve: voltage vs gap

With the interrelationships in the equations 1, 2 and 3 the possibility is given to acquire information whether the gripper grasps an object and by which force it is grasped. Moreover, the user will get to know the size and the elasticity characteristic of the object. Calibrating the gripper by force and by gap provides the possibility to get accurate sensory information to be able to handle microobjects in a reliable way without damaging them.

V. EXPERIMENTAL RESULTS

The microgripper has been tested by gripping some objects. First of all, the reference curve has been recorded. Fig. 9 shows the typical result. After that, a human hair was gripped. For example, the microgripper touched the human hair at 40 V. With Fig. 8 can be obtained, that the hair has a diameter of approximately 58 μm. For example, $\Delta R_{grasp, 1}$ at the stack voltage 20 V is equal 3 Ω, cp. Fig. 9. Hence, from Fig. 5 can be concluded, that the human hair is held with 0.064 N. With regard to the mentioned equations 7 and 9, it can be found that the gripping force is equal to 0.0624 N.

Further closing of the microgripper effects the rise of the gripping force, due to growing ΔR_{grasp} . The fact that the resistance of the strain gauge does not remain constant in the array of 40V down to 0 V represents that the hair is deformed by the gripper.

The inherent hysteresis of the piezo stack is negligible due to the fact, that the active gripper arm is pre-stressed via a torsional moment and a pre-stress force presses continuously on the piezo stack. Hence, the curves are matching well. But the fact, that the curves in Fig. 7 and Fig 8 are not ideal linear points to an influence of a little non-linearity of the strain-gauge or the stiffness of the gripper arm. The stiffness of the gripper arm (including tips) has to be essentially larger than the stiffness of the flexure hinge.

To acquire information about the capability of this version of the microgripper and of the deployability with the determined resolution, an Expancel® microsphere has been grasped, cp. Fig. 10. This very soft microsphere consists of a polymer shell encapsulating a gas and was used as an alternative for a biological cell. By viewing Fig. 9 it can be seen, that the sensor system is not able to detect the cell. Moreover, the resolution already mentioned in chapter 4 is sufficiently high to smush the Expancel®.

Fig. 9: Reference and grasping curves (practice)

With the assumption that there is an allside pressure around the object to be handled, it can be assumed that the relative variation of the volume can be described by:

$$K_b = \frac{E}{3(1-2\nu)}, \quad (10)$$

with K_b as the bulk modulus and ν as the Poisson ratio ($\nu = 0.2 \dots 0.5$). Thus, with the in chapter 4 mentioned resolution it can be obtained that the Young's modulus of the object must exceed approximately 1.8 MPa.

Fig. 10: Microgripper handling an Expancel®

Fig. 11 shows the Young's modulus of different materials. Thus, it can be derived that objects more elastic than smooth rubber can be detected by the gripper's sensor system. Further, it is clear from Fig. 9 and Fig. 11, that the smushed Expancel® must have a Young's modulus smaller than 1.8 MPa.

Fig. 11: Young's modulus of different materials, cp. [10]

VI. FORCES IN THE MICROWORLD

Micromanipulation differs greatly from conventional manipulation in some aspects. These differences are caused by the small dimensions of the parts to be manipulated. Gravity is almost negligible compared to adhesion or electrostatic forces when objects are smaller than 100 μm. The biggest problems arise from these surface forces which become dominant with decreasing the part dimensions, as to electrostatic forces (electrostatically charged objects or base materials), surface tension forces because of humidity, and van der Waals forces [11]. Phenomena such as objects sticking together or sticking to the microgripper have been observed during this development.

Thus, if microscopic objects are to be handled, the so-called scaling effects must be faced. The most frequent effect caused by these unfamiliar force ratios is that a grasped object remains sticking at one jaw of the microgripper when trying to drop it. Possible approaches to face this problem are to optimize the gripping surface or to

involve a second robot or system which is equipped with a "helping hand" consisting of a simple needle-shaped gripper tip. It can brush off the object, minimising the contact faces by the small dimensions [12]. Therefore, to save space the mentioned two robot problem has been reduced to an one robot system consisting of the microgripper and a fine positioning 3-DOF Stewart endeffector developed in [13], cf. Fig. 12. The translational expansion of the tip is approximately 9 μm, the two rotational amplitudes are ± 100μm (up - down), and ± 25μm (left - right).

Fig. 12: Gripper system

VII. NEW DESIGN

To extend the gap of the gripper, the length of the active gripper arm has to be enlarged or a different piezo stack has to be used. Further, the point of load incidence has to be minimized. Fig. 12 shows the new design of the microgripper. With the dimensions already mentioned in chapter 2 and the linear motion of the new piezo stack ($l \sim 35$ mm, $x_{max, new} \sim 22$ μm at 150 V) and the point of load incidence of the piezo stack, the maximum gap $d_{max, new}$ is approximately 400 μm.

Fig. 13: Principle of the new design

VIII. CONCLUSION

In this paper, the development of a novel tactile force-sensing microgripper based on a flexure hinge fabricated in stainless steel by wired Electro Discharge Machining (EDM) has been described. The low-cost gripper was equipped with a commercial semiconductor strain-gauge and a piezo stack. The gripper consists of a passive and an active gripper arm and shows mostly linear characteristics. The gripper has been fabricated and calibrated. The calibration by force and by gap provides the possibility to get accurate sensory information to be able to handle microobjects in a reliable way without damaging them. Thus, the new working principle provides the possibility to acquire information whether the gripper grasps an object and by which force it is grasped. Moreover, the user will get to know the size and the elasticity characteristics of the object.

The experimental results show, that the microgripper's sensor system provides a resolution which is sufficient for most of the micromanipulation tasks. The gripper is able to be applied in a scanning electron microscope and in an optical microscope.

In the future, an optimised flexure hinge will be developed and a suited analysis circuit will be implemented to enhance the resolution and consequently to enlarge the application fields. It is assumed, that some biological cells or bacteria may be handled by advanced microgrippers. But, for example, to handle a cell with a diameter of 50 μm and a Young's modulus equal to 10 kPa the sensor system should have a minimal resolution in the area of low μN . Furthermore, an automated gripping and force control system will be developed. The microgripper will be implemented on an automated 6-DOF microrobot with closed-loop control to obtain a fully autonomous micromanipulation unit.

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