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Small-size Robotic Tools with Force Sensing

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Abstract. The design problem of small-size robotic tools for performing contact tasks is discussed in the paper. Such robotic effectors are usually based on compact compliant mechanisms what enables to minimize dimensions and exhibits some specific features, as to force sensing capabilities. These devices, (as grippers, cutters, scissors,…) are especially used for manipulation with small - soft or fragile materials, or with living objects. In order to prevent any damages such kind of manipulation require sensing contact forces for on –line monitoring, or direct haptic control of the robot positioning system. There are typical examples as for instance: medical devices used in surgery with force reflecting capability or force / feedback control and grippers for manipulation with fragile / soft – living tissues.

Keywords: micro-robotic, compact compliant mechanisms, force sensing, robotic effectors, grasping of soft object

1. Introduction

The robot to be able to execute any specific operation must be equipped by an "appropriate" tool. In general, the more complex tasks should be executed, the more sophisticated tools are need. It could be said that the performance level of a robotic system, as whole, directly corresponds to the quality of tools that interact with environment. In principle, more sophisticated robotic hands should be normally equipped by several sets of sensors (tactile, force, force/moment, proximity) what enables to apply some given level of adaptive / intelligent behaviour of such robotic systems. The most universal tool represents human hand that served as example for many solutions of artificial multi-fingered grippers. The human hand as tool and of natural development during many thousands years with the goal of maximal universality satisfy needs of humans living in natural environment. There were for instance: climbing on trees, or, grasping very large variety of objects; as to form and mass, that human is able to move. Unfortunately, the human hand can not be used as example for construction of robotic tools for industrial applications; especially for grasping small objects (less then 2 mm) and precise manipulations.

In general, it is considered that the sophisticated robotic system should work in non-exactly specified (unstructured) environment. This fact results in need of sensors that give information for corrections of prescribed actions. Naturally these sensors are mainly concentrated in tools, i.e. close to the process.

In principle there are three categories of robotic tools:

- Tools for manipulations with objects: i.e. grasping, holding and caring parts.
- Tools that directly (physically) interact with environment(cutters, scissors, probes, arc welding guns, …)
- Tools without physical contact with environment (sprayers, gas welding guns, scanners, …)

Specific problems arise in cases of manipulation with small soft and fragile objects where further features and restrictions are given. There are for instance:

- The tool should be adequately small, i.e. its dimensions should correspond to objects and tasks. To keep minimal dimensions and mass of such small devices can not be constructed from discrete parts. This practically results in design of the compact compliant mechanism for grasping and moving fingers.
- When grasping soft / living tissue or fragile objects the tool must be equipped by the grasp / contact force sensing capability.

Manipulations with such objects in not exactly defined environment require integration of some error correction / compensation method (active or passive). Well known active error correction methods are based on sensing the grasp and contact force / moment reactions that arise between object and environment. For this purpose many constructions of tactile and multi-component force / moment sensors have been developed (Yousef, et al., 2010). They are usually mechanically integrated in gripper fingers, or in the robot wrist; i.e. between the gripper / tool and the end robot flange. Although such solution is suited for manipulations with larger objects / tools performing fine operations with small soft / fragile objects requires sensing force / moment interactions as closest as possible to the place of contact; in the ideal case directly in fingers / tool.

2. Tasks formulation

The tasks to be necessary solved for optimal designs of micro-robotic tools especially for manipulation with small soft objects are formulated in this part. We focus to force that arise between end-effector, object and environment and evaluate sensing possibilities.

Suppose a common situation, in Fig. 1, where the grasped soft /fragile object is in physical contact with environment. It is strictly prescribed that no force acting on the object can exceed a given value. There are:

- The grasp force between finger and object surfaces (normal force).
- The contact force that arise between object and environment. In general the 3 component force vector should be considered.

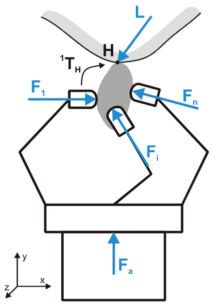

Fig. 1. Grasped object with contact forces

As obvious, the stable grasp will become if the following condition is satisfied:

$$\vec{L} \leq \sum_{n} {}^{i}T_{H} . \vec{F}_{i} \qquad (1)$$

where L is the external force vector and F_i are contact forces between fingers and object surfaces, T is the force transformation matrix between H reference system and contact of fingers.

Because of all these forces can result in damage of object they should be sensed / supervised.

This principal requirement should be taken into account yet in designing the gripper / tool and during performing the task, as well. The problem of grasp and external force / torque sensing is not new and many sophisticated robot grippers / tools have been designed. The majority of these effectors are oriented to manipulation with "normal size" objects; i.e. objects having dimensions within 5 - 50 mm and masses within 50 – 500 grams. Unfortunately, the majority of principles used for constructions of these effectors are hardly acceptable for design of small size grippers / effectors for grasping soft / fragile objects with dimensions less then 2 mm and mass less then 5 grams. When compare particular functional parts there following reasons:

- *Mechanisms for moving fingers:* The dimensions of this mechanism should be adequately small. So it can not be built from discrete parts. The single solution is concept based on compact - elastically compliant structures (Howell, 2001) (Smith, 2000) and using appropriate fabrication technology.
- *Sensing the grasp forces:* As the mass of objects and manipulation dynamics are relatively small, the grasp / contact forces are given more-less by static conditions. Sensors for this purpose should be fully integrated in inner surfaces of fingers (PVDF), directly in fingers, or on some elastic parts of finger mechanisms.
- *Sensing external force reactions:* For sensing external reaction the three component of force must be measured.
- *Actuators:* Designing small effectors some specific requirements are given on actuators.

Characteristics of the above functional parts and design problems of compliant mechanisms, sensing and actuators for this purposes are discussed below.

3. Building the small size tools

3.1. Applicable actuators

By comparison of actuators used in robotics and micro-robotic devices from the point of view grasping process actuators for grippers of small and soft objects should comply:

- *Bigger force effects*: for correct work of micro-device the actuator must guarantee the safe grasp of the object and not to overcome some given deformation forces / torques
- *Minimal dimensions:* the aim is to find an optimal ratio between actuator displacement and output force or moment.
- *Possibility of output force control*: because of the fingers of a gripper are relativity rigid or partially deformable it is necessary to combine both (see below) approach for grasping of small soft objects; i.e. sensing and control (of output force).
- *And others*

The brief overview of representative actuators could be selected as drive units for compliant elastic mechanisms with output force control possibility is given below.

The electromagnetic (solenoid) actuator (EM) is most simple drive can be used as source of motions for micro-robotic devices. According to (Zięba,

2003) the output force of an electromagnetic actuator is expressed

$$F_e = \frac{1}{2} i^2 \frac{dL(x)}{dx} \qquad (2)$$

where i is the current overflowing in electromagnet coil, *L(x)* is the self-inductance of coil and it is nonlinear dependent from core position.

Most frequently used actuators in drivers for compliant mechanisms work on the principle of piezoelectric phenomenon. According to (Ballas, 2007) the output force of a piezoelectric beam actuator is

$$F_p(l_b, t) = \frac{\kappa U(t) n}{l_b} \qquad (3)$$

where κ expresses construction, mechanical and piezoelectric properties of beam and piezoelectric plates. n is number of piezoelectric pair plates, l_b is beam length and $U(t)$ is connected electrical voltage.

For applications where relatively slow are required the wire actuators based on shaped memory alloys (SMA) are suited. As indicate (Grant and Hayward, 2000) they enable constrained force control. For the output for force we have

$$F_{SMA} = \frac{a_f n}{K_g} K_p \left[\int_0^{t_f} I_f^2(t) R_f dt + C_i \right] \qquad (4)$$

where n -is the number of fibbers, K_g -is the displacement gain, a_f -the fibber cross section, I_f the current per fibber, R_f the fibber resistance, C_i is an integration constant and K_p is constant defined by heat (started, finished, etc.) thermo-elastic constant, mass of the fibber. The prolongation of SMA wires is normally about 4% of heir length.

Other actuators suited for driving micro-robotic devices with control of output force possibility are: thermal actuators (Zelinski, 2001), electrostatic (capacitive) actuators (Marquès et. al., 2005). The output force, in all above principles, is controllable by changing electrical variables as voltage or current.

3.2. Force sensing

The problem of grasping soft objects can be solved by two ways. The first solution consists of sensing grasp force by a contact / tactile sensor with consequent force control. This approach is presented in (Yussof, 2009), (Wada, 2000) and (Osswald, 2001). The conclusion of such approach is that position of force sensors must be most close to fingers.

Another approach to solve soft grasping is based on flexible (soft) fingers. During grasping the finger deflects and adapts to the shape of an object. This approach is solved mainly in the works (Brown, 2010), (Yoshikawa, 2008), (Byoung-Ho, 2004) and others.

Next task is sensing contact forces on the end effector mechanisms / structure (Tholey, 2005), (Krejci, 2010) and (Yamada, 2009). As acceptable solution is using of more force sensor with control system based on the thoroughgoing system dynamics mathematical model.

As the majority of Analysed small and micro-devices are usually produced by micro-machining technologies a proper solution of force sensing represent applying the strain gauges sensors integrated directly on surface of deformable parts of mechanisms.

For strain gauge sensor is known dependence between resistance and surface deformation

$$\frac{\Delta R}{R} = k\varepsilon \qquad (5)$$

where k is the strain gauge sensitivity.

4. The design of the small size grippers

The designs of a two-finger and three-finger grippers with force sensing and control capabilities are studied. In both cases most suitable positions of strain-gauge sensors on the compliant mechanisms are evaluated. Principal motion mechanisms are shown in Fig. 2.

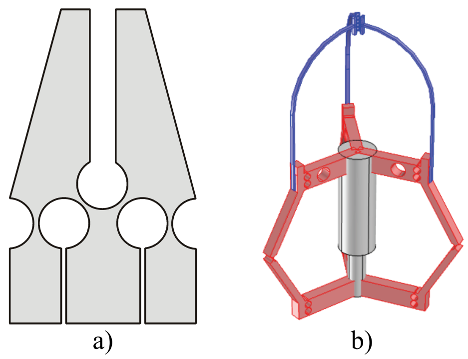

Fig. 2. Analysed robotic tools a) planar, b) three-dimensional

4.1. Analysis of the planar gripper / tool

The task of placing the strain gauge force sensor on compact elastic structure is solved. The goal is get the most relevant information about grasp and contact forces.

The first step is necessary to modify designed structure in order to create deformable parts for strain-gauge sensors. This modification of kinematic structure with sensing grasp and external forces is shown on in Fig. 3.

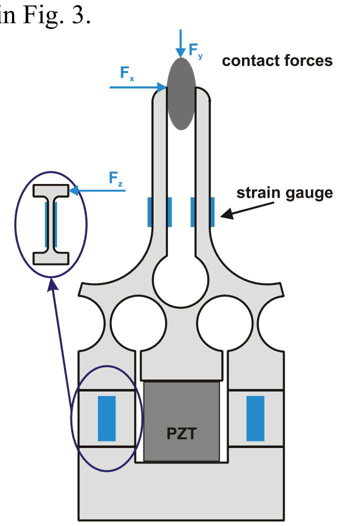

Fig. 3. Modified micro-gripper with force sensing

Modifications of the mechanism follow the possibility of sensing strains directly on the compliant finger structure and possibility to measure desired forces. Two variants of proposals in Figs. 3 and 4 for planar gripper were studied.

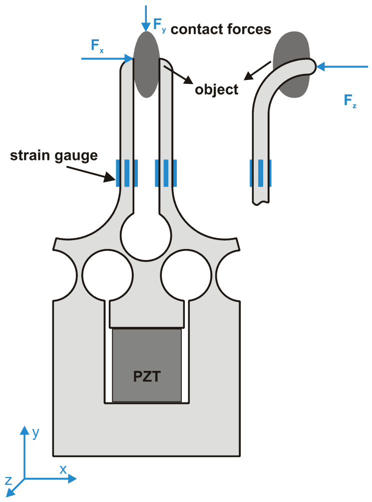

Fig. 4. Modified micro-gripper with force sensing – bending of micro-gripper fingers

The solution in Fig. 4 enables to measure all forces directly in fingers.

4.2. Analysis of three-finger RCC gripper

The task of sensing grasp and contact forces in an RCC gripper is relatively simplified. For adequate force sensing is not necessary change any mechanical structure. Strain gauges are placed direct on surfaces of flat fingers (see. Fig. 5.).

Difference between force sensing on planar gripper and tree-fingered griper is in processing signals from strain-gauge sensor outputs. The signal processing procedures include different transformations contact forces have to be calculated with respect to the given coordinate system.

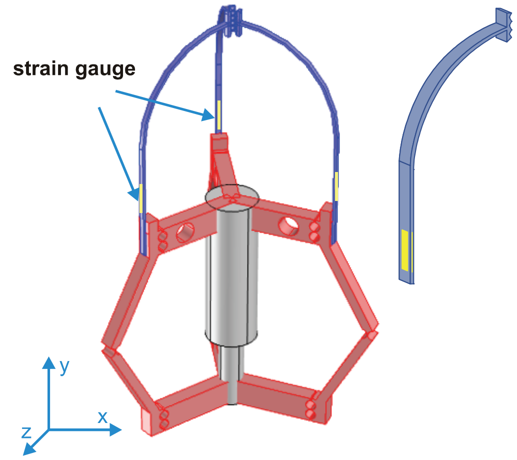

Fig. 5. RCC gripper with force sensing

4.3. Force sensing algorithm

When express the data processing algorithm consists of two phases:

- *During object grasp:* the grasp force is controlled When object grasped the values of grasp force controlled. After the grasp – the sensor values are reset.
- *Manipulation with object*: new sensory data are processed and contact force components are calculated.

In general, the relation between output voltage from sensors and forces in analysed

$$U = f\left(F_g\right) + f\left(F_c\right) \qquad (6)$$

where U is output voltage from compensation circuit processing signals from strain gauges, $f\left(F_g\right)$ is the function of output signals / voltages from circuits processed signals from strain gauges sensors during grasping and $f\left(F_c\right)$ is function of output signals / voltages that represent contact forces between robotic tool and environment

5. Conclusion

The design problem of small-size robotic tools for performing the contact tasks was discussed in this paper. We have specified the boundary condition for micro-robotic devices actuators from the point of view of grasping process. The main condition is possibility of output force control by the actuator. Next, solutions of force sensing for two examples of micro robotic tools were shown. As force sensor we have used strain gauges. Force sensing algorithm has been formulated.

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