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Design and Control of a Teleoperated Microgripper for Microsurgery

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Abstract

A remotely controlled microgripper has been developed as an end-effector for a six-degree-of-freedom force-reflecting motion-scaling system. The microgripper is small and lightweight, and features relatively high force and stroke compared to other designs. Furthermore, force sensing enables the accurate measurement and control of tool-tissue forces, and the emulation of different mechanical devices. This paper presents the design of the microgripper and describes some control methods that have been implemented.

1. Introduction

In microsurgery, the range of tasks that can be performed is limited by the manual dexterity of the microsurgeon. Hand tremor, fatigue, and lack of kinesthetic feedback are some of the limiting factors. Therefore, there would be considerable merit in any new microsurgical devices that could help microsurgeons in manipulating tissues.

A 6-DOF teleoperation system is being developed at UBC with the objective of providing the microsurgeon with scaled motion and force feedback [1]. The system uses a dual-stage coarse-fine motion architecture to achieve fine-motion teleoperation over a large workspace (see Figure 1). The fine-motion stage consists of a hand-held master manipulator and a teleoperated slave manipulator that track each other's motions (Figure 2). Both are 6-DOF magnetically levitated (maglev) devices that share a common stator. The slave manipulator is equipped with a miniature *ATI* force/torque sensor to measure the 6-DOF tool-tissue forces, and an interchangeable end-effector such as a scalpel or microgripper is mounted at the end.

A microsurgeon using the system would use the hand-held master to control the movements of the end-effector tool, and would receive force feedback as the tool experiences forces from its environment. Position and force scaling factors are programmable, as is filtering of undesirable motions such as hand tremor.

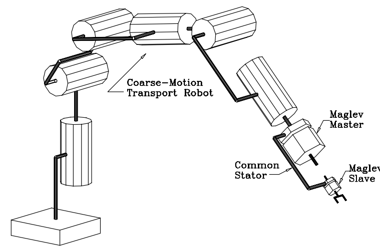

Figure 1. UBC Motion-Scaling Teleoperation System

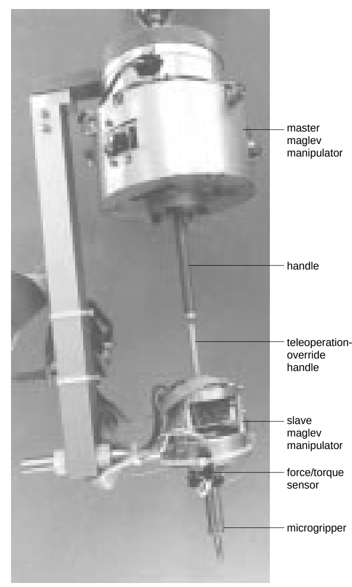

Figure 2. Fine-motion stage

In order for teleoperation systems such as this one to be practical for microsurgery, useful end-effectors must be developed. Most microsurgical tasks require gripping motions in order to hold vessels, microsuture, microneedles, and other small objects. Therefore, a microgripper would be an essential tool.

There also is a need for improved *hand-held* microsurgical instruments. The drawbacks of conventional forceps include the relatively large 4 mm finger travel required for actuation, and the 180° arrangement imposed on the positions of the thumb and forefinger. In addition, the mechanical stiffness of conventional forceps limits the surgeon's ability to maintain a steady finger force.

Furthermore, a microgripper instrumented with force sensors would enable the measurement of microsurgical forces resolved into gripping force and 6-DOF "wrist" force components. Similar measurements have been performed in a limited way by Charles and Williams [2]. However, the physical design of conventional instruments makes it difficult to accurately measure wrist and gripping forces.

With respect to requirements, the microgripper must be compact and lightweight (under 10 grams) in order to minimize loading effects on the maglev slave manipulator. It must also possess a motion range close to the 0–4.5 mm of conventional microsurgical forceps (e.g., *Dumont* #5). For gripping force, a previous study of vitreoretinal microsurgery reports typical tool-tissue forces up to 16 grams [2]. In addition, the commonly used *Acland* vascular clamp is available with a clamping force of 10, 15, or 25 grams. Therefore, the microgripper must be capable of producing a similar range of forces, and must be equipped with sensors to enable accurate measurement and control.

Existing microgripper designs are limited. One design that uses piezoelectric bimorphs weighs 43 grams and can achieve only 0.4 grams force over a 2 mm motion range [3]. Another design that uses piezoelectric actuation was reported to achieve 60 grams force over 3 mm, at the expense of size ($50 \times 100 \times 25$ mm) and weight (200 grams) [4]. Other designs that use shape-memory alloy (SMA) [5] or piezoelectric motors [6] [7] for actuation provide slow response or difficult control of gripping force.

To better address the requirements for size, weight, speed, motion range, and gripping force, a new design has been developed. It employs a flexural suspension and a single unidirectional actuator to achieve bilateral gripping action (see Figure 3). Two actuation methods have been investigated: a miniature solenoid actuator, and an enclosed hydraulic transmission. The hydraulic transmission system uses miniature electro-formed nickel bellows and flexible tubing (Figure 4). This actuation method is simple, lightweight, and compact, and possesses the additional advantage of being self-contained, requiring no external power sources.

Although the master and slave bellows are mechanically coupled, the motion of the operator's hand could be decoupled from the system by using a conventional actuator to squeeze the master bellows. Majima and Matsushima describe a 1-DOF teleoperation system that uses a hydraulic transmission system to transmit motion from a D.C. motor to a microgripper, in order to measure mechanical properties of different tissues [8]. A tendon-driven microgripper could be used in a similar manner to distinguish tissues possessing different mechanical properties during minimally invasive surgery (MIS). This could facilitate tasks such as the location of the ureter in laparoscopic hysterectomy operations, since laparoscopic surgeons, like microsurgeons, receive virtually no kinesthetic feedback of the tissues that they manipulate.

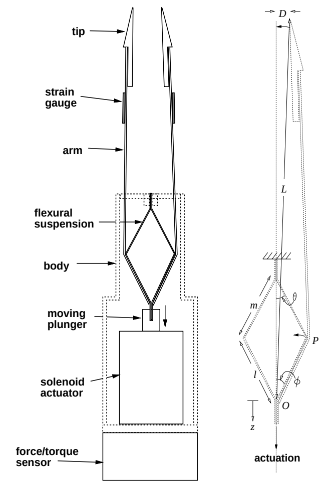

Figure 3. Microgripper (cross-sectional view)

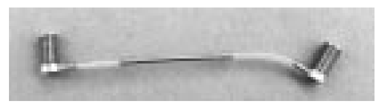

Figure 4. Hydraulic actuation/transmission system

A prototype microgripper that uses solenoid actuation has been built. This paper presents the design of the microgripper and its teleoperation master, and describes some control methods that have been used.

2. Design

2.1. Kinematics

The microgripper is a planar mechanism. The diamond-shaped flexural suspension acts as a motion amplification and translation mechanism, transforming unidirectional downward motion into symmetric bilateral gripping motion (see Figure 3). As a first approximation, the flexural suspension and gripper arms are modelled as rigid links. The actuator pulls on the flexural suspension at point O, causing the point P to trace a small arc about O. The lever arm L amplifies this motion to the tip of the gripper arm. In the case where $l = m$ ($\theta = \phi$),

$$\Delta z = 2l(\cos\phi - \cos\phi_0)$$

Table 1. Microgripper characteristics

UBC Microgripper	
Mass	5.4 g
Dimensions:	
Length	45 mm
Diameter at base	12.5 mm
Flexural suspension:	
Material	Brass
Thickness	0.06 mm
Dimensions:	
$l = m$	5 mm
$\phi_0 = \theta_0$	30 °
L	25 mm
Max. gripping force:	
Continuous	10 g
Peak	20 g
Tip displacement	0 – 2.5 mm

$$\Delta D = L \sin(\phi - \phi_0)$$

and it can be shown that

$$\Delta D = -\frac{1}{2}\left(\frac{L}{l}\right)\left(\frac{\cos\frac{\phi-\phi_0}{2}}{\sin\frac{\phi+\phi_0}{2}}\right)\Delta z \quad .$$

At rest, $\phi = \phi_0$, and this becomes

$$\Delta D = -\frac{1}{2}\left(\frac{L}{l}\right)\left(\frac{1}{\sin\phi_0}\right)\Delta z \quad .$$

As ϕ_0 decreases, $\frac{\Delta D}{\Delta z}$ increases; i.e., position gain increases with smaller angles. However, at smaller angles, greater force is also required to overcome the stiffness of the material. Therefore, the force capability of the actuator affects the choice of ϕ_0. This tradeoff of position gain *vs.* force also affects the choices of l, m, and L. Table 1 gives the dimensions of the flexural suspension that was used for the microgripper prototype. Furthermore, as the actuator pulls on the flexural suspension, z increases, ϕ and θ decrease, and greater force is required to further extend the flexural suspension. This characteristic matches well with the force-displacement properties of a solenoid actuator.

2.2. Actuation

A miniature solenoid actuator was chosen because of its light weight, small size, rectilinear motion, and relatively high force capabilities. The *Electro-Mechanisms PO-25* weighs 2.8 grams, is readily available for under \$10, and could easily be sterilized using dry heat up to 180 °C. The actuator is a unidirectional device whose force depends on the position of the plunger (see Figure 5). With constant current, the actuator's pulling force increases as the plunger approaches the end plug. However, a return spring of a certain stiffness can be used to oppose the plunger's motion, making it possible to achieve repeatable bidirectional motions.

The force-displacement profiles of the solenoid actuator and the flexural suspension were individually measured using a z-positioning stage and a force sensor. Figure 6 shows the stiffness curve of the flexural suspension superimposed with the region of the actuator's

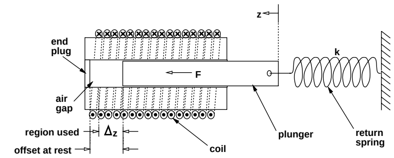

Figure 5. Solenoid actuator with return spring

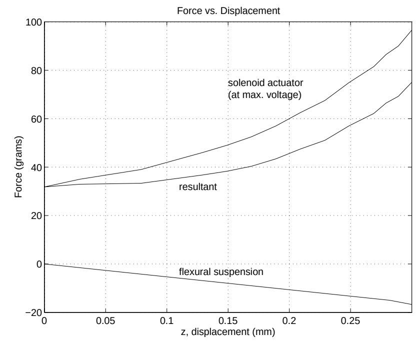

Figure 6. Force vs. Displacement for solenoid actuator and flexural suspension

force-displacement curve that was used for the prototype microgripper. This 0.3 mm region corresponds to the offset of the plunger (at rest) from the end plug by 0.32 mm, and the measurement of z as shown in Figure 5. Once the flexural suspension is joined to the plunger, the resulting usable force would be as indicated in Figure 6.

2.3. Sensing

Gripping force is measured using metal-foil strain gauges (refer to Figure 3). Each gauge forms one arm of a lead-wire temperature-compensated quarter-bridge arrangement, with the strain signal amplified by an instrumentation amplifier circuit. In order to further reduce the affects of temperature on strain measurements, the bridge excitation is pulsed; i.e., using a positive square wave with a small duty cycle. Gripping force was calibrated by hanging known weights off the tip of each microgripper arm.

2.4. Microgripper Master

In order to remotely control the gripping motion of the microgripper, a tool handle that senses the force of the microsurgeon's grasp has been built. Held like a pencil, it provides an intuitive surgeon-machine interface that can be mounted either directly onto the base of the microgripper for a hand-held instrument (Figure 7), or onto the master manipulator of the fine-motion teleoperation system for motion scaling in six degrees of freedom (Figure 2). The handle uses one strain gauge mounted on a stiff stainless steel beam to measure the gripping force at the surgeon's fingers

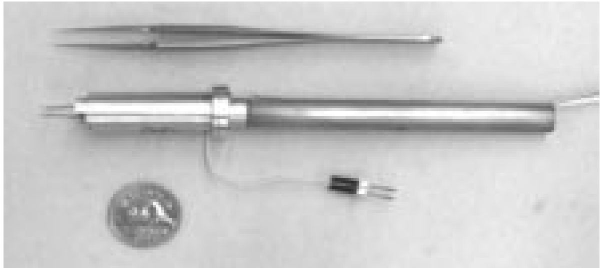

Figure 7. Forceps and hand-held microgripper

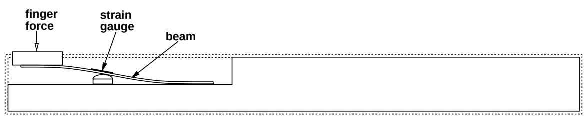

Figure 8. Microgripper master

(see Figure 8). Its characteristics are listed in Table 2. Because the handle provides a stiff interface to the fingers, it should enable steadier finger force with reduced fatigue [9].

3. Control

3.1. Hybrid Control

Simple open-loop control of the microgripper has been implemented as shown in Figure 9. Digital signal conditioning of the finger force, F_{master}, consists of deadband and low-pass filter functions. A current directly proportional to F_{master} drives the solenoid actuator of the microgripper. Open-loop shaping of this F_{master}-to-current relationship could also be done. The resulting solenoid force is balanced by the flexural suspension, resulting in an equilibrium position of the gripper arms.

Figure 10 shows the finger force and the resulting gripping force when the microgripper controlled in open-loop was used to grip and release a soft object. The scaling factor, n_g, was set to 0.05. This down-scaling of force from the surgeon's fingers, together with the deadband and low-pass filtering, reduces the affects of hand tremor on tool motion. This alone could reduce the possibility of slippage or unintentional application of excessive gripping force.

Closed-loop position control is unnecessary since the microgripper would be used under an operating microscope, with the microsurgeon's visual feedback closing the control loop. However, the relationship between finger force and gripping force depends on the mechanical compliance of the object being held. Moreover, it is difficult to judge tool-tissue forces from visual information alone. Therefore, a hybrid control scheme that uses closed-loop force control has been implemented to

Table 2. Microgripper master characteristics

Microgripper Master	
Mass	20 g
Dimensions:	
Length	90 mm
Diameter	9.5 mm
Force sensing:	
Finger force measured	0 – 150 g
Finger force used	10 – 100 g
Finger travel	0 – 1.25 mm

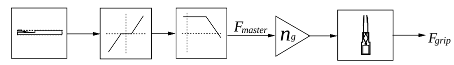

Figure 9. Open-loop control

enable more precise control of gripping force.

The hybrid controller uses a closed-loop PID control approach to enforce force tracking during contact, and uses open-loop control when the microgripper is in free motion. To obtain a smooth transition between the two control modes, the controller uses a linear combination of open-loop and closed-loop control, as shown in Figure 11.

The weighted contributions of open-loop and closed-loop control are determined by the weighting factors, w_o and w_c. If the gripping force, F_{grip} lies below $F_{contact}$, the threshold of the deadband in Figure 11, then $w_c = 0$ and $w_o = 1$. Therefore, open-loop control is employed when the microgripper is in free motion. As gripping force increases beyond the contact threshold, the contributions from open-loop and closed-loop control are shifted until eventually, w_c saturates at 1, and $w_o = 0$. Therefore, during contact, closed-loop control is used. Figure 12 shows a step response under closed-loop control with $F_{limit} = 4.0$ g. Because the solenoid actuator's force is dependent on plunger displacement, gains have been scheduled to optimize response.

In addition, a saturation function can be used to impose a programmable limit on the gripping force, thereby reducing the possibility of unnecessary trauma to tissues (refer to Figure 11). Figure 13 illustrates the behaviour of the hybrid controller with $F_{contact} = 0.1$ g and a force limit, $F_{limit} = 4.0$ g.

3.2. Device Emulation

The microgripper could be changed so that it would be useful for a greater variety of tasks. For example, an obvious physical modification might be to change its jaws in accordance with standard microsurgical instruments such as needle drivers, clamps, or bipolar coagulator forceps. However, other physical mechanisms can be emulated by simply altering the control scheme implemented in software. For example, a 6-DOF maglev manipulator was used to emulate differ-

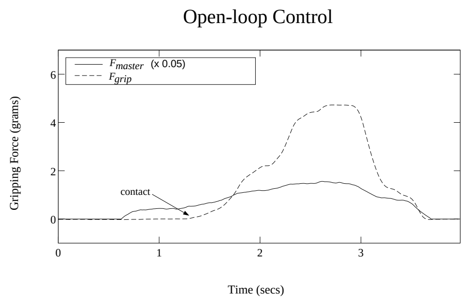

Figure 10. Gripping force under open-loop control

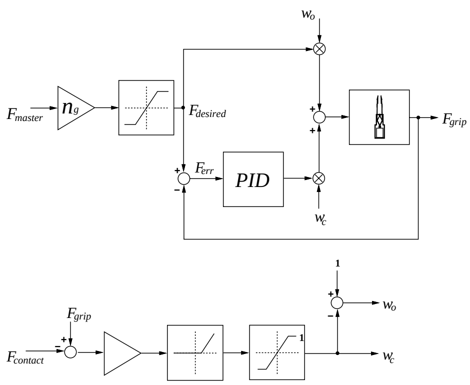

Figure 11. Hybrid control

ent mechanisms such as plunger, slider, translator, rotator, and RCC devices [10]. A similar maglev manipulator was used to emulate static friction and contact with a hard surface [11].

Here, the microgripper's single degree of freedom can also be controlled in different ways to yield other useful devices. For example, the hybrid position-force control scheme described above could be modified so that the microgripper servoes to the greatest force applied so far (see Figure 14). Thus, the microgripper would emulate a hemostat. Figure 15 shows the microgripper's behaviour under hemostat emulation control with a force limit at 4.0 grams.

Not only would this hemostat possess more stops than any conventional instrument with mechanical stops, but it would also enable much more gentle actuation and release. Moreover, the constant force would reduce the pressure required to maintain a firm hold on tissues. This could make the microgripper extremely useful as a needle driver, clamp, or "third-hand" tool, especially for solo-surgery. At present, methods for obtaining traction or retraction of tissues are typically limited to the use of guide sutures held stationary by a trained assistant, lead weights, mosquito clamps, slits in the background material, or cleats in the clamp-approximator.

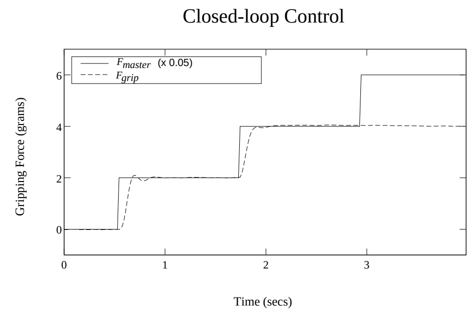

Figure 12. Step response with force limit

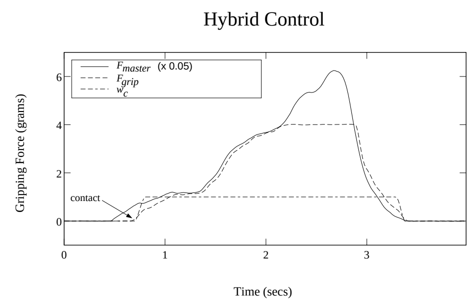

Figure 13. Gripping force under hybrid control

4. Summary of Features

The microgripper and its teleoperation master possess many useful features, and offer some advantages over conventional forceps:

1. Scaling and digital filtering of the force measured at the surgeon's fingers can minimize the effect of hand tremor on the microgripper's motion. This alone could greatly extend the resolution with which a microsurgeon can achieve smooth, controlled gripping motions.
2. Force sensing enables the application of programmable force limits to reduce the possibility of trauma to tissues. Furthermore, control methods can be used to emulate different physical mechanisms.
3. The microgripper enables the measurement of microsurgical forces resolved into gripping force and 6-DOF wrist force components. The mechanical decoupling of the surgeon's finger motion from that of the microgripper also makes it possible for the microsurgeon to employ different grasps of the tool.
4. The microgripper handle is stiffer than conventional forceps, and requires only a light squeeze to control the microgripper. This should reduce hand fatigue and enable steadier fine-resolution control.
5. The microgripper design is compact, lightweight, and scalable. Stroke and force are relatively high compared to other designs, and control of gripping force is fast and simple.

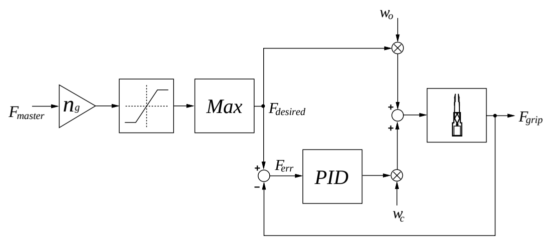

Figure 14. Hemostat emulation control

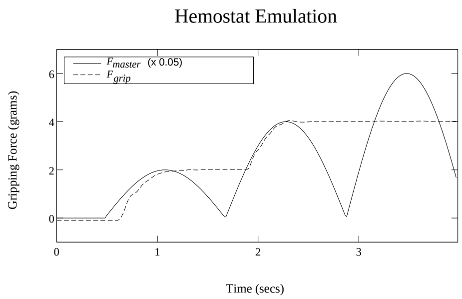

Figure 15. Gripping force under hemostat emulation control

5. Conclusions

The design of a teleoperated microgripper has been presented, and control using different methods has been demonstrated. This lightweight, compact device has the potential to increase a microsurgeon's manual dexterity since gripping forces can be scaled down from the fingers to the operating site. Force sensing further enables the measurement and control of tool-tissue forces.

It has also been shown that digital control methods can be used with the microgripper to emulate different mechanisms. Furthermore, digital filters can be used to reduce the effects of hand tremor, thereby minimizing the possibility of unnecessary trauma to tissues. Whether the microgripper is used as a hand-held instrument, a "third-hand" tool, or an end-effector for a telerobotic motion-scaling system, it has the potential to be a valuable tool for microsurgery.

Upcoming experiments should reveal how manual dexterity is affected by the use of the microgripper and motion-scaling system in a microsurgical environment. In addition, microsurgery experiments will be conducted using the microgripper in order to measure tool-tissue forces during microsurgery. As it would be relatively easy to build a force-feedback master for the microgripper, this is also planned for future work.

Acknowledgements

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