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TITLE

Hybrid Position/Force Control of an Active Handheld Micromanipulator for Membrane Peeling

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Hybrid Position/Force Control of an Active Handheld Micromanipulator for Membrane Peeling

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Abstract

Background: Procedures within the field of macular surgery require micron-scale manipulation and control of sub-tactile forces.

Methods: Hybrid position/force control of an actuated handheld microsurgical instrument is presented as a means for simultaneously improving positioning accuracy and reducing forces to prevent avoidable trauma to tissue. The system response was evaluated, and membrane-peeling trials were performed by four test subjects in both artificial and animal peeling models.

Results: Hybrid position/force control reduced RMS force by 45% within the artificial model and 33% in the animal model, while maximum force was reduced by 59% and 54% in respective models as compared to position control.

Conclusions: A hybrid position/force control system has been implemented that successfully attenuates forces and minimizes unwanted excursions during microsurgical procedures such as membrane peeling. Results also suggest that improvements in safety using this technique may be attained without increasing the duration of the procedure.
**Introduction**

Membrane peeling within the eye involves a variety of difficult challenges that must be properly addressed in order to successfully restore a patient’s vision. Procedures involve peeling the epiretinal membrane (ERM), internal limiting membrane (ILM), or both from surface of the retina. The ILM is a natural structure that develops with thickness on the order of 3.5 µm thick or less. It serves to separate the vitreous body from the retina and guide the nerve fiber layers during development phases (1). The ERM forms as an idiopathic condition, or the result of trauma, or secondary to other eye diseases in 4-11% of the population over age 50. It consists of a fibrous layer which forms over the ILM (2) ranging in thickness between 33 and 89 µm (3). As the ERM develops and thickens, light reaching the retinal surface is attenuated. The ERM also applies varying tension force to the retina, causing it to distort in a condition known as macular pucker. The progressive stretching of a macular pucker can result in a retinal tear, referred to as a macular hole. These conditions impair the patient’s vision, and if left untreated can lead to retinal detachment and complete loss of vision.

Surgeons use long thin tools ranging from 0.5 to 0.9 mm in diameter to access the eye and perform precise manipulations close to the retina. Execution of each procedure is influenced by factors such as hand tremor, patient movement, and instrumentation. Failure to properly execute the procedure often leads to complications, the most common in membrane peeling being iatrogenic tears and retinal trauma (4–6). Success depends greatly on a surgeon’s previous experience, hand-eye coordination, and fine motor skills.

Recent investigation has identified that peeling the ILM in addition to the ERM can reduce future ERM formation and improve the patient’s visual outcome following macular hole repair (7,8). Surveys taken to identify directions for improvement in ophthalmic procedures have indicated that positioning accuracy and tactile perception have high importance (9). Surgeon accuracy has been reported to be in the range of 50 to 285 µm in
various tasks (10–12). This accuracy represents from 0.6 to 8.6 times the thickness of the ERM, and 14 times the ILM thickness at best.

Gupta, Jensen, and de Juan reported the human tactile threshold as 7.5mN (13). However, tearing of the retina is recorded to occur in the range of 7.7 mN in rabbit models (14). Further tests with porcine retina samples have reported tearing between 6.1 mN to 12.4 mN depending on the direction of forces applied (15). In addition, Jagtap and Riviere reported scleral interaction forces tend to be much larger than the forces between the instrument tip and the retina (16). As important as tactile feedback in these procedures may be, these results indicate that tactile feedback without assistance is unachievable for the average surgeon. As a result surgeons primarily rely on visual cues and experience to coordinate their movements rather than tactile feedback.

**Robotic Assisted Membrane Peeling**

Previous approaches to enhancing surgeon positioning and force control have included motion scaling, tremor reduction, haptic feedback, and semi-automated control (17). These approaches have been implemented on multiple robotic systems (18–21); one such platform is the cooperatively-controlled Steady-Hand Eye Robot from Johns Hopkins which uses a stiff non-backdrivable arm to improve positioning accuracy (22). Force feedback has been developed through auditory cues to the surgeon (22) based on measurements provided by a miniature force sensor (23–25). Latt et al. have developed a one-degree-of-freedom (1DOF) handheld instrument to maintain tissue contact through force control for applications in confocal laser endomicroscopy (26). The work focuses solely on force control, and does not seek to improve surgeon positioning accuracy.

Our approach utilizes Micron, a handheld micromanipulator that includes a human-in-the-loop system for increasing positioning accuracy (27,28). Micron is capable of micron-level
detection and positioning as well as force sensing at the millinewton level using a 2DOF force sensor developed at Johns Hopkins University (29). Previous work with Micron focusing on membrane peeling involved vision-based virtual fixtures to limit position and velocity during membrane peeling (30). This approach was successful in limiting applied force; however, the addition of force sensing has potential to yield a more robust system for surgery in vivo.

Preliminary results with Micron using hybrid position/force control involved membrane peeling by a single non-surgeon operating on an artificial phantom (31). The present paper describes the addition of a Kalman-based feedforward component to improve force control, and includes experiments with three novices and a trained microsurgeon testing the system in an animal model in vivo of retinal peeling, in addition to the previous artificial phantom.
Materials and Methods

Micron, a Fully Handheld Micromanipulator

Micron is a fully handheld 6DOF micromanipulator. The manipulator is a miniature Gough-Stewart platform attached between the end-effector and a cylindrical handle. The platform is actuated by six piezoelectric linear actuators (SQL-RV-1.8 SQUIGGLE® motor, New Scale Technologies, Inc., Victor, N.Y.) operated at 1kHz sampling and capable of reaching a 4mm x 4mm cylindrical workspace (28). The position-control loop in Micron is designed to compensate for normal hand tremor and increase fine positioning accuracy down to the micrometer scale (32). This is achieved by sensing the 6DOF pose of the handle and end-effector, and filtering the measurement to determine the desired motion. The end-effector is then actuated to provide active error compensation, recovering the desired motion. A lowpass filter at 1.5 Hz is currently used for normal tremor reduction.

Position of the manipulator handle and end-effector are sensed at 1 kHz a custom optical tracking system known as ASAP (Apparatus to Sense Accuracy of Position). Three frequency modulated LEDs are mounted on both the handle and end-effector which are detected by two position-sensitive detectors (PSDs) within a 27 cm$^3$ workspace with less than 10µm RMS noise (33).

Previous work has focused on using Micron for enhanced positioning accuracy, by itself (32) and in conjunction with computer vision (34). More recent developments have been toward developing semi-automated procedures (35) and a preliminary force control system for membrane peeling (31).

Millinewton Force Sensor

Direct force feedback is accomplished using a custom 2DOF temperature-compensated force sensor developed at Johns Hopkins University (29). The sensor is constructed from a thin
titanium shaft 0.5 mm in diameter, with three optical fibers embedded 120° apart around the circumference of the shaft. Each fiber has a 10-mm long fiber-Bragg grating (FBG) placed 5 mm from its end to measure displacement. A calibration procedure is performed after assembly to correlate the instrument tip displacement to force.

The sensing elements are placed at the distal end of the sensor in order to directly measure the tool-tissue interaction forces. Previous work by Jagtap, et al. determined that, in order to accurately sense forces at the retina, the sensor must be placed inside the eye, beyond the incision, in order to avoid the much larger tissue interaction forces at the sclerotomy (16). The overall diameter of the assembly is 0.71 mm to be compatible with standard 25ga ophthalmic surgical instruments. Sensing is accomplished using an optical sensing interrogator (SM130-700 from Micron Optics, Inc., Atlanta, GA) which scans each fiber at 2 kHz to a resolution of 1 pm. This allows a resolution of 0.25 mN to be achieved by the sensor.

**Hybrid Position/Force Control**

The hybrid position/force control system utilizes Micron’s previously developed position-control loop (32) integrated with a direct force-control loop (31). The system is similar to the classic hybrid position/force control originally proposed by Craig and Raibert (36). A notable difference from the classic control method is the lack of the compliance-selection matrix for exclusively defining force or position control. While this can cause instabilities at higher frequencies (37), the slow movements executed during clinical peeling procedures ensure that input stays below roughly 2 Hz (32). The position loop acts to smooth the motion of the end-effector, removing unwanted tremor disturbances. To increase positioning accuracy and regulate applied forces, the position loop is always active, while the force control loop is activated only if the sensed force exceeds a defined threshold. Once active, the necessary position correction from the force loop is added to the filtered output of
the position loop. A block diagram of the implemented hybrid position/force control is shown in Figure 1.

Conversion from force sensor coordinates to world coordinates is performed by a rotation matrix based on calibration between the sensor output and the tip movement of Micron. Coordinates are then considered with respect to the handle for purposes of control. A Kalman filter is then implemented to provide a feedforward term for decreased latency and noise within the lower force loop. Gravity compensation in the control loop is not necessary due to the light weight of the sensor; gravity force is sufficiently mitigated by zeroing the sensor while the manipulator is being held in a peeling orientation.

The force-control loop utilizes three levels of control to provide a seamless integration of the control system during procedures. A soft and a hard constraint for force are specified; for forces below the soft constraint no force control is active. A transition region is specified for forces between the soft constraint and the hard constraint: force error is scaled linearly to provide a correction according to equation (1). If the sensed force is above the hard constraint, the unmodified force error is sent to the control system in order to mitigate any tissue damage.

Since Micron is a fully handheld manipulator, the only stationary coordinates are referenced to ASAP. This does not provide a useful physical relation for evaluating the tasks. To provide relevance for data analysis, all forces are reported with respect to the body frame of the manipulator, as illustrated in Figure 2. Twelve trials were performed in each model by the four subjects while position and hybrid control modes were randomly varied (n=24 for each mode). A one-way ANOVA was then calculated to determine the statistical significance of the maximum force along each axis, the duration of the trials, and the number of tears observed in the animal model.

**Experimental System**
Four subjects performed membrane peeling under a board-approved protocol. One subject was a trained vitreoretinal surgeon with 37 years of surgical experience. The other three subjects were non-clinicians, with varying levels of familiarity with Micron. Membrane-peeling procedures were performed under 16x magnification using a Zeiss OPMI 1 surgical microscope and custom peeling fixtures for the artificial phantom and the egg model (described below). Procedures were also recorded at 30Hz for review through the surgical microscope using two Flea2 1024x768 cameras (Point Grey Research, Inc., Richmond, B. C.).

**Artificial Membrane Model**

An artificial membrane model was used to provide a repeatable method with which to validate the performance of the control system. Previous models used to simulate membrane peeling have included New-Skin® Liquid Bandage (38) on various surfaces, Glad® ClingWrap on Sorbothane® rubber (30), and Clear Bandages (39) on PTFE. Sorbothane® rubber was desirable as a substrate for its tissue-like properties (40). New-Skin® Liquid Bandage and Glad® ClingWrap are useful models, but posed difficulties while peeling with a pick due to their stiffness. Clear bandages exhibited a much higher adherence to the rubber surface compared to PTFE, and could not be used.

Polydimethylsiloxane (PDMS) was chosen instead as an artificial membrane model due to its widespread use in microfabrication and tissue engineering. To prepare the model, a 30-μm layer of PDMS was spin-coated onto a silicon wafer. The PDMS was then sectioned into rectangular strips, 5.2 mm x 20 mm, and transferred onto a layer of Sorbothane® rubber. The width of the strip was chosen to mimic the approximate force exhibited during retinal peeling procedures. Repeatability of the model was verified by peeling 15 samples from the Sorbothane® rubber surface while attempting to maintain a constant velocity. A surgeon’s feedback about the model confirmed that mechanical behaviour was similar to the ILM.
The setup for the artificial model is depicted in Figure 3. Subjects were trained to peel the PDMS layer from the Sorbothane® rubber while holding the tool orthogonal to the peel direction in order to accurately record force data. In keeping the tool orthogonal to the peeling direction, the y-axis was oriented roughly normal to the surface of the rubber, and the x-axis was aligned roughly with the direction of the peel, as shown in Figure 4.

**Animal Model in vivo**

The animal model setup can be seen in Figure 5. Fertilized chicken eggs were chosen as a membrane-peeling model in vivo. This model has been described previously in the literature for simulation of retinal membrane peeling and other retinal manipulations, and is similar to the ERM (41,42). A significant advantage to this model is that damage to the underlying chorioallantoic membrane causes the membrane to bleed, providing an additional realistic biological means for evaluation of the peeling forces.

Newly fertilized eggs were obtained from a local farm (Eichner’s Farm Market, Wexford, PA) and incubated until 12 or 13 days old. Trials were performed by removing the eggshell to expose the inner shell membrane (ISM) and the chorioallantoic membrane (CAM). A volume of saline was used to moisten the ISM to simulate conditions within the natural eye. An initial tear was created in the membrane followed by smaller grasping and peeling motions to remove the ISM. As peeling progressed, the egg was rotated to maintain the orientation of Micron within the 4-cm³ workspace of ASAP. The tool was oriented perpendicular to the peeling direction during trials, in order to provide accurate measurement of the forces applied to the tip, since the 2DOF sensor does not sense force parallel to the tool shaft.

Non-surgeon subjects were given significant training (>3 hours) to learn the peeling motions and coordinate the proper orientation of Micron in the ASAP workspace. Each trial
consisted of peeling a circular section of the ISM away from the CAM. Force and the number of damaged regions of the CAM (i.e., “retinal tears” in the model) were recorded.

**Results**

**System Response**

To test the response properties of the hybrid control system without the human in the loop, Micron was clamped in place, and the tip of the manipulator fixed in Sorbothane® rubber, such that any displacement would result in a measured force. The sensor was then zeroed, and a sinusoidal position stimulus was injected at frequencies ranging from 0.5 Hz to 30 Hz.

The resulting gain and phase response are shown in Figure 6. The system was determined to have a maximum attenuation of 23dB, decreasing logarithmically after 0.4 Hz. The system then exhibits a sharper decrease in attenuation after 0.8 Hz. The zero-crossing occurs at 15 Hz and corresponds to a sharp decrease in phase to -180° at frequencies above the crossing. As motion during microsurgical procedures tends to be slow, movement generally occurs at frequencies less than 2 Hz (32), which corresponds to an maximum attenuation of 13dB. This is sufficient for limiting forces during microsurgical procedures and our peeling trials.

**Artificial Membrane Model**

The artificial model was used for evaluation of the control system with a human in the loop in a conveniently reproducible model. Results from repeated peelings while trying to maintain a constant velocity determined the RMS peeling force to be $5.2 \pm 2.2$ mN across
samples. From these results the soft and hard constraints for peeling were set to 2 mN and 4 mN respectively in both the positive $x$- and $y$-directions (direction of peeling). Along the negative $x$- and $y$-directions (opposite the direction of peeling) both constraints were set to zero such that the hard constraint is immediately active.

The RMS force across all combined trials and the maximum force from each trial were examined under position control and under hybrid position/force control. RMS force was reduced by 32% along the $x$-axis and 41% along the $y$-axis. Maximum force across trials under position control was found to be $7.48 \pm 2.70$ mN along the $x$-axis and $10.03 \pm 3.52$ mN along the $y$-axis. This corresponds to a mean reduction of 46% along the $x$-axis and 63% along the $y$-axis, as shown in Figure 7. A significant difference between position and hybrid control was found; $F(1,46) = 35.4, p < 0.05$ along the $x$-axis and $F(1,46) = 70.4, p < 0.05$ along the $y$-axis.

The mean duration of trials under position control was $80.74 \pm 64.14$ s and $69.73 \pm 40.42$ s under hybrid control; this was not found to be a significant variation ($F(1,46) = 0.51, p < 0.05$).

Histograms of the forces recorded across all trials in the artificial model are presented in Figure 10 for both the $x$- and $y$-axis. The occurrences are normalized with respect to the total number of samples recorded.

**Animal Model in vivo**

While training participants in the biological model, soft and hard constraints of 2 mN and 6 mN were chosen along both directions of the $x$-axis and along the positive $y$-axis; both constraints were set to zero along the negative $y$-axis. These constraints were found to be sufficient for preventing damage to the underlying CAM. A sample dataset of approximately 28 s duration is given in Figure 8 in which the effect of the hybrid control can be observed. RMS forces were found to be reduced by 34% along the $x$-axis and 36% along the $y$-axis. The
maximum forces along the $x$- and $y$-axis under position control were respectively found to be $15.73 \pm 5.52$ mN and $12.52 \pm 5.30$ mN. Under hybrid control the maximum forces were found to be $7.20 \pm 1.43$ mN and $5.22 \pm 1.33$ mN along the $x$- and $y$-axis, respectively. This corresponds to a significant reduction in the maximum force by 54% along the $x$-axis ($F(1,46) = 53.7, p < 0.05$) and 58% along the $y$-axis ($F(1,46) = 42.8, p < 0.05$), as shown in Figure 9.

The mean number of tears per procedure of the CAM was found to be $1.38 \pm 1.41$ without hybrid control and $0.75 \pm 1.11$ with hybrid control, which did not correspond to a significant improvement ($F(1,46) = 2.91, p < 0.05$). A histogram of the forces recorded across all trials is presented in Figure 11 for both the $x$- and $y$-axis. The occurrences are normalized with respect to the total number of samples recorded within the animal model.

No significant difference in the duration of the trials (displayed in Table I) was found in the animal model ($F(1,46) = 0.13, p < 0.05$).
Discussion

The results presented suggest that hybrid position/force control with an active handheld micromanipulator is an effective method for enhancing microsurgical positioning accuracy and control of force. Maximum force was reduced significantly in both peeling models. When computing the vector sum of the axes, total reduction in the RMS force of the artificial model was 36\% and 56\% in maximum force. A reduction of 31\% in total RMS force and 56\% in maximum force were observed in the model. This reduction in force to levels below those observed for tearing has potential to mitigate the risk of iatrogenic retinal tears and trauma when translated to clinical use, especially in the case of the maximum force as these excursions have the most potential to cause trauma.

In addition, no significant difference was found in the duration of the procedure. Thus an increase in patient safety during membrane peeling may be attained without increasing the duration of the procedure.

Future work will include additional benchtop testing with a sclerotomy constraint, followed by testing in animal eyes in vivo.
Acknowledgements

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Disclosures and Ethics

As a requirement of publication author(s) have provided to the publisher signed confirmation of compliance with legal and ethical obligations including but not limited to the following: authorship and contributorship, conflicts of interest, privacy and confidentiality and (where applicable) protection of human and animal research subjects. The authors have read and confirmed their agreement with the ICMJE authorship and conflict of interest criteria. The authors have also confirmed that this article is unique and not under consideration or published in any other publication, and that they have permission from rights holders to reproduce any copyrighted material. Any disclosures are made in this section. The external blind peer reviewers report no conflicts of interest.
References


### Tables

I. Duration of Trials under Position and Hybrid Control for Peeling Trials

<table>
<thead>
<tr>
<th>Model</th>
<th>Position Control (s)</th>
<th>Hybrid Control (s)</th>
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<tbody>
<tr>
<td>Artificial</td>
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<td>69.7 ± 40.4</td>
</tr>
<tr>
<td>Biological</td>
<td>196.6 ± 100.6</td>
<td>205.4 ± 70.4</td>
</tr>
</tbody>
</table>
Figure 1. Block diagram of the hybrid position/force control loop implemented on Micron. The upper position loop estimates hand tremor and has been discussed in previous work (32). The force control loop implements a coordinate transform to align the force frame to the position frame and a Kalman filter for feedforward estimation. When the defined force threshold is exceeded the force control loop correction is added to the position output to provide simultaneous tremor suppression and force control.
Figure 2. Micron, a handheld micromanipulator and force sensor assembly are shown above. The position coordinate frame is shown in white with axes denoted with ‘p’ subscript. The force sensor frame is shown in orange at the tip and axes are denoted with subscript ‘f’. A coordinate transform is generated after the assembly to align the two frames in the control loop. **Forces presented in this paper are with respect to the body frame (white)** in which the positive y direction will correspond to the primary direction of the peel and the positive x direction corresponds to the left of the tip if holding Micron.
Figure 3. The surgical setup for artificial membrane peeling experiments showing a) ASAP optical tracker b) surgical microscope c) optical interrogator d) Micron and force sensing pick e) PDMS and Sorbothane ® layer.
Figure 4. (top) Peeling of a PDMS layer depicting the force axis in the body frame (bottom) The ideal alignment of the tool and sorbothane layer is depicted. The sensing plane is shown in the body frame with force in the x axis roughly aligned with the direction of the peel and force in the y axis aligned with the surface normal.
Figure 5. Completed peeling procedure shown in the animal model with the Micron tool tip shown in peeling orientation. The top of the egg is removed to expose the ISM and CAM and saline added to moisten the membrane. Peeling the ISM is performed using a surgical microscope. During peeling the forces along the x axis roughly correspond to forces tangential to the CAM while y axis forces are roughly aligned with the surface normal of the CAM.
Figure 6. System response of the hybrid position/force control loop with the handpiece rigidly clamped. A sinusoidal position displacement was introduced at logarithmically spaced frequencies 0.1 to 20 Hz, each frequency was sampled with $n \geq 2$. A maximum attenuation of 23 dB is observed below 0.4 Hz and decreases to 13 dB at 2 Hz, the maximum expected frequency. The zero crossing occurs at 15 Hz.
Figure 7. Artificial model peeling results across trials showing a reduction of RMS forces of 32% along the x-axis and 41% along the y-axis (upper) and a reduction in maximum forces by 46% along the x-axis and 63% along the y-axis (lower).
Figure 8. Sample peeling dataset from the animal model showing force influence under position and hybrid control, the dataset was lowpass filtered at 40 Hz to remove noise. A hard constraint of 6 mN along both the x axis (tangential to CAM) and y axes (normal to CAM) is indicated by the dotted line. The RMS force (bottom) is depicted for both position and hybrid control. Forces under hybrid control can be observed to be much lower in magnitude and stay below the hard constraint of 6 mN, while position controlled peeling frequently exceeds this constraint.
Figure 9. Peeling results across trials within the animal model showing a reduction of RMS forces of 34% along the x-axis and 36% along the y-axis (upper) and a reduction in maximum forces by 54% along the x-axis and 58% along the y-axis (lower).
Figure 10. Normalized distribution of forces observed along the $x$-axis (top) and $y$-axis (bottom) in the artificial model. Higher forces can distinctly be identified as occurring more frequently along both axes under position control. Hybrid control is observed to have predominantly higher frequencies of occurrence in the lower range of forces.
Figure 11. Normalized distribution of forces observed along the $x$-axis (top) and $y$-axis (bottom) in the animal model. Higher forces can be seen to occur more frequently along both axes under position control. Hybrid control can be observed to have predominantly higher frequencies in the lower range of forces.