Active Tremor Compensation via Robotic Handheld Instrument and Wearable Orthosis

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Active Noise/Disturbance Compensation

- Low signal-to-noise ratio applications
  - Physiological tremor – micromanipulation
  - Pathological tremor – activities of daily living

Active Pathological Tremor Compensation in Wearable Orthosis

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Active Pathological Tremor Compensation in Wearable Orthosis

Pathological Tremor

Muscle Actuation

Functional Electrical Stimulation

Intended motion

Tremor

Pathological Tremor Model

Zero-phase Filtering and Learning Algorithm

Sensor Fusion

Accelrometer

Task

Muscle Activity
Active Physiological Tremor Compensation in Handheld Microsurgical Instrument

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Microsurgery with Active Handheld Instrument

- Visual Feedback
- Engineering Solutions
- Motion Sensing
- Micron
- Technical Details
- Visuomotor Control System
- Noisy, Tremulous Motion

Active Physiological Tremor Compensation in Handheld Microsurgical Instrument

Involuntary Hand Movement for Healthy People

- Physiological Tremor
  - Roughly sinusoidal, \(\leq 50\, \mu\text{m rms, 8-12 Hz}\)
- Others: Myoclonic jerk, drift
Physiological Tremor and Microsurgery

- Complicates microsurgical procedures and makes certain delicate interventions impossible

Vitreoretinal Microsurgery

- Removal of membranes \( \leq 20 \, \mu m \) thick from front or back of retina

Vitreoretinal Microsurgery

- Injection of anticoagulant using intraocular cannulation to treat retinal vein (~\( \phi 100 \, \mu m \)) occlusion
Physiological Tremor and Microsurgery

- Impact on microsurgeons
  - 2 of 10 surgeons become microsurgeons

- Factors affecting tremor
  - Fatigue – strenuous exercise etc.
  - Caffeine/alcohol consumption (withdrawal syndrome)
  - Lack of practice – long vacation etc.
  - Age – experience vs hand stability

- Microsurgeons’ consensus:
  - 10 μm positioning accuracy

Microsurgery with Active Handheld Instrument

- Visual Feedback
- Motion Sensing
- Micron
- Estimation of erroneous motion
- Noisy, Tremulous Motion
- Manipulation of tip for active error compensation

Comparison of Robotic Solutions

- Telerobotics
- ‘Steady Hand’ robot
- Active Handheld Instrument
  - Cheap
  - Unobtrusive
  - Dexterity
    - Limited workspace
    - No motion scaling
    - No ‘third hand’

- Telerobotics
  - > US$1M
  - > US$150K

- ‘Steady Hand’ robot
  - < US$15K
  - Unobtrusive

- Active Handheld Instrument
  - Disposable surgical needle
  - Manipulator System
  - Sensing System

- Length: 150 mm long
- Diameter: Ø20(16) mm
- Weight <100 g
- 6 DOF inertial at the back end
- 3 DOF piezoelectric driven parallel manipulator at front end with disposable surgical needle
- Signal processing and control performed by PC via ADC & DAC
Microsurgery with Active Handheld Instrument

- Visual Feedback
- Motion Sensing
- Resolution
- Accuracy

On-board Sensing System

- All-accelerometer inertial measurement unit (IMU):
  - 3 dual-axis miniature MEMS accelerometers
  - Analog Devices ADXL-203: 5mm x 5mm x 2mm, < 1g
- Housed in 2 locations

Differential Sensing Kinematics

- Body acceleration sensed by accelerometer at location \( \{i\} \):
  \[ A_i = A_i^{CG} + g + \Omega \times \Omega \times P_{Bi} + \alpha \times P_{Bi} \]
- Differential Sensing
  \[ A_{ij} = A_j - A_i = ([\Omega \times \Omega] + [\alpha \alpha]) P_{ij}, i, j = 1, 2, 3 \]
- Solve system of nonlinear equations for \( \Omega = [\omega_x, \omega_y, \omega_z]^T \) by Gauss-Newton or Levenberg-Marquart method

Sensing Kinematics

- Updating quaternions:
  \[ \dot{q}(t) = \Omega(t)q(t), \quad \Omega = \frac{1}{2} \begin{bmatrix} \Omega_{13} \Omega_{23} \Omega_{32} \end{bmatrix} \]
- Directional Cosines matrix
  \[ \hat{w} C_B^w = \hat{w} C_B^w \hat{A} - \hat{w} \hat{g} \]
- Tip Displacement:
  \[ \hat{w} P_{tip}(t) = \hat{w} P_{tip}(t-T) + \int_{t-T}^{t} \hat{w} \dot{A}_E(r)dr + \int_{t-T}^{t} \hat{w} C_B^w(\Omega \times)^B P_{tip} \]
Sensing Resolution (Error Variance) Analysis

- Sensing resolution dependent on sensor noise floor
- Angular Sensing
  - Sensing equation: \( A_{ij} = f(\Omega) = ([\Omega \times] [\Omega \times] + [\alpha \times]) P_{ij} \)
  - Covariance: \( C(A_{ij}) = C(\Omega) P_{ij} \)
  - \( P_{ij} \uparrow, C(\Omega) \downarrow \)

Proposed All-Accelerometer vs Conventional Inertial Measurement Unit

- All-accelerometer IMU
  - Maximzed \( P_{ij} \) with physical constraint of a slender handheld instrument
- Conventional IMU (3A-3G)
  - Tokin CG-L43D rate gyros x 3

<table>
<thead>
<tr>
<th></th>
<th>3G-3A Error std. dev. (deg/s)</th>
<th>6A Error std. dev. (deg/s)</th>
<th>Noise reduction / resolution improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \omega_x ) &amp; ( \omega_y )</td>
<td>1.41</td>
<td>1.08 ( \times 10^{-2} )</td>
<td>99.3% / 130x</td>
</tr>
<tr>
<td>( \omega_z )</td>
<td>1.41</td>
<td>4.42 ( \times 10^{-2} )</td>
<td>96.9% / 32x</td>
</tr>
</tbody>
</table>

Angular Sensing Resolution Comparison

- Small angular velocity & sensor noise floor
  - All-accelerometer IMU
  - Better orientation estimation → more complete removal of gravity → better translation estimation

Sensing Resolution (Error Variance) Analysis

- Translational Sensing
  - \( 2 \) accelerometers in each sensing direction:
    \[
    \frac{1}{\sigma_A^2} = \frac{1}{\sigma_{d_x}^2} + \frac{1}{\sigma_{d_y}^2} \rightarrow \sigma_A = \frac{\sigma_{d_i}}{\frac{1}{\sigma_{d_i}} + \frac{1}{\sigma_{d_y}}} \]
  - Sensing resolution improves by a factor of \( \sqrt{2} \)
- Better orientation estimation → more complete removal of gravity → better translation estimation
Integration Drift of Inertial Sensors

- Integration drift
  - Erroneous DC Offset
  - Ramp
  - Quadratic
  - Error accumulates and grows unbounded over time
- Poor sensing accuracy

Measurement Model

- Measurement model allows error analysis and compensation
- Measurement Model = Physical (Deterministic) Model + Stochastic Model

Experimental Observations

- $\alpha = 90^\circ$, $\beta = -180^\circ$ to $180^\circ$
- $\alpha = 30^\circ$ & $150^\circ$, $\beta = -180^\circ$ to $180^\circ$

Phenomenological Modeling

- Bias, $B_i(V_y, V_z) = B_x + g_x(V_y) + h_x(V_z)$
- Scale Factor,
  $SF_x(V_z) = r_{x2}V_z^2 + r_{x1}V_z + r_{x0}$
- Model
  $A_x = (V_x - B_x(V_y, V_z)) / SF_x(V_z)$
Sensing Results - Translation

<table>
<thead>
<tr>
<th></th>
<th>Linear Model</th>
<th>Proposed Physical Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rmse (mm/s²)</td>
<td>300</td>
<td>31*</td>
</tr>
<tr>
<td>Bias (mm/s²)</td>
<td>272</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Scale Factor (mm/s²)</td>
<td>6</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Error Reduction (%)</td>
<td>89.7</td>
<td>-</td>
</tr>
</tbody>
</table>

* ADXL-203 rated rms noise = 22.1 mm/s²

Residual Zero Offset - Integration Drift

Analytical Integration

Real-time modeling of Tremor

Acceleration: \[ y_2 = \sum_{i=0}^{L-1} \left( a_i \sin(2\pi(f_o + \frac{r}{G})k) + b_i \cos(2\pi(f_o + \frac{r}{G})k) \right) \]

Velocity: \[ \int y_1 = \sum_{i=0}^{L-1} \left( \frac{a_i}{2\pi(f_o + \frac{r}{G})} \cos(2\pi(f_o + \frac{r}{G})k) - \frac{b_i}{2\pi(f_o + \frac{r}{G})} \sin(2\pi(f_o + \frac{r}{G})k) \right) \]

Position: \[ \int \int y_1 = \sum_{i=0}^{L-1} \left( \frac{a_i}{2\pi(f_o + \frac{r}{G})^2} \sin(2\pi(f_o + \frac{r}{G})k) + \frac{b_i}{2\pi(f_o + \frac{r}{G})^2} \cos(2\pi(f_o + \frac{r}{G})k) \right) \]
Vision Aided Inertial Sensing

Sensor Fusion

Microscopy with Camera

Microsurgery with Active Handheld Instrument
Zero Phase Filtering

- Phase lag = time delay
- Separation of tremor from the intended motion without introducing phase lag
  - Prediction/projection capability
  - Adaptive
    - Non-linear phase response of IIR filter, i.e. phase characteristic changes with frequency

Fourier Linear Combiner (FLC)

- Truncated Fourier series to adaptively estimate amplitude and phase of periodic signal with known frequency ($\omega_0$)

Weighted-frequency Fourier Linear Combiner (WFLC)

- Extends FLC to also adaptively estimate the frequency using another LMS algorithm
- Band-pass filter to select the band of interest
  - Assumption: rate of change of the dominant input signal frequency is slow
- Zero-phase notch (band-stop) filter effect
Weighted-frequency Fourier Linear Combiner (WFLC) Experiment

- 1 DOF motion canceling experiment
- Ave. rms tremor amplitude reduced 69%

Frequency adaptation in WFLC

The frequency adaptation becomes unstable due to the presence of two frequencies 8 & 8.6 Hz

Tremor Recordings

Bandlimited Multiple FLC

- To estimate the tremor signal within a band of frequencies or comprising of multiple frequency components (modulated signals)
- Corresponding weight will adapt to the corresponding frequency of the input signal
- Can deal with input signals of multiple frequency components unlike WFLC
Comparative Performance: Estimation Errors

Presence of two frequencies 8 and 8.6 degrades the performance of WFLC.

Performance of BMFLC with Real-Tremor

Analytical Integration via BMFLC

- Frequency components remain constant in BMFLC
- Once the weights adapt, the weights can also be assumed to be constant

By Performing analytical integration:

\[ y_i = \sum_{r=0}^{L} \left( \frac{a_r}{2\pi(f_0 + \frac{r}{G})} \right) \sin(2\pi(f_0 + \frac{r}{G})k) + \frac{b_r}{2\pi(f_0 + \frac{r}{G})} \times \cos(2\pi(f_0 + \frac{r}{G})k) \]

\[ \int y_i = \sum_{r=0}^{L} \left( \frac{a_r}{(2\pi(f_0 + \frac{r}{G}))^2} \right) \sin(2\pi(f_0 + \frac{r}{G})k) + \frac{b_r}{(2\pi(f_0 + \frac{r}{G}))^2} \times \cos(2\pi(f_0 + \frac{r}{G})k) \]

\[ \int \int y_i = \sum_{r=0}^{L} \left( \frac{a_r}{(2\pi(f_0 + \frac{r}{G}))^3} \right) \sin(2\pi(f_0 + \frac{r}{G})k) + \frac{b_r}{(2\pi(f_0 + \frac{r}{G}))^3} \times \cos(2\pi(f_0 + \frac{r}{G})k) \]
Microsurgery with Active Handheld Instrument

- Visual Feedback
- Motion Sensing
- MICRON
- Visuomotor Control System
- Noisy, Tremulous Motion
- Manipulation of tip for active error compensation
- Estimation of erroneous motion
- High precision tracking control
- Mechanism design

Vitreoretinal Micronics

Manipulator Design

- 3 DOF piezoelectric-driven parallel manipulator
  - 1 actuator per axis, max effective stroke = 12.5 µm
  - Motion amplification = 9.4x, total stroke > 100 µm
- Tool tip approximated as a point, hence only 3 DOF manipulation
- Parallel manipulator design because
  - Rigidity, compactness, and design simplicity

Design of Parallel Mechanism

- Flexure Based Mechanism
- Monolith design using Stereolithography (SLA)
  - Ø22 x 58 mm
- IEEE EMBS 2005 (Shanghai) Best Student Design Competition winner
  - David Choi (CMU) et al.

Piezoelectric Actuator Hysteresis

- Pros:
  - High bandwidth
  - Fast response
  - High output force
- Cons:
  - Hysteresis
- ~15% of max. displacement
- Hysteresis is rate-dependent

Pros: 25 Hz
Cons: 5 Hz
Commercial Piezo-System with Feedback Controller

- Piezo-driven 3 axis micro-positioner
  - Polytec-PI, Germany, NanoCube™ P-611
  - >$10,000
  - Feedback sensors: strain gages
  - Tracking a 10 Hz, 100 µm p-p sinusoid
- Hysteresis still present
- Low-pass filtered behavior

Feedforward Controller with Inverse Hysteresis Model

- Develop an invertible mathematical model that closely describes the hysteretic behavior of a piezoelectric actuator
- Prandtl-Ishlinskii Model

Prandtl-Ishlinskii (PI) Operator

- Rate independent backlash operator:
  \[ H_r = \max \{ x(t) - r, \min \{ x(t) + r, y_0 \} \} \]
- Linearly weighted superposition of backlash operators:
  \[ y(t) = \tilde{w}_{\Phi}^T \tilde{H}_r [x, \tilde{y}_0](t) \]

Inverse PI Hysteresis Model

- Reflection about Y = X (45° line)
Tremor Tracking Results

- Tracking recordings of real tremor using 1 piezoelectric stack
  - \( \text{Rmse} = 0.64\% \) of max ampl.; \( \text{Max error} = 2.4\% \) of max ampl.

Experimental Results

**Adaptive Feedforward Controller**

- Eliminate parameter identification
- Weight adapting mechanism: Recursive Least Square

\[
\dot{w}^T \hat{S}_w [\dot{w}^T (z) H (z, \hat{y}_d)](t)
\]

\[
\dot{z}(t) = w_b (z(t)) \approx u_t + b z(t)
\]

**Real-time Active Compensation – 1 DOF Disturbance, 1 DOF Compensation**

<table>
<thead>
<tr>
<th>rmse ± σ (µm)</th>
<th>0.0943 ± 0.0159</th>
</tr>
</thead>
<tbody>
<tr>
<td>rmse / actuator’s stroke length (%)</td>
<td>0.31</td>
</tr>
<tr>
<td>max error ± σ (µm)</td>
<td>0.3899 ± 0.0291</td>
</tr>
<tr>
<td>max error / actuator’s stroke length (%)</td>
<td>1.30</td>
</tr>
</tbody>
</table>
Real-time Active Compensation – 1 DOF Disturbance, 3 DOF Compensation

Real-time Active Compensation – Handheld
- 5 DOF sensing by 2 orthogonal position sensitive detectors
- No inertial sensing
- Non-surgical scenario

Active Pathological Tremor Compensation in Wearable Orthosis

Pathological Tremor
Pathological Tremor: Causes & Symptoms

- 3-12 Hz
- From < 10 mm (fingers) to > 100 mm (arm)
- Common medical conditions
  - Essential tremor (postural tremor)
  - Parkinson’s disease (resting tremor)
  - Cerebellar dysfunction (intention tremor)
    - e.g. stroke, multiple sclerosis, Wilson’s disease

Impact of Pathological Tremor

- Affects 5-9% of the population age > 40
- Activities of daily living become challenging or impossible
- Social embarrassment and isolation
- Lifetime cost per patient > US$1M

Treatment Options

- Drug therapy
  - > 50% are not responsive to drug
- Stereotactic surgery
  - Cost, psychological barrier, chances of complication
- Assistive technology
  - Active tremor compensation via wearable orthosis
    - A 20-100 ms electromechanical time delay between Electromyograph (EMG) signals and muscle actuations

Active Tremor Compensation in Wearable Orthosis
System Overview

Filtering
- Tremor Filter
- EMG Filter

Sensing
- Camera system
- Parameters Identification
- Sensor Fusion
- Signal Processing
- Tremor model

Musculo-skeletal system
- Intended EMG
- FES-Controller
- Intended motion / position info
- Model information

Compensation
- Inv. Arm Model
- Model information

Musculo-skeletal system
- Tremor EMG
- Intended EMG
- Tremor motion

Feedback Control System

Controller
- Stimulators
- Sensors e.g. EMG

Musculoskeletal System

Robot Arm vs Human Arm
- Actuation system
  \[ T_m = K_i i \]
  \[ e = K_f \omega_m \]
  \[ V_a = iR + L \frac{di}{dt} + e \]

Electrical Motor
Muscle (Hill-Type)

Robot Arm vs Human Arm
- Links
  VS.
  Kinematics & Dynamics are solved in similar ways

Manipulator
Skeleton
Musculoskeletal Model of Upper Limb

- Well studied and established

Key Challenges

- Sensing
  - How can we know what upper limb movement (tremulous + voluntary) will occur from the sensed SEMG of the muscles?

Key Challenges

- Filtering
  - How can we differentiate between tremulous & voluntary SEMG of the muscles?

Key Challenges

- Functional Electrical Stimulation
  - How can we use FES to generate (anti-)tremulous movement in the upper limbs?
Musculoskeletal Modeling of Tremor in Upper Limbs

- To understand the roles and characteristics of the skeletal muscles responsible for each type of tremor
- To study SEMG-movement relationship

Pathological Tremor Study

- 18 control subjects, 5 Parkinson’s Disease patients, 6 Essential Tremor patients, 1 Psychogenic tremor patient, and 1 Holmes’ tremor patient

Tremor Study

- 120 patients with movement disorder
  - Parkinson Diseases – resting tremor (>30)
  - Essential Tremor – postural tremor (>30)
  - Multiple Sclerosis, Stoke, etc. – intention tremor (>30)
  - Others (~10)
- 30 healthy people
  - Age 16-85
  - No personal & family medical history of tremor
- National Neuroscience Institute, Singapore

Data Collection

- Record sensor data of patients performing
  - Standard diagnostics: finger to noise, finger to finger, stretched out, drawing spirals, etc.
- Sensors
  - SEMG: 16 channels (8 muscle groups, mostly agonist & antagonist pairs) per limb
  - Accelerometers: 3 x tri-axial per limb
  - Goniometers: 1 per limb
  - Position and Orientation sensor: Vicon optical sensing system (4 cameras)
Sensing

- SEMG
- Accelerometers
- Goniometer
- Optical Sensors

Model

Sensor Fusion

Muscle Activity & Physical Movement

Muscle Contraction Property

Muscle mechanical model (Hill-type)

CE: Contractile Element
SE: Series Elastic Element
PE: Passive Element (Parallel Elastic Element)

Phenomenological Modeling of Upper Limb Tremor from EMG

The spring damper system is tuned to the actual tremor frequency

Sensor Fusion – Kalman Filtering

- EMG-derived joint angle as predictor
- ACC-derived joint angle as corrector

\[
\theta_{EMG}(k) = c_{EMG}(1)EMG(k) + c_{EMG}(2)
\]

\[
\theta_{ACC}(k) = c_{ACC}(1)ACC(k) + c_{ACC}(2)
\]

- Estimate of joint angle

\[
\hat{\theta}(k) = \theta_{EMG}(k) + \frac{\sigma_{EMG}^2}{\sigma_{EMG}^2 + \sigma_{ACC}^2}(\theta_{ACC}(k) - \theta_{EMG}(k))
\]
Results

Kalman filter for elbow flexion-extension of PD patient (sitting, arm resting on thigh)

\[ \sigma^2_{\text{true}} = 0.1045 \]
\[ \sigma^2_{\text{error}} = 0.022 \] (78.76% reduction)

Frequency content of original tremor

Frequency content of the compensated tremor

Power of original tremor = 7.315
Power of compensated tremor = 0.902

The power of the tremor is reduced by 87.67%

Tremor Filtering via ANN

- Cascade Correlation Neural Networks with extended Kalman Filtering
- Experiments with 11 multiple sclerosis patients (intention tremor)
- Smoother trajectory
- Reach and dwell in target circle 31.8% faster
  - Mean over 29 tests

Functional Electrical Stimulations

- Controlling electrical pulses to stimulate the intact peripheral nerve to actuate muscles
  - Usually used to restore the motor functions for the paralyzed patients
- Prochazka et al. (1992) demonstrated the effectiveness of FES for tremor attenuation
  - Offline trial & error tuning of intensity and phase

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Muscle Activation

- Fatigue
- Muscle Activation
- Stimulation Artifact
- FES Controller Design
- Simulation Result of Tremor Suppression

**Muscle Activation**

- Electrical stimulus
- Latent period
- Twitch
- Contraction
- Relaxation
- Summation
- Tetanic contraction
- Fatigue

**Stimulation Artifact**

- Blocking window
  - Turn off EMG channels when stimulation is on

**FES Controller Design**

**Simulation Result of Tremor Suppression**

- No ethical clearance on patient trial yet
Wearable Orthosis

- Wearable bands thin enough to be worn under sleeves
- Battery powered
- Microcontroller based
- Beyond the first step
  - False alarm
  - EEG

Questions & Comments

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