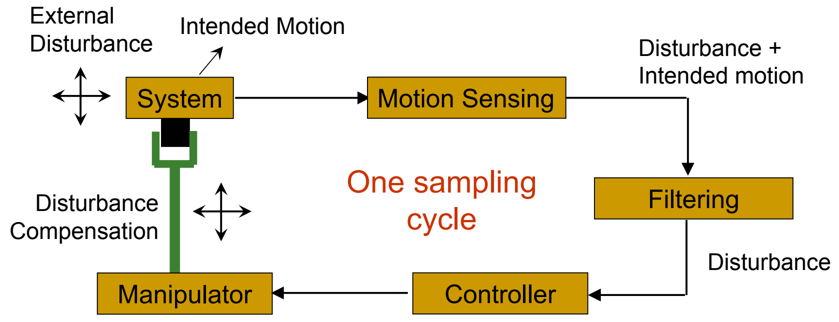
Active Tremor Compensation via Robotic Handheld Instrument and Wearable Orthosis

Wei Tech ANG
Assistant Professor
School of Mechanical and Aerospace Engineering
Nanyang Technological University, Singapore
wtang@ntu.edu.sg

NANYANG TECHNOLOGICAL UNIVERSITY

Active Noise/Disturbance Compensation



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

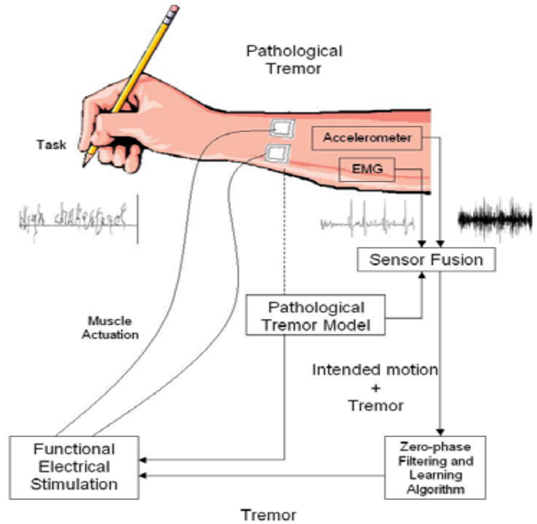
NANYANG TECHNOLOGICAL UNIVERSITY

Active Pathological Tremor Compensation in Wearable Orthosis

Wing Lok AU	National Neuroscience Institute
Philippe POIGNET	LIRMM, U of Montpellier II
Markus RANK (Exch Student)	Technische Universitaet Muenchen
Cheng Yap SHEE	Nanyang Technological University
Louis TAN	National Neuroscience Institute
Adela TOW	Tan Tock Seng Hospital
Kalyana VELUVOLU	Nanyang Technological University
Ferdinan WIDJAJA	Nanyang Technological University
Dingguo ZHANG	Nanyang Technological University

NANYANG TECHNOLOGICAL UNIVERSITY

Active Pathological Tremor Compensation in Wearable Orthosis



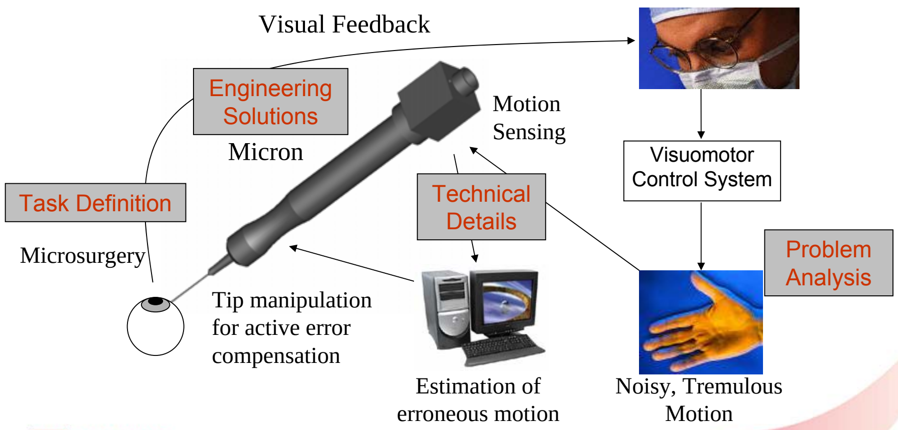
NANYANG TECHNOLOGICAL UNIVERSITY

Active Physiological Tremor Compensation in Handheld Microsurgical Instrument

David CHOI	Carnegie Mellon University
Mingli HAN	Nanyang Technological University
Thiam Chye LIM	National University Hospital
Yee Siang ONG	Singapore General Hospital
Cameron RIVIERE	Carnegie Mellon University
Cheng Yap SHEE	Nanyang Technological University
U-Xuan TAN	Nanyang Technological University
Kalyana VELUVOLU	Nanyang Technological University
Tun Latt WIN	Nanyang Technological University

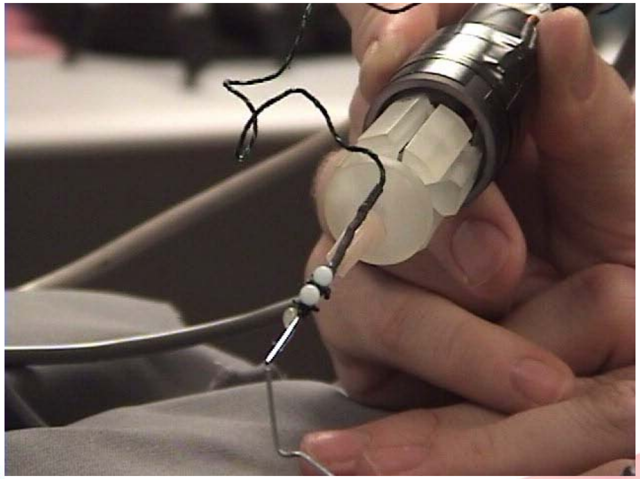
NANYANG TECHNOLOGICAL UNIVERSITY

Microsurgery with Active Handheld Instrument



NANYANG TECHNOLOGICAL UNIVERSITY

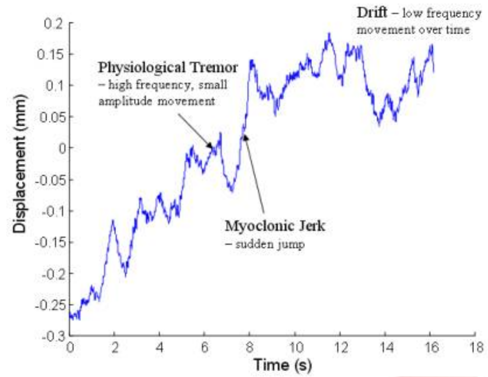
Active Physiological Tremor Compensation in Handheld Microsurgical Instrument



NANYANG TECHNOLOGICAL UNIVERSITY

Involuntary Hand Movement for Healthy People

- Physiological Tremor
  - Roughly sinusoidal, ≤50 µm rms, 8-12 Hz
- Others: Myoclonic jerk, drift



NANYANG TECHNOLOGICAL UNIVERSITY

Physiological Tremor and Microsurgery

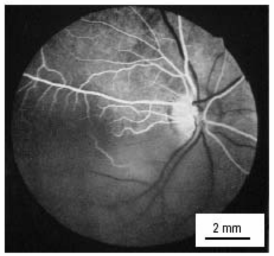
- Complicates microsurgical procedures and makes certain delicate interventions impossible

Vitreoretinal Microsurgery

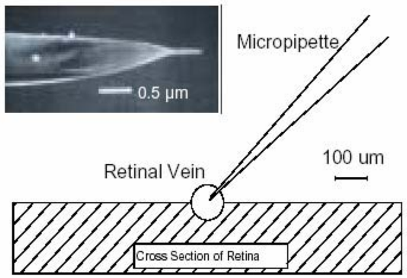
- Removal of membranes ≤ 20 μm thick from front or back of retina

Vitreoretinal Microsurgery

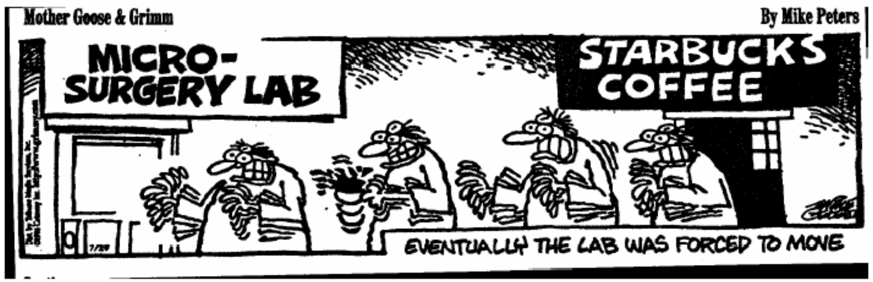
- Injection of anticoagulant using intraocular cannulation to treat retinal vein (~∅100 μm) occlusion



Retina with occluded retinal vein



Physiological Tremor and Microsurgery

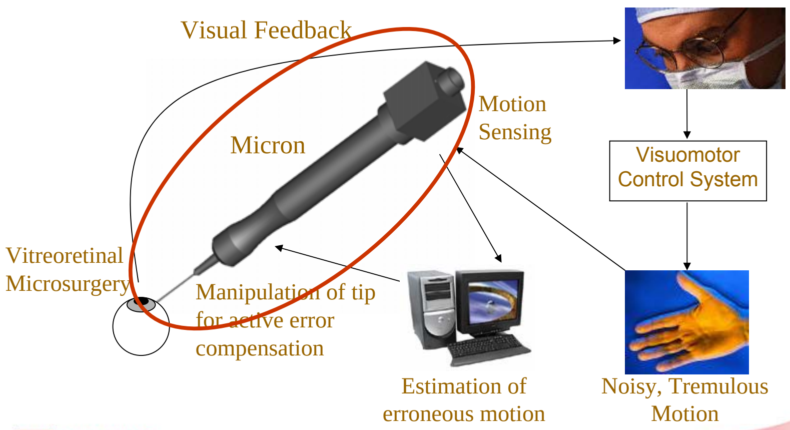


Physiological Tremor and Microsurgery

- 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

NANYANG TECHNOLOGICAL UNIVERSITY

Microsurgery with Active Handheld Instrument



NANYANG TECHNOLOGICAL UNIVERSITY

Comparison of Robotic Solutions

- Telerobotics
- 'Steady Hand' robot
- Active Handheld Instrument
  - ✓ Cheap
  - ✓ Unobtrusive
  - ✓ Dexterity
  - × Limited workspace
  - × No motion scaling
  - × No 'third hand'

Obtrusive

> US$1M

> US$150K

< US$15K

Unobtrusive

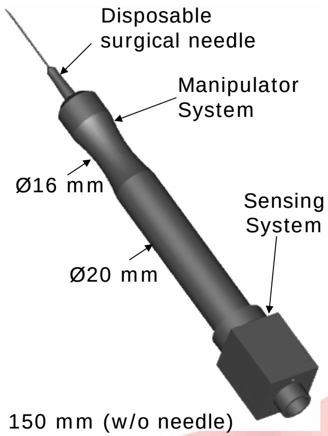

Da Vinci


Steady Hand robot, Johns Hopkins Univ,

NANYANG TECHNOLOGICAL UNIVERSITY

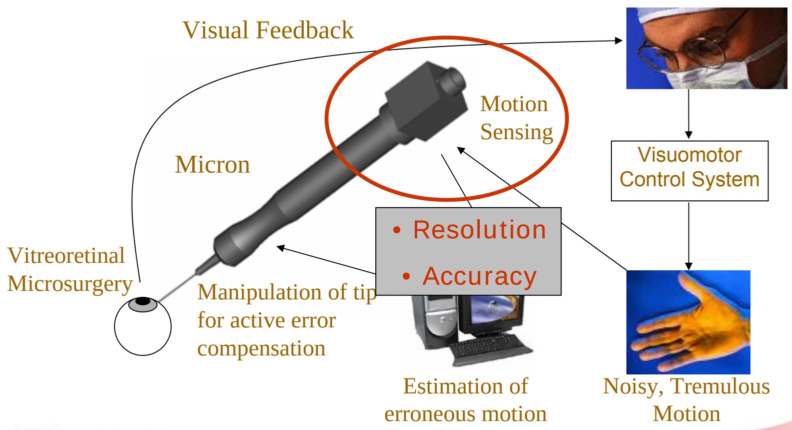
Micron Current Prototype

- 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



NANYANG TECHNOLOGICAL UNIVERSITY

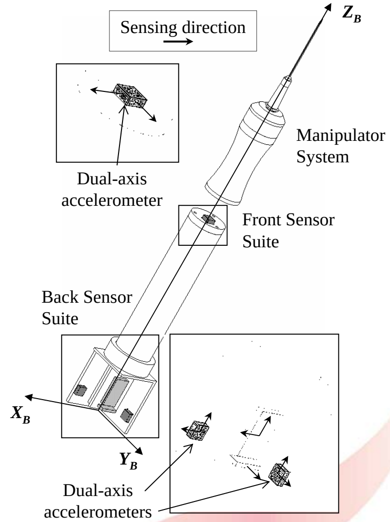
Microsurgery with Active Handheld Instrument



NANYANG TECHNOLOGICAL UNIVERSITY

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



NANYANG TECHNOLOGICAL UNIVERSITY

Differential Sensing Kinematics

- Body acceleration sensed by accelerometer at location {*i*}:

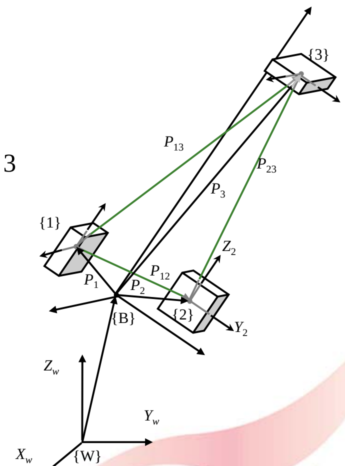
$$A_i = A_{CG} + g + \underbrace{\Omega\times\Omega\times P_{Bi} + \alpha\times P_{Bi}}_{\text{Rotation–induced Accelerations}}$$

- Differential Sensing

$$A_{ij} = A_j - A_i = \left([\Omega\times][\Omega\times]+[\alpha\times]\right)P_{ij}, i, j = 1, 2, 3$$

$$A_{13} = \begin{bmatrix} a_{13x} \\ \bullet \\ \bullet \end{bmatrix}, A_{23} = \begin{bmatrix} \bullet \\ a_{23y} \\ \bullet \end{bmatrix}, A_{12} = \begin{bmatrix} \bullet \\ \bullet \\ a_{13z} \end{bmatrix}$$

- Solve system of nonlinear equations for $\Omega = [\omega_x\ \omega_y\ \omega_z]^T$ by Gauss-Newton or Levenberg-Marquart method



NANYANG TECHNOLOGICAL UNIVERSITY

Sensing Kinematics

- Updating quaternions:

$$\dot{q}(t) = \tilde{\Omega}(t)q(t),\ \tilde{\Omega} = \frac{1}{2}\left[\begin{array}{c|c} [\Omega\times]_{3\times3} & \Omega_{3\times1} \\ \hline -\Omega^T_{1\times3} & 0 \end{array}\right]$$

- Directional Cosines matrix

$$^{W}C_B = \begin{bmatrix} q_0^2+q_1^2-q_2^2-q_3^2 & 2(q_1q_2-q_0q_3) & 2(q_1q_3+q_0q_2) \\ 2(q_1q_2+q_0q_3) & q_0^2-q_1^2+q_2^2-q_3^2 & 2(q_2q_3-q_0q_1) \\ 2(q_1q_3-q_0q_2) & 2(q_2q_3+q_0q_1) & q_0^2-q_1^2-q_2^2+q_3^2 \end{bmatrix}$$

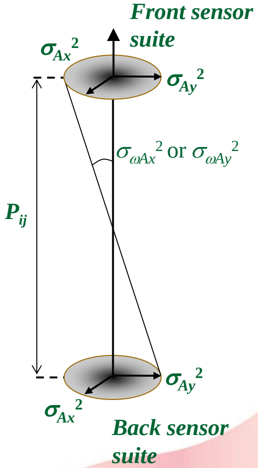
- Gravity Removal: ${}^{W}A_E = {}^{W}C_B\,{}^{B}A - {}^{W}g$
- Tip Displacement:

$$^{W}P_{tip}(t) = {}^{W}P_{tip}(t-T) + \int\int_{t-T}^{t} {}^{W}A_E(\tau)d\tau d\tau + {}^{W}C_B(t)[{}^{B}\Omega\times]\,{}^{B}P_{tip}$$

NANYANG TECHNOLOGICAL UNIVERSITY

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:
    $C(A_{ij}) = C(\Omega)\, P_{ij}$
  - $P_{ij}\uparrow$, $C(\Omega)\downarrow$



NANYANG TECHNOLOGICAL UNIVERSITY

Proposed All-Accelerometer vs Conventional Inertial Measurement Unit

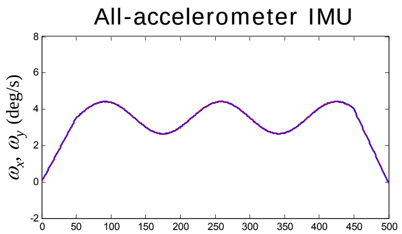
- All-accelerometer IMU
  - Maximized P_{ij}, with physical constraint of a slender handheld instrument
- Conventional IMU (3A-3G)
  - Tokin CG-L43D rate gyros x 3

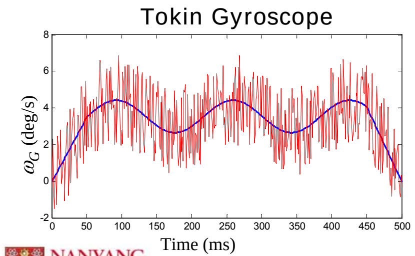
	3G-3A Error std. dev. (deg/s)	6A Error std. dev. (deg/s)	Noise reduction / resolution improvement
ω_x & ω_y	1.41	1.08×10^{-2}	99.3% / 130x
ω_z	1.41	4.42×10^{-2}	96.9% / 32x

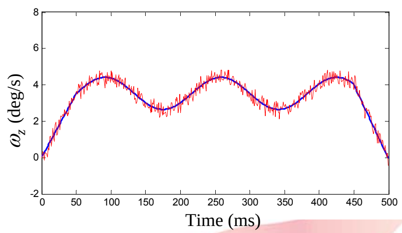
NANYANG TECHNOLOGICAL UNIVERSITY

Angular Sensing Resolution Comparison

- Small angular velocity & sensor noise floor







NANYANG TECHNOLOGICAL UNIVERSITY

Sensing Resolution (Error Variance) Analysis

- Translational Sensing
  - 2 accelerometers in each sensing direction:

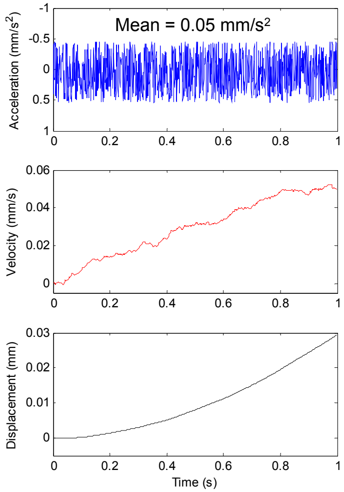
$$\frac{1}{\sigma_A^2} = \frac{1}{\sigma_{Ai}^2} + \frac{1}{\sigma_{Aj}^2} \rightarrow \sigma_A = \frac{\sigma_{Ai}}{\sqrt{2}}$$

  - Sensing resolution improves by a factor of $\sqrt{2}$
- Better orientation estimation $\rightarrow$ more complete removal of gravity $\rightarrow$ better translation estimation

NANYANG TECHNOLOGICAL UNIVERSITY

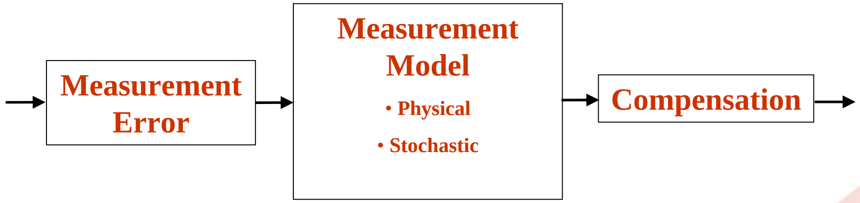
Integration Drift of Inertial Sensors

- Integration drift
  - Erroneous DC Offset $\xrightarrow{\int}$ Ramp $\xrightarrow{\int}$ Quadratic
  - Error accumulates and grows unbounded over time
- Poor sensing accuracy



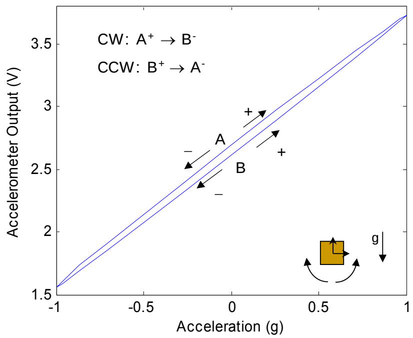
Measurement Model

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

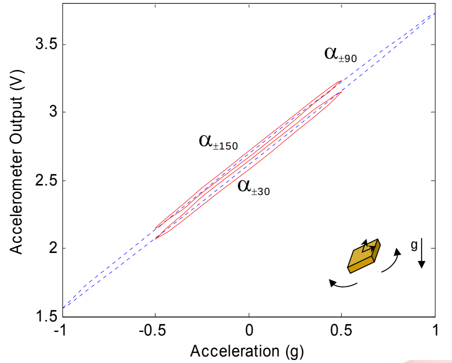


Experimental Observations

$\alpha = 90°$, $\beta = -180°$ to $180°$



$\alpha = 30°$ & $150°$, $\beta = -180°$ to $180°$

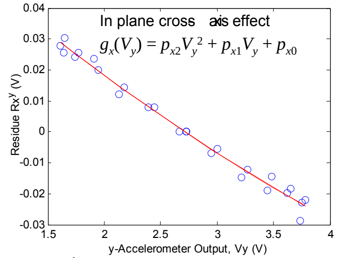


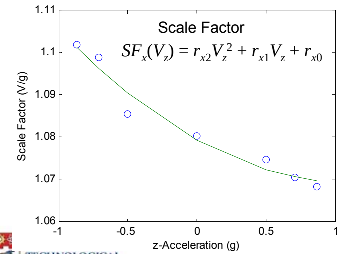
Phenomenological Modeling

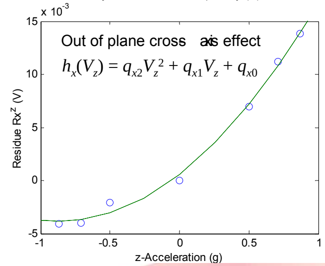
- Bias, $B_x(V_y, V_z) = B_x + g_x(V_y) + h_x(V_z)$
- Scale Factor,

  $SF_x(V_z) = r_{x2}V_z^2 + r_{x1}V_z + r_{x0}$
- Model

  $A_x = (V_x - B_x(V_y, V_z)) / SF_x(V_z)$



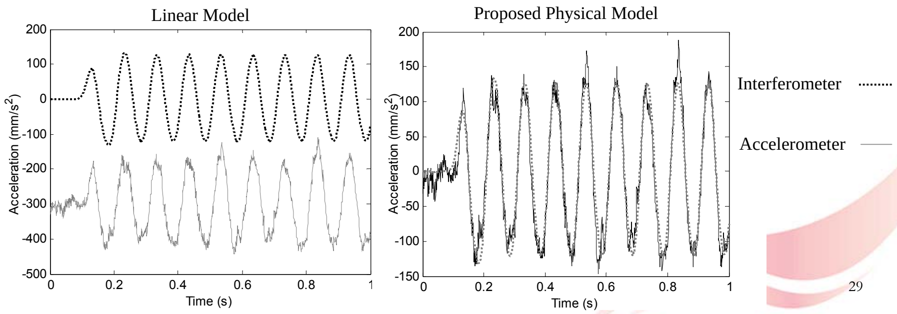




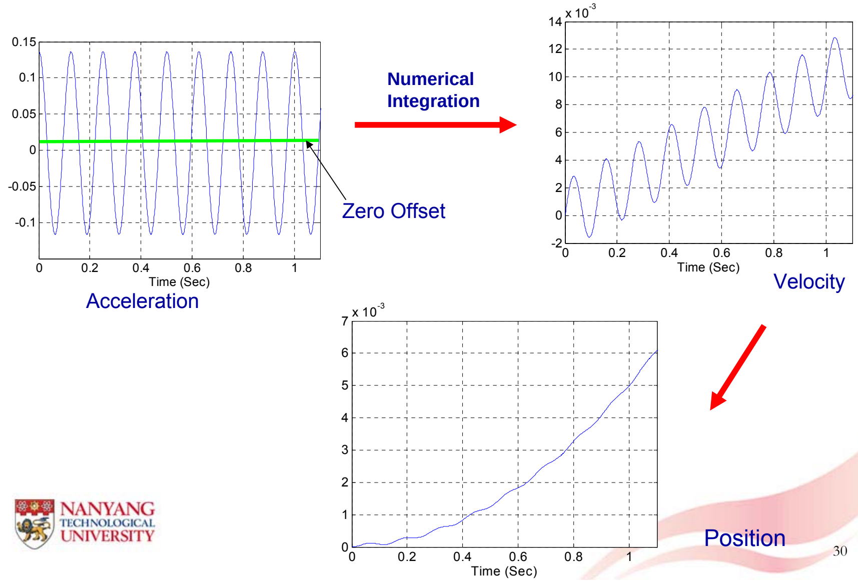
Sensing Results - Translation

	Rmse (mm/s²)	Bias (mm/s²)	Scale Factor (mm/s²)
Linear Model	300	272	6
Proposed Physical Model	31*	<5	<1
Error Reduction (%)	89.7	-	-

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



Residual Zero Offset - Integration Drift



Analytical Integration

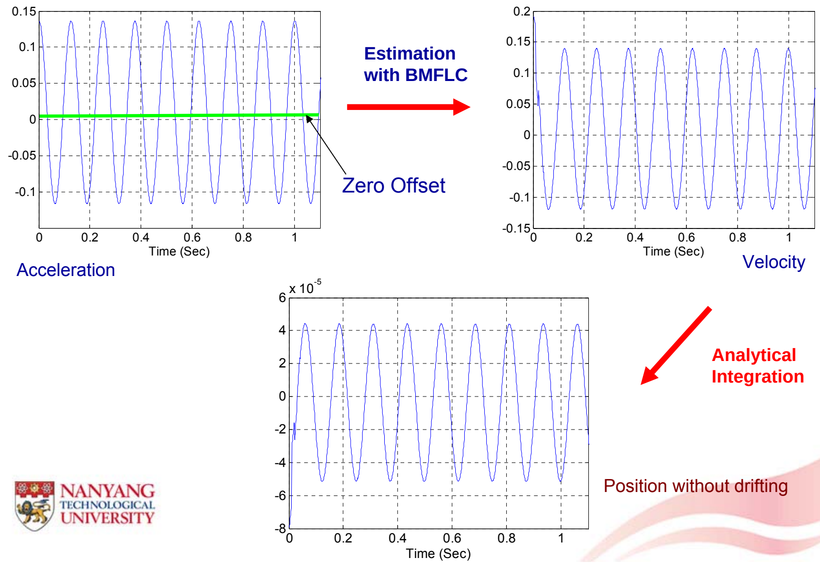
Real-time modeling of Tremor

Acceleration: $$y_k = \sum_{r=0}^{L=(f-f_0)G} a_r \sin(2\pi(f_0+\frac{r}{G})k) + b_r \cos(2\pi(f_0+\frac{r}{G})k)$$

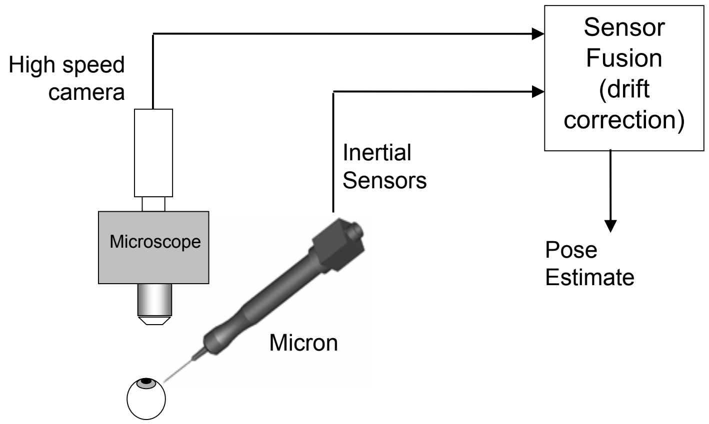
Velocity: $$\int y_k = -\sum_{r=0}^{L}\left[\frac{a_r}{(2\pi(f_0+\frac{r}{G}))}\cos(2\pi(f_0+\frac{r}{G})k) - \frac{b_r}{(2\pi(f_0+\frac{r}{G}))}\sin(2\pi(f_0+\frac{r}{G})k)\right]$$

Position: $$\iint y_k = -\sum_{r=0}^{L}\left[\frac{a_r}{(2\pi(f_0+\frac{r}{G}))^2}\sin(2\pi(f_0+\frac{r}{G})k) + \frac{b_r}{(2\pi(f_0+\frac{r}{G}))^2}\cos(2\pi(f_0+\frac{r}{G})k)\right]$$

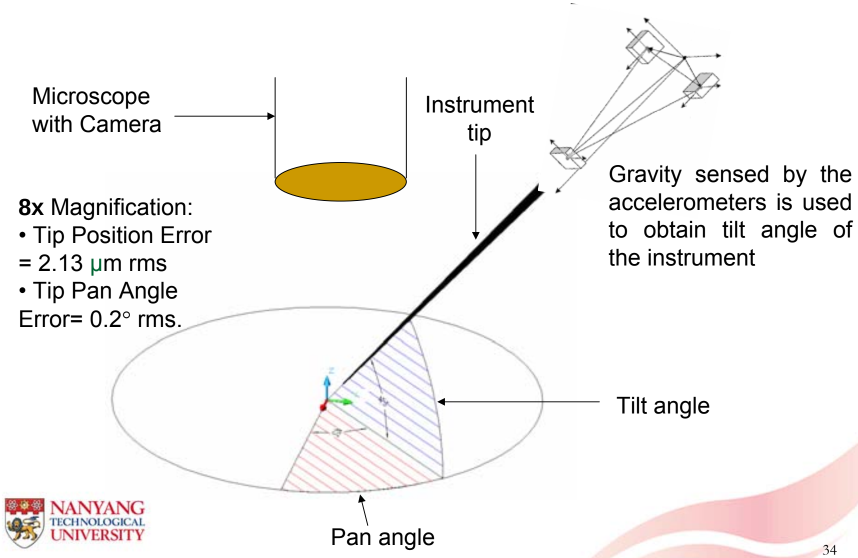
Analytical Integration



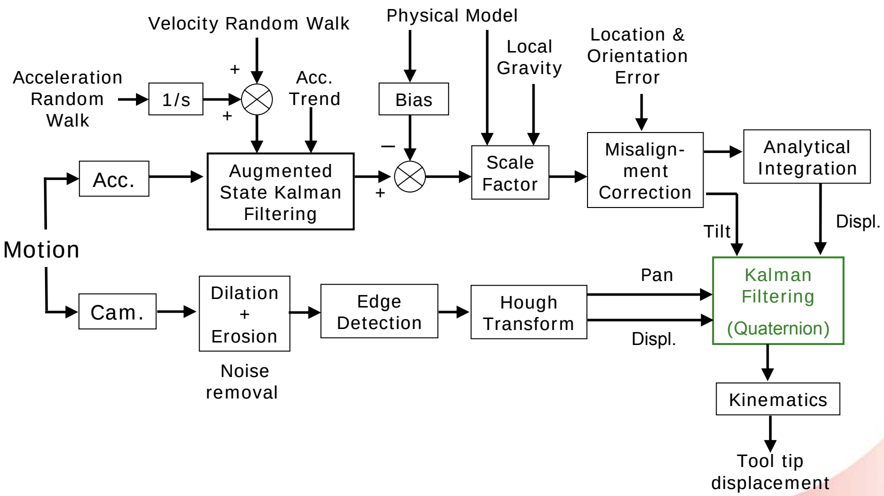
Vision Aided Inertial Sensing



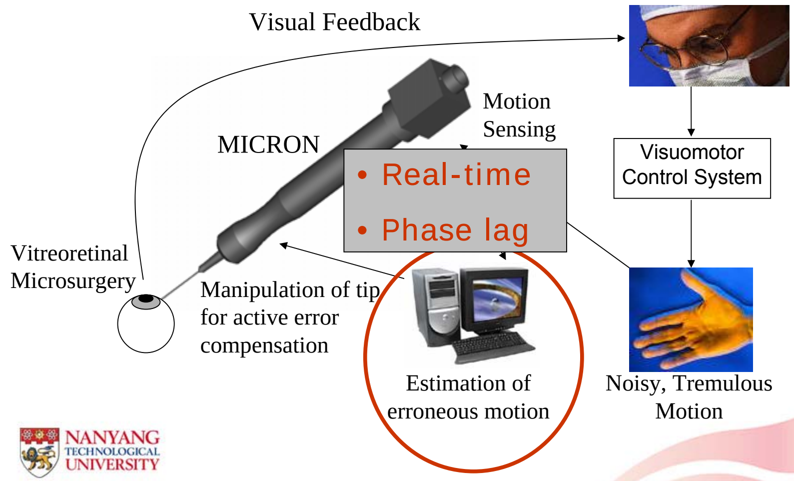
Vision Aided Inertial Sensing



Sensor Fusion



Microsurgery with Active Handheld Instrument



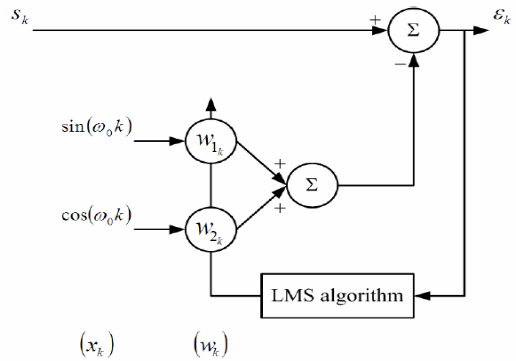
Zero Phase Filtering

- 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

NANYANG TECHNOLOGICAL UNIVERSITY

Fourier Linear Combiner (FLC)

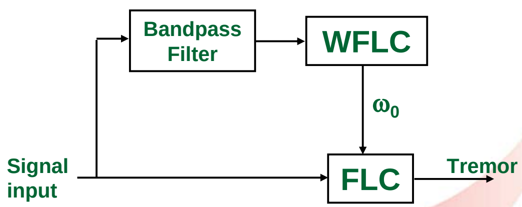
- Truncated Fourier series to adaptively estimate amplitude and phase of periodic signal with *known frequency* (ω_0)



NANYANG TECHNOLOGICAL UNIVERSITY

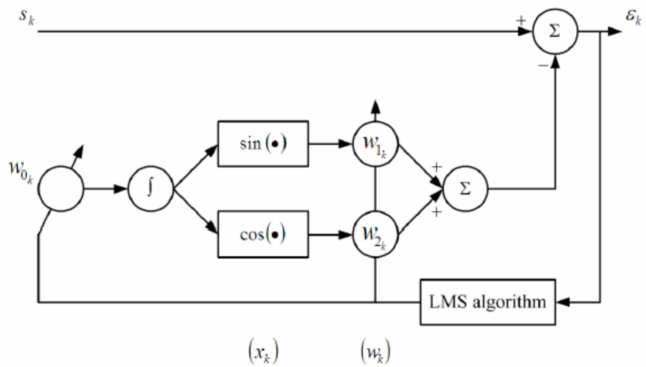
Weighted-frequency Fourier Linear Combiner (WFLC)

- 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



NANYANG TECHNOLOGICAL UNIVERSITY

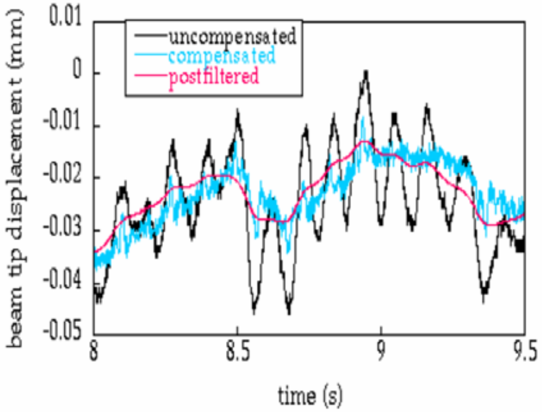
Weighted-frequency Fourier Linear Combiner (WFLC)



NANYANG TECHNOLOGICAL UNIVERSITY

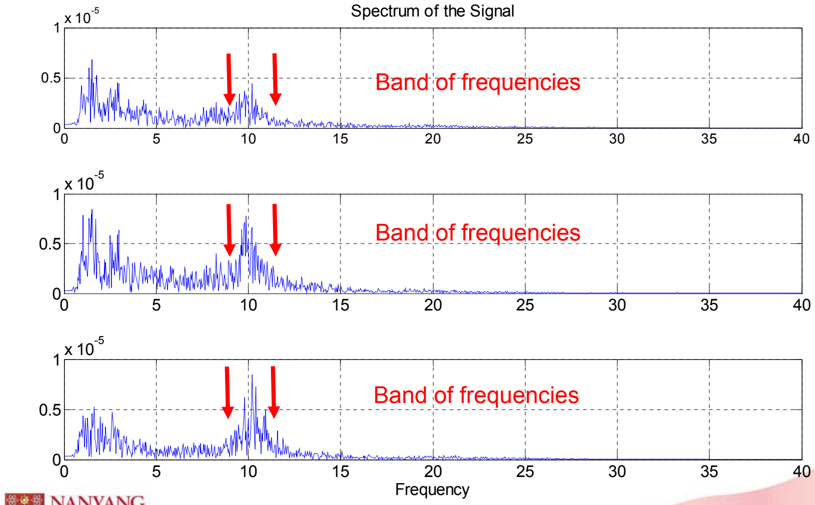
Weighted-frequency Fourier Linear Combiner (WFLC) Experiment

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



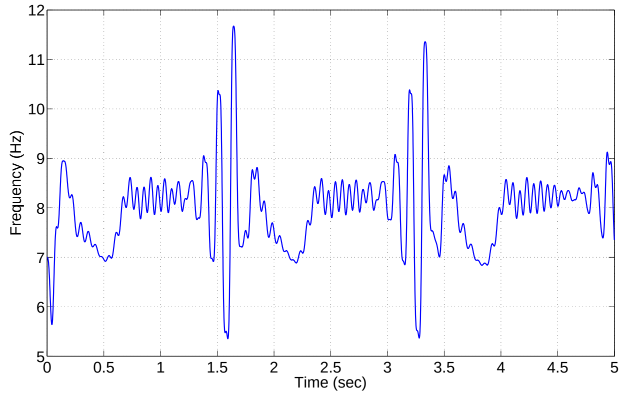
NANYANG TECHNOLOGICAL UNIVERSITY

Tremor Recordings



NANYANG TECHNOLOGICAL UNIVERSITY

Frequency adaptation in WFLC

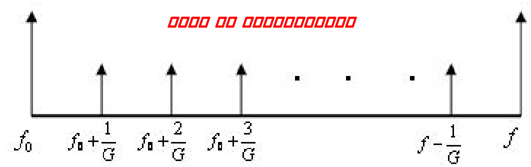


The frequency adaptation becomes unstable due to the presence of two frequencies 8 & 8.6 Hz

NANYANG TECHNOLOGICAL UNIVERSITY

Bandlimited Multiple FLC

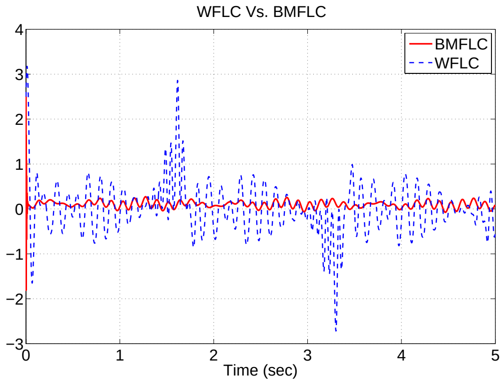
- To estimate the tremor signal within a band of frequencies or comprising of multiple frequency components (modulated signals)



- Corresponding weight will adapt to the corresponding frequency of the input signal
- Can deal with input signals of multiple frequency components unlike WFLC

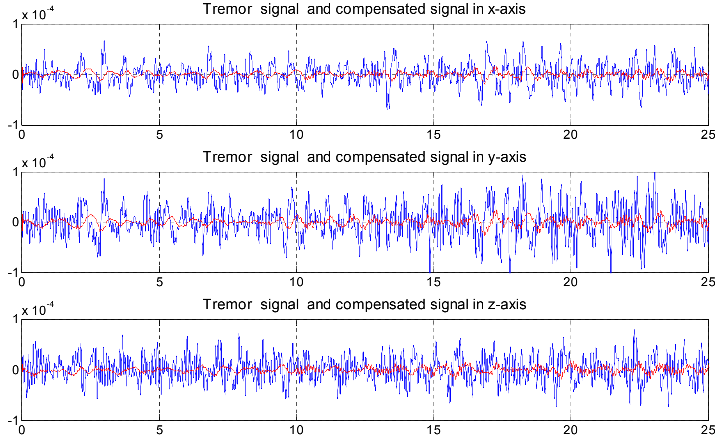
NANYANG TECHNOLOGICAL UNIVERSITY

Comparative Performance : Estimation Errors



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

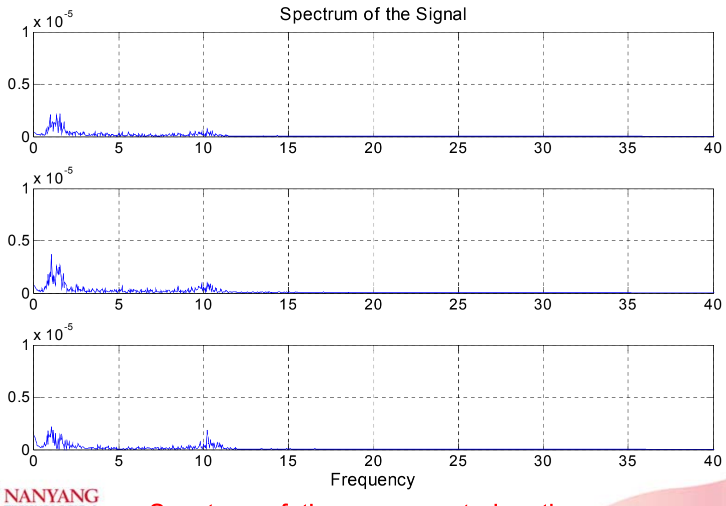
Performance of BMFLC with Real-Tremor



Red line shows the compensated motion

Band of BMFLC: 3- 12 Hz.

Performance of BMFLC with Real-Tremor



Spectrum of the compensated motion.

Analytical Integration via BMFLC

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

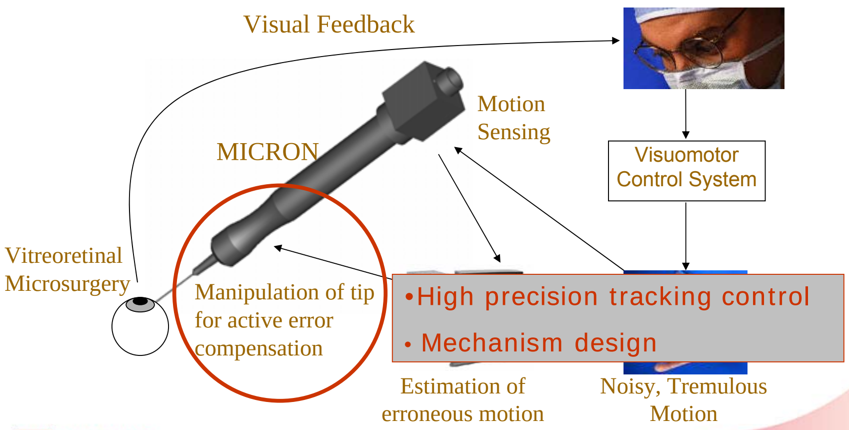
By Performing analytical integration:

Acceleration: $$y_k = \sum_{r=0}^{L=(f-f_0)G} a_r \sin(2\pi(f_0+\frac{r}{G})k) + b_r \cos(2\pi(f_0+\frac{r}{G})k)$$

Velocity: $$\int y_k = -\sum_{r=0}^{L}\left[\frac{a_r}{(2\pi(f_0+\frac{r}{G}))}\cos(2\pi(f_0+\frac{r}{G})k) - \frac{b_r}{(2\pi(f_0+\frac{r}{G}))}\sin(2\pi(f_0+\frac{r}{G})k)\right]$$

Position: $$\iint y_k = -\sum_{r=0}^{L}\left[\frac{a_r}{(2\pi(f_0+\frac{r}{G}))^2}\sin(2\pi(f_0+\frac{r}{G})k) + \frac{b_r}{(2\pi(f_0+\frac{r}{G}))^2}\cos(2\pi(f_0+\frac{r}{G})k)\right]$$

Microsurgery with Active Handheld Instrument



NANYANG TECHNOLOGICAL UNIVERSITY

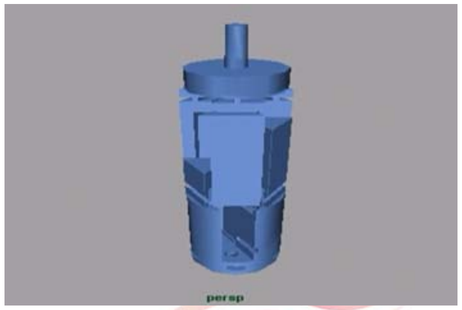
Manipulator Design

- 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

NANYANG TECHNOLOGICAL UNIVERSITY

Design of Parallel Mechanism

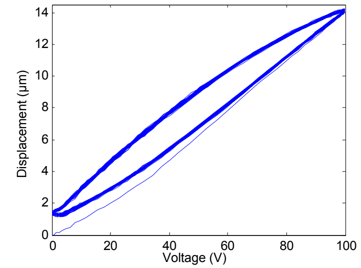
- Flexure Based Mechanism
- Monolith design using Stereolithography (SLA)
- ∅22 x 58 mm
- IEEE EMBS 2005 (Shanghai) Best Student Design Competition winner
  - David Choi (CMU) et al.

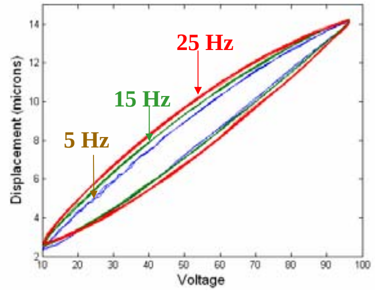


NANYANG TECHNOLOGICAL UNIVERSITY

Piezoelectric Actuator Hysteresis

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

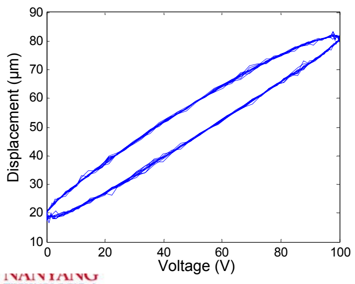


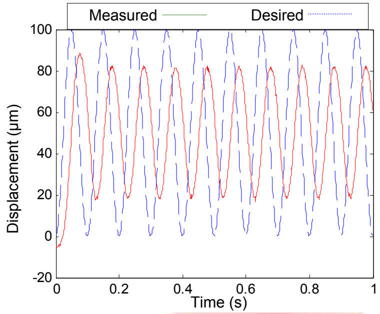


NANYANG TECHNOLOGICAL UNIVERSITY

Commercial Piezo-System with Feedback Controller

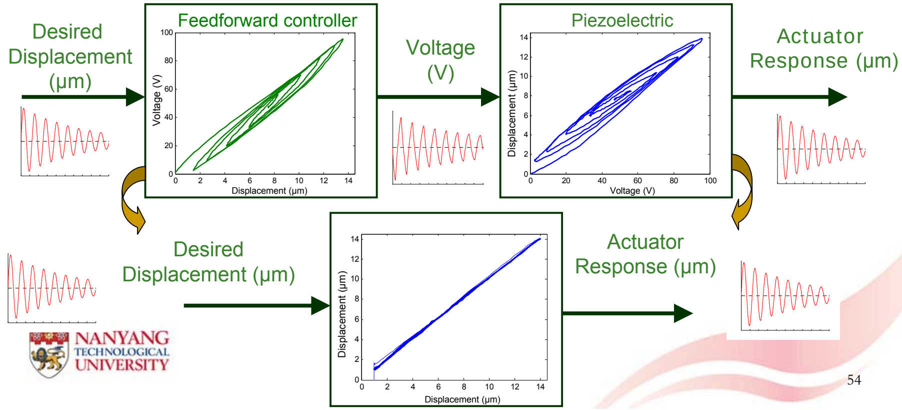
- Piezo-driven 3 axis micro-positioner
  - Polytec-PI, Germany, NanoCube™ P-611
  - >$ 10,000
  - Feedback sensors: strain gages
  - Tracking a 10 Hz, 100 μm p-p sinusiod
    - Hysteresis still present
    - Low-pass filtered behavior





Feedforward Controller with Inverse Hysteresis Model

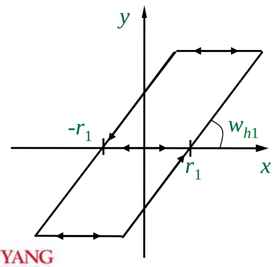
- Develop an invertible mathematical model that closely describes the hysteretic behavior of a piezoelectric actuator
- Prandtl-Ishlinskii Model

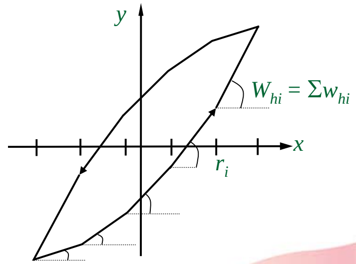


Prandtl-Ishlinskii (PI) Operator

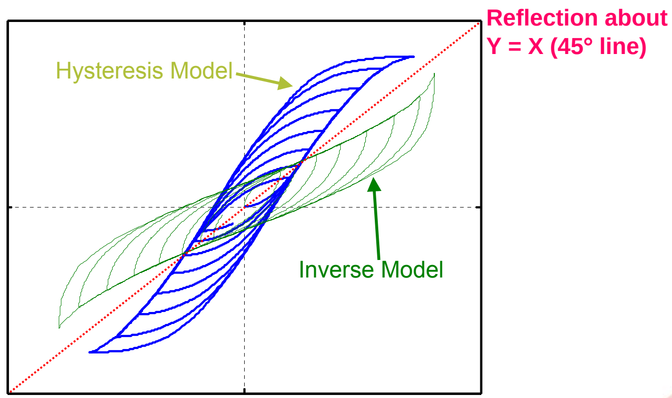
- Rate independent backlash operator:
  $H_r = \max\{x(t) - r, \min\{x(t) + r, y_0\}\}$
- Linearly weighted superposition of backlash operators:

$$y(t) = \vec{w}_h^T \vec{H}_r\left[x, \vec{y}_0\right](t)$$



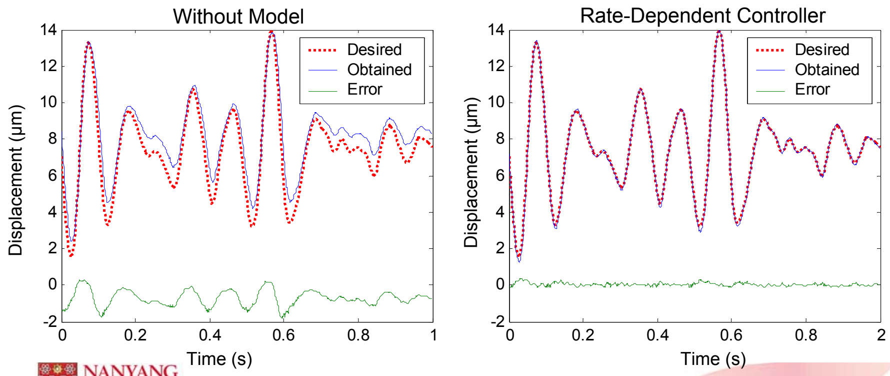


Inverse PI Hysteresis Model



Tremor Tracking Results

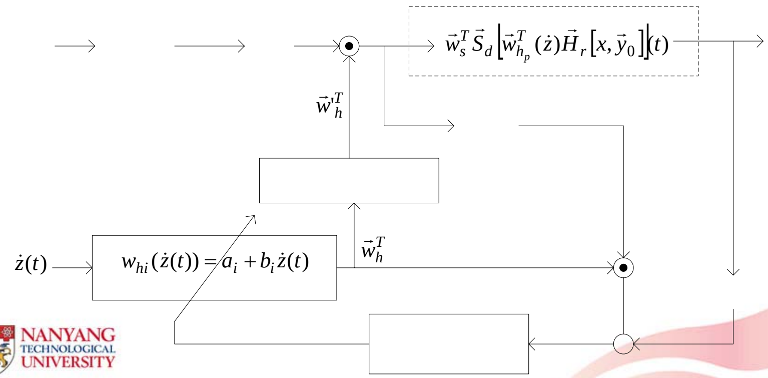
- Tracking recordings of real tremor using 1 piezoelectric stack
  - Rmse = 0.64% of max ampl.; Max error = 2.4% of max ampl.



NANYANG TECHNOLOGICAL UNIVERSITY

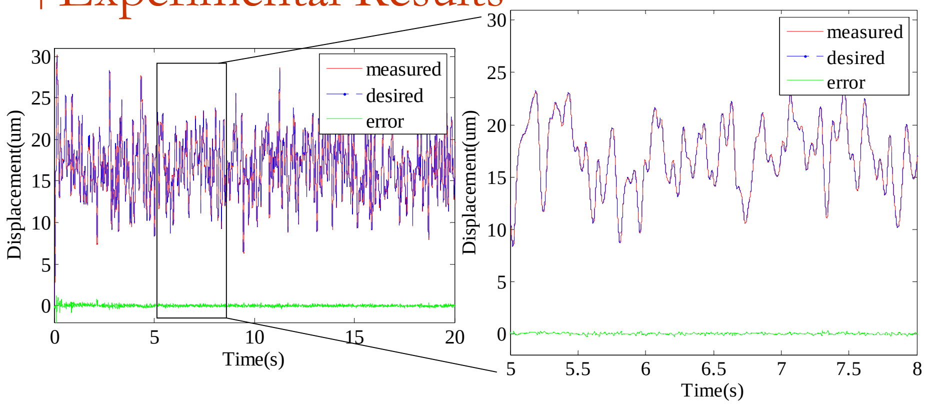
Adaptive Feedforward Controller

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



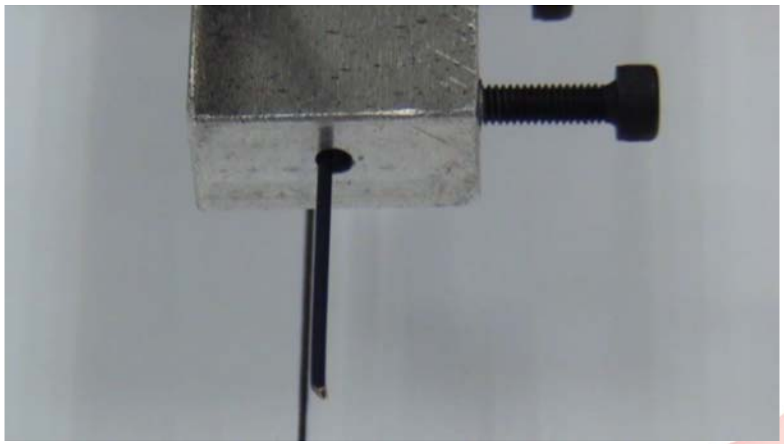
NANYANG TECHNOLOGICAL UNIVERSITY

Experimental Results



	Adaptive Rate-dependent Controller
rmse $\pm\,\sigma$ (μm)	0.0943 ± 0.0159
rmse / actuator's stroke length (%)	0.31
max error $\pm\,\sigma$ (μm)	0.3899 ± 0.0291
max error / actuator's stroke length (%)	1.30

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



y_d

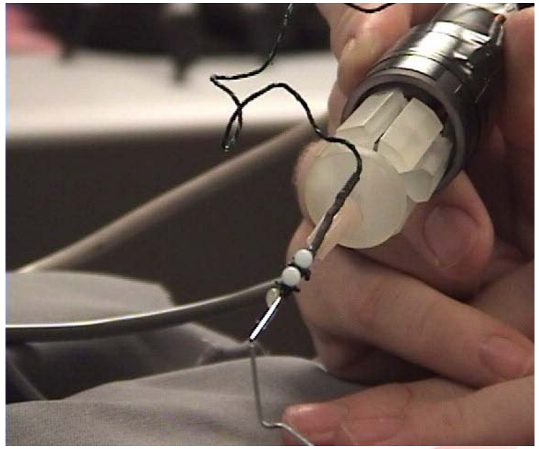
NANYANG TECHNOLOGICAL UNIVERSITY

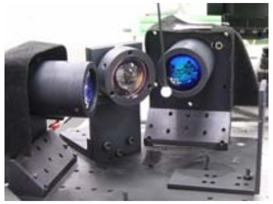
Real-time Active Compensation – 1 DOF Disturbance, 3 DOF Compensation

NANYANG TECHNOLOGICAL UNIVERSITY

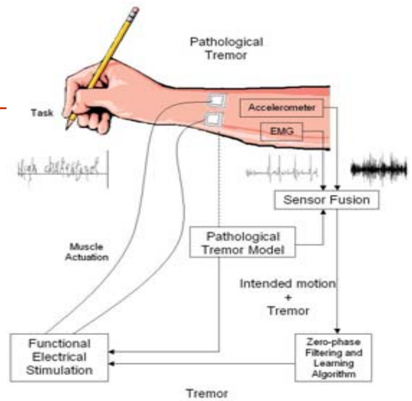
Real-time Active Compensation – Handheld

- C. Riviere (2006), Carnegie Mellon Univ.
- 5 DOF sensing by 2 orthogonal position sensitive detectors
- No inertial sensing
- Non-surgical scenario





Active Pathological Tremor Compensation in Wearable Orthosis



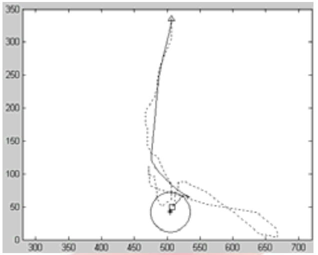
NANYANG TECHNOLOGICAL UNIVERSITY

Pathological Tremor

NANYANG TECHNOLOGICAL UNIVERSITY

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

buttoning

writing

typing

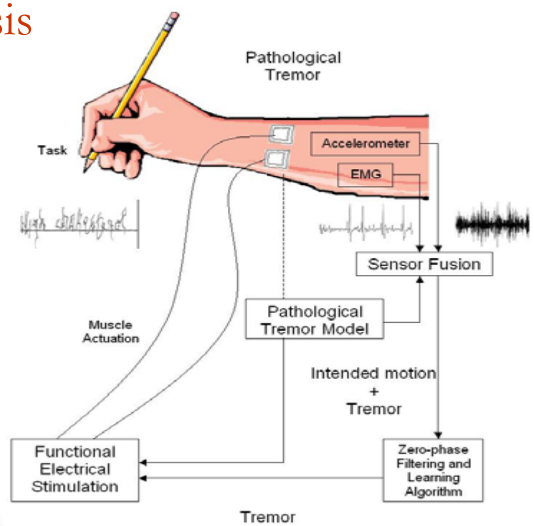
Inserting a key

- Social embarrassment and isolation
- Lifetime cost per patient > US$1M

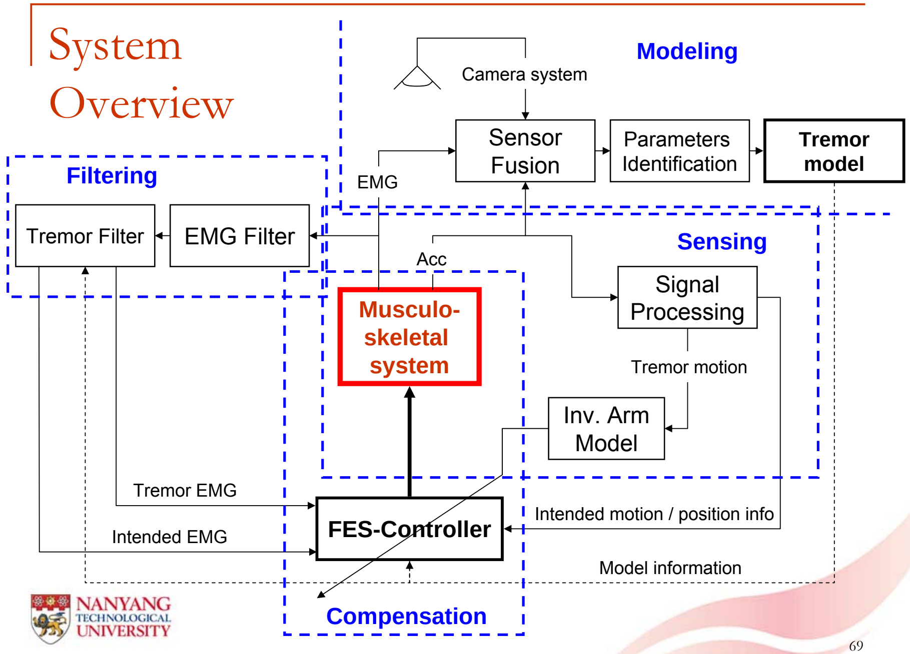
Treatment Options

- 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

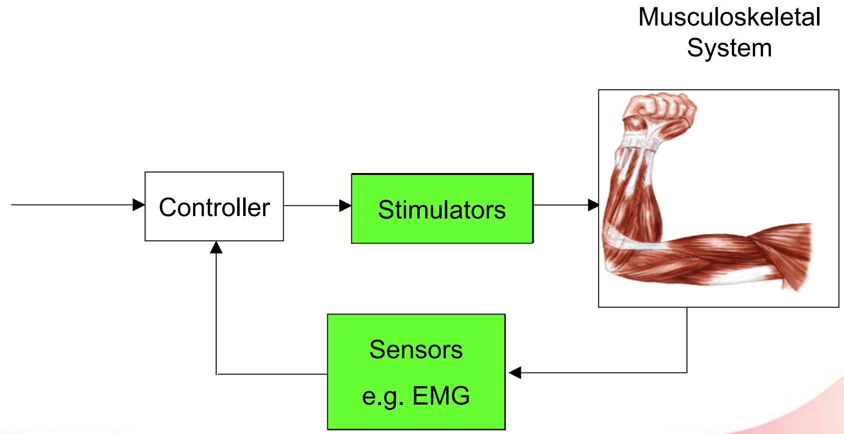
Active Tremor Compensation in Wearable Orthosis



System Overview



Feedback Control System

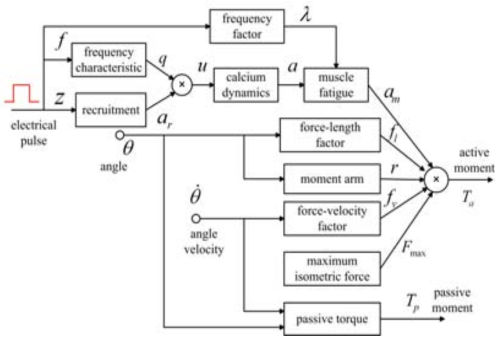


Robot Arm vs Human Arm
- Actuation system

$$T_m = K_t i$$

$$e = K_t \omega_m$$

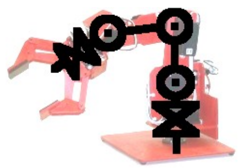
$$V_a = iR + L\frac{di}{dt} + e$$



Electrical Motor

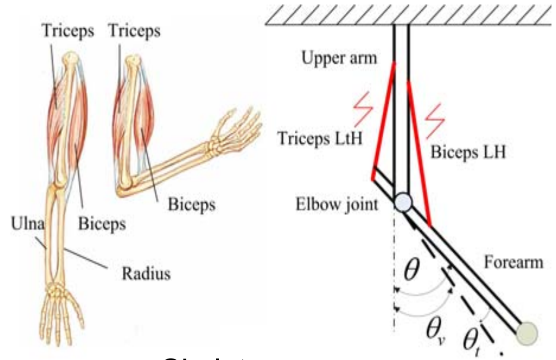
Muscle (Hill-Type)

Robot Arm vs Human Arm
- Links



Manipulator

VS.

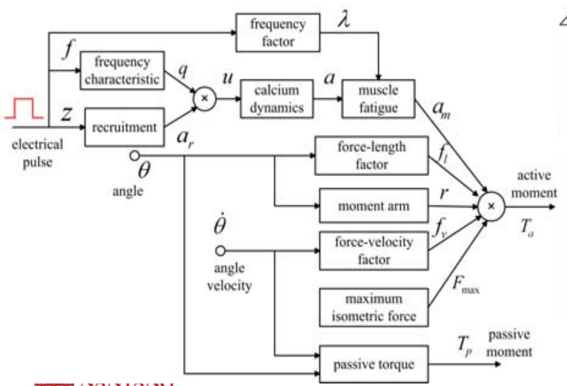


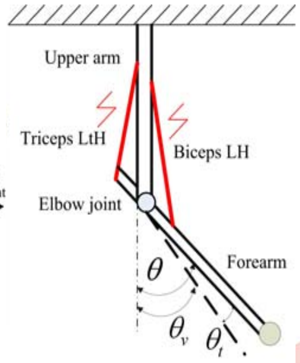
Skeleton

Kinematics & Dynamics are solved in similar ways

Musculoskeletal Model of Upper Limb

- Well studied and established

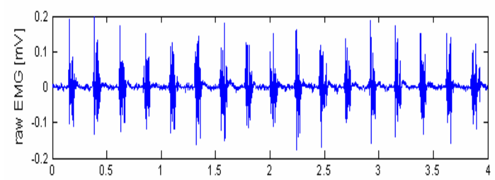


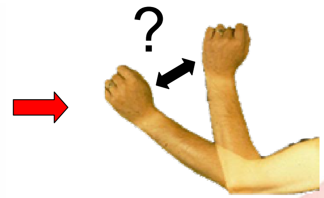


NANYANG TECHNOLOGICAL UNIVERSITY

Key Challenges

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

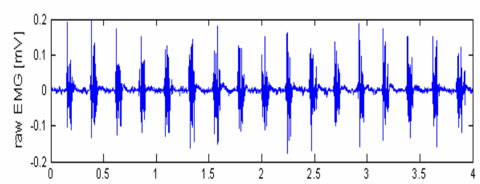




NANYANG TECHNOLOGICAL UNIVERSITY

Key Challenges

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



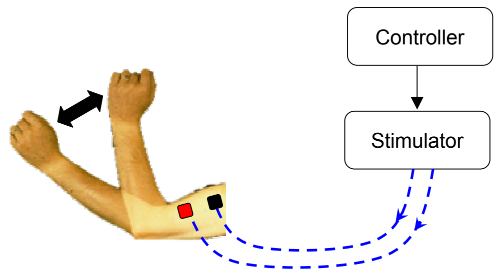
Tremor

Intended Movement

NANYANG TECHNOLOGICAL UNIVERSITY

Key Challenges

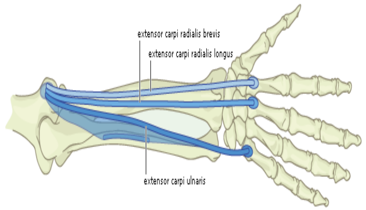
- Functional Electrical Stimulation
  - How can we use FES to generate (anti-)tremulous movement in the upper limbs?

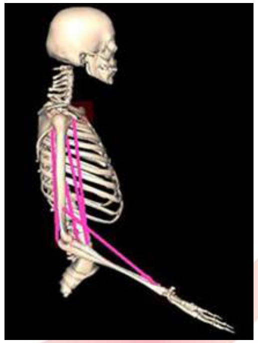


NANYANG TECHNOLOGICAL UNIVERSITY

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





NANYANG TECHNOLOGICAL UNIVERSITY

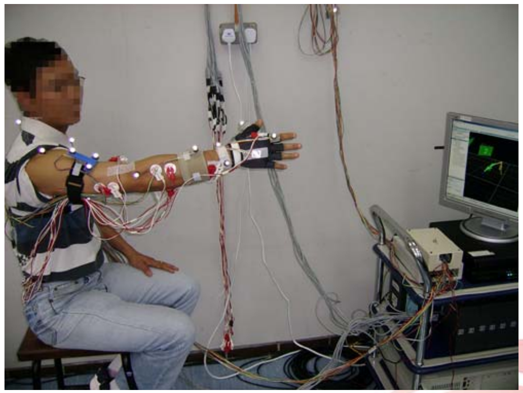
Tremor Study

- 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

NANYANG TECHNOLOGICAL UNIVERSITY

Pathological Tremor Study

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



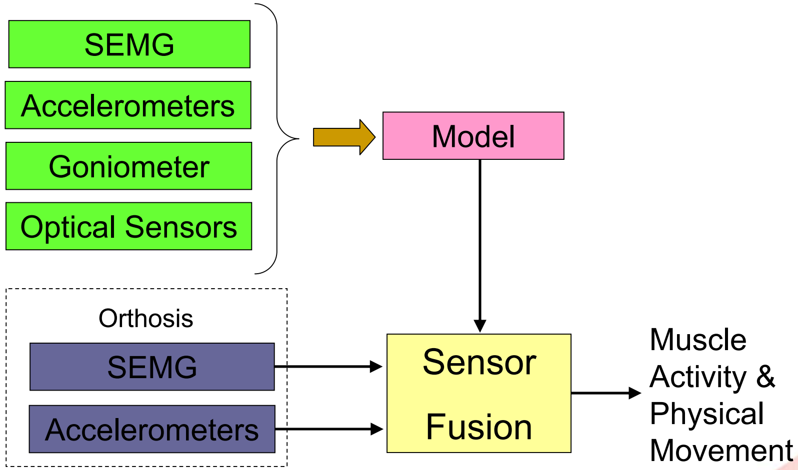
NANYANG TECHNOLOGICAL UNIVERSITY

Data Collection

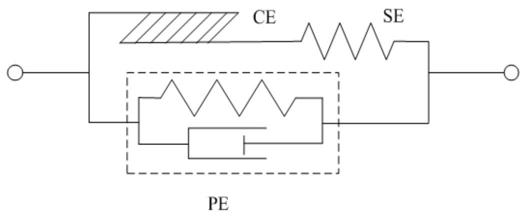
- Record sensor data of patients performing
  - Standard diagnostics: finger to noise, finger to finger, stretched out, drawing spirals, etc.
- Sensors
  - SEMG: 16 channels (8 muscle groups, mostly agonist & antagonist pairs) per limb
  - Accelerometers: 3 x tri-axial per limb
  - Goniometers: 1 per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

NANYANG TECHNOLOGICAL UNIVERSITY

Sensing



Muscle Contraction Property



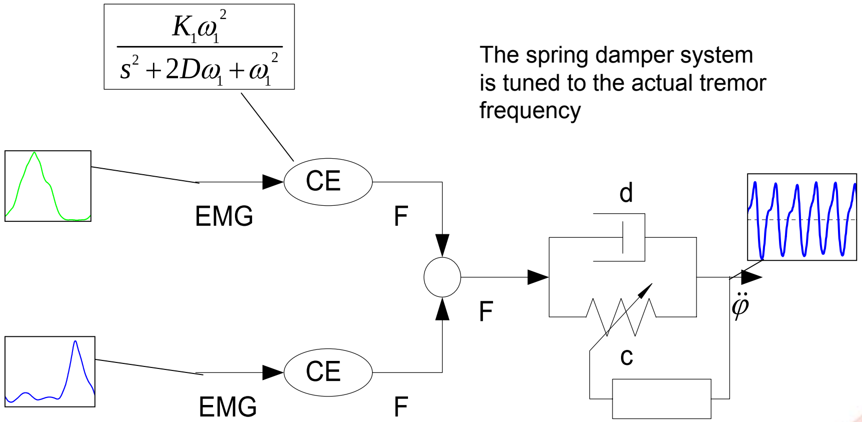
Muscle mechanical model (Hill-type)

CE : Contractile Element

SE : Series Elastic Element

PE : Passive Element (Parallel Elastic Element)

Phenomenological Modeling of Upper Limb Tremor from EMG



Sensor Fusion – Kalman Filtering

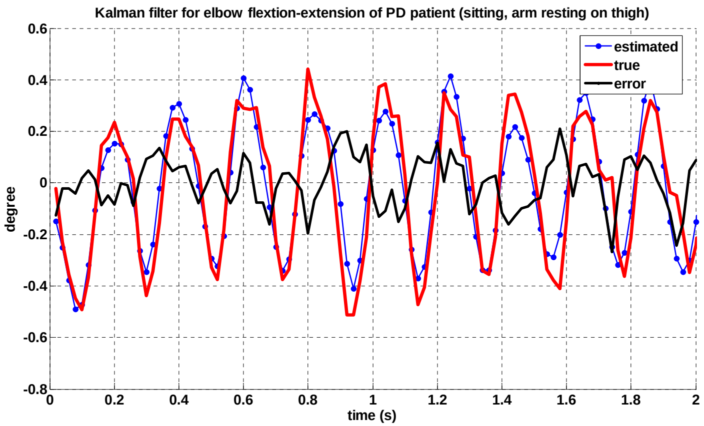
- EMG-derived joint angle as predictor
- ACC-derived joint angle as corrector

$$\theta_{EMG}(k) = c_{EMG}(1)EMG(k) + c_{EMG}(2)$$
$$\theta_{ACC}(k) = c_{ACC}(1)ACC(k) + c_{ACC}(2)$$

- Estimate of joint angle

$$\theta(k) = \theta_{EMG}(k) + \frac{\sigma_{EMG}{}^2}{\sigma_{EMG}{}^2 + \sigma_{ACC}{}^2}(\theta_{ACC}(k) - \theta_{EMG}(k))$$

Results

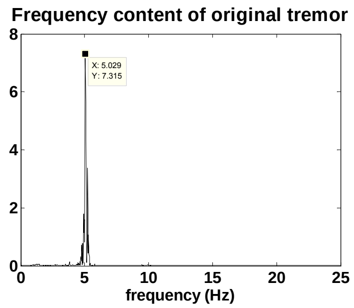


$\sigma^2_{true} = 0.1045$

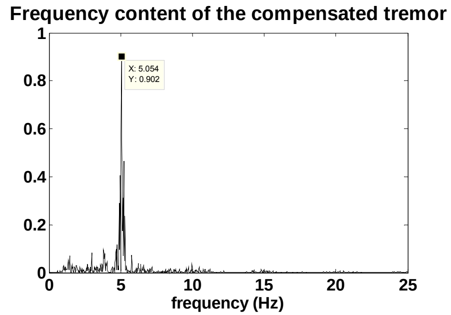
$\sigma^2_{error} = 0.022$ (78.76% reduction)

NANYANG TECHNOLOGICAL UNIVERSITY

Results



Power of original tremor = 7.315



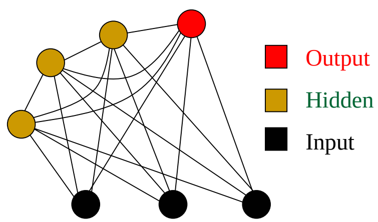
Power of compensated tremor = 0.902

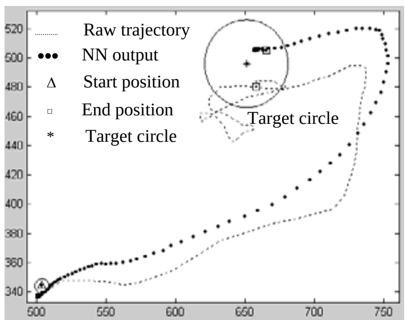
The power of the tremor is reduced by 87.67%

NANYANG TECHNOLOGICAL UNIVERSITY

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

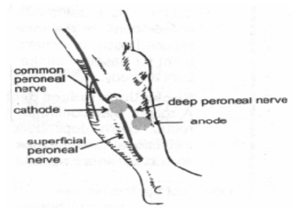


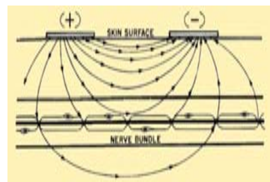


NANYANG TECHNOLOGICAL UNIVERSITY

Functional Electrical Stimulations

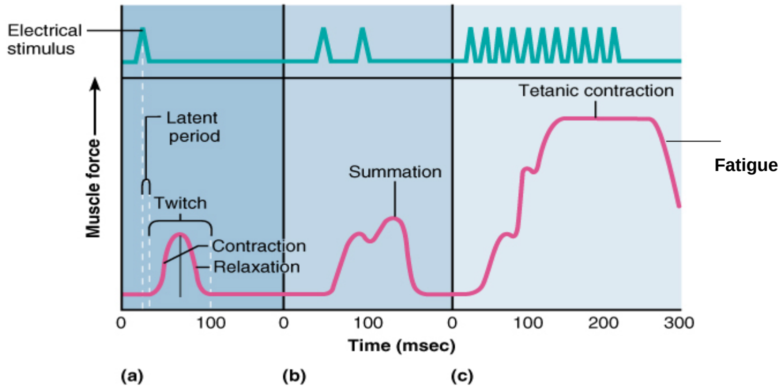
- Controlling electrical pulses to stimulate the intact peripheral nerve to actuate muscles
  - Usually used to restore the motor functions for the paralyzed patients
- Prochazka *et al.* (1992) demonstrated the effectiveness of FES for tremor attenuation
  - Offline trial & error tuning of intensity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





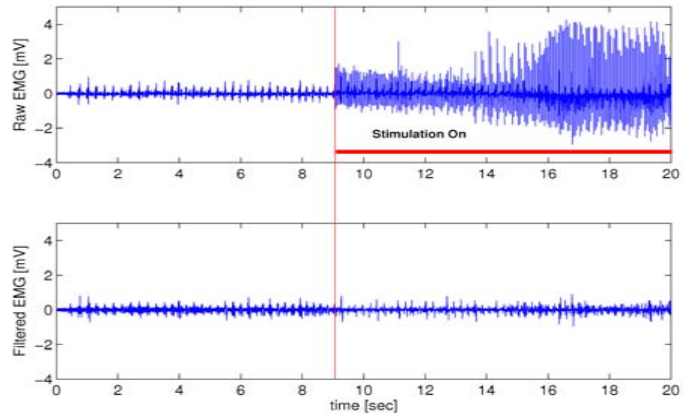
NANYANG TECHNOLOGICAL UNIVERSITY

Muscle Activation

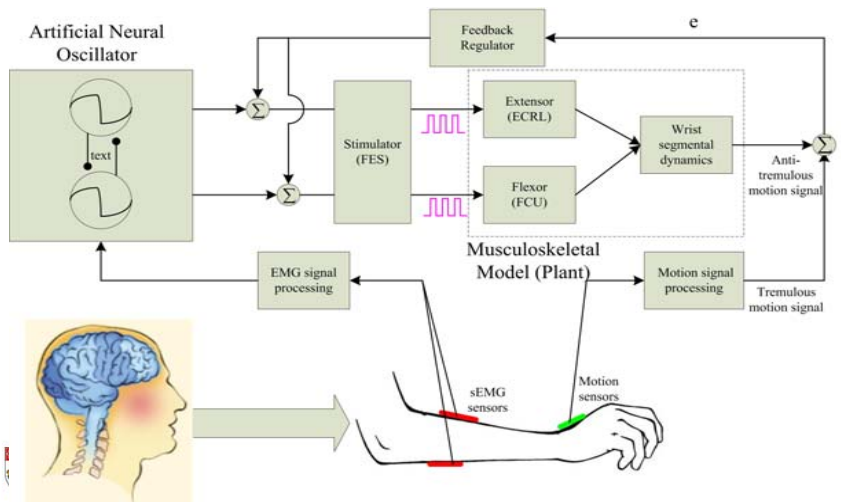


Stimulation Artifact

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

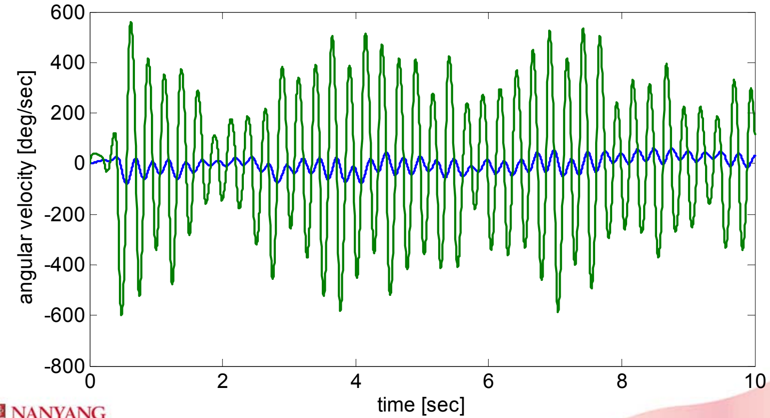


FES Controller Design



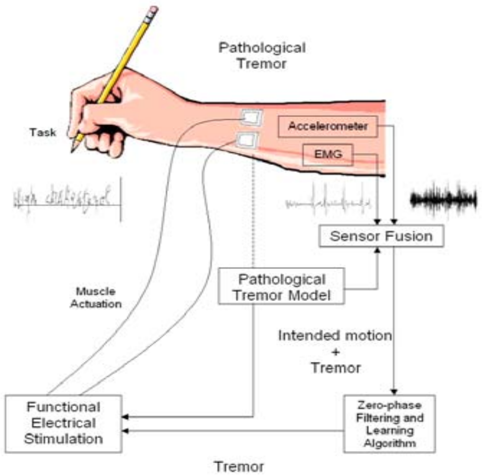
Simulation Result of Tremor Suppression

- 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



NANYANG TECHNOLOGICAL UNIVERSITY

Questions & Comments

Wei Tech ANG

School of Mechanical & Aerospace Engineering

Nanyang Technological University

Singapore

wtang@ntu.edu.sg

http://www.ntu.edu.sg/mae/centres/rrc/biorobotics/biorobotics.htm

NANYANG TECHNOLOGICAL UNIVERSITY