Real-time Identification of Human Finger Electrical impedance for haptic Rendering

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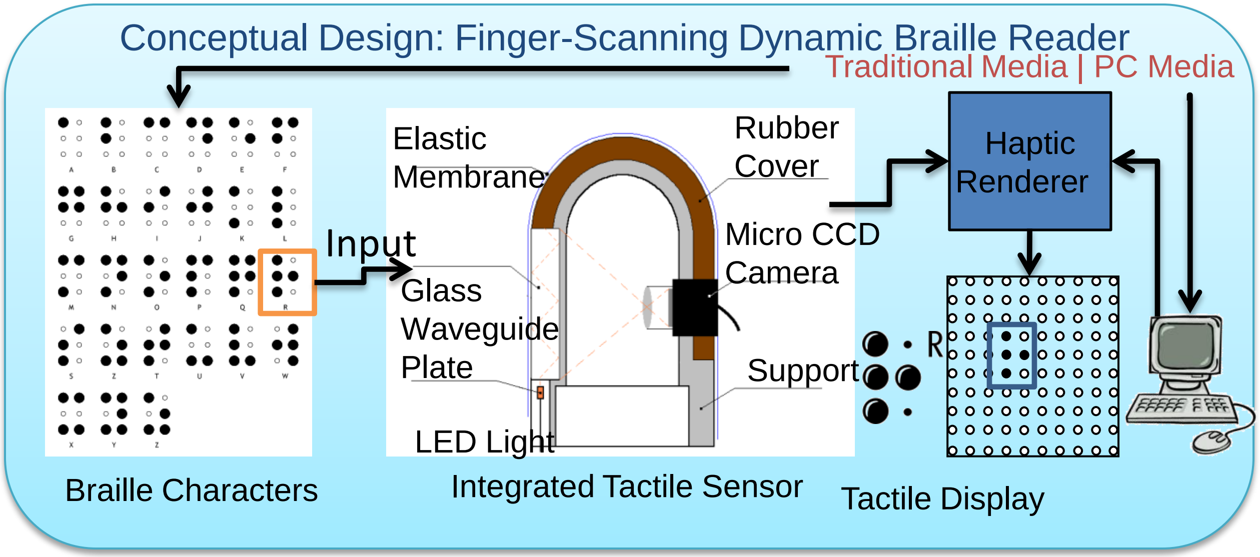
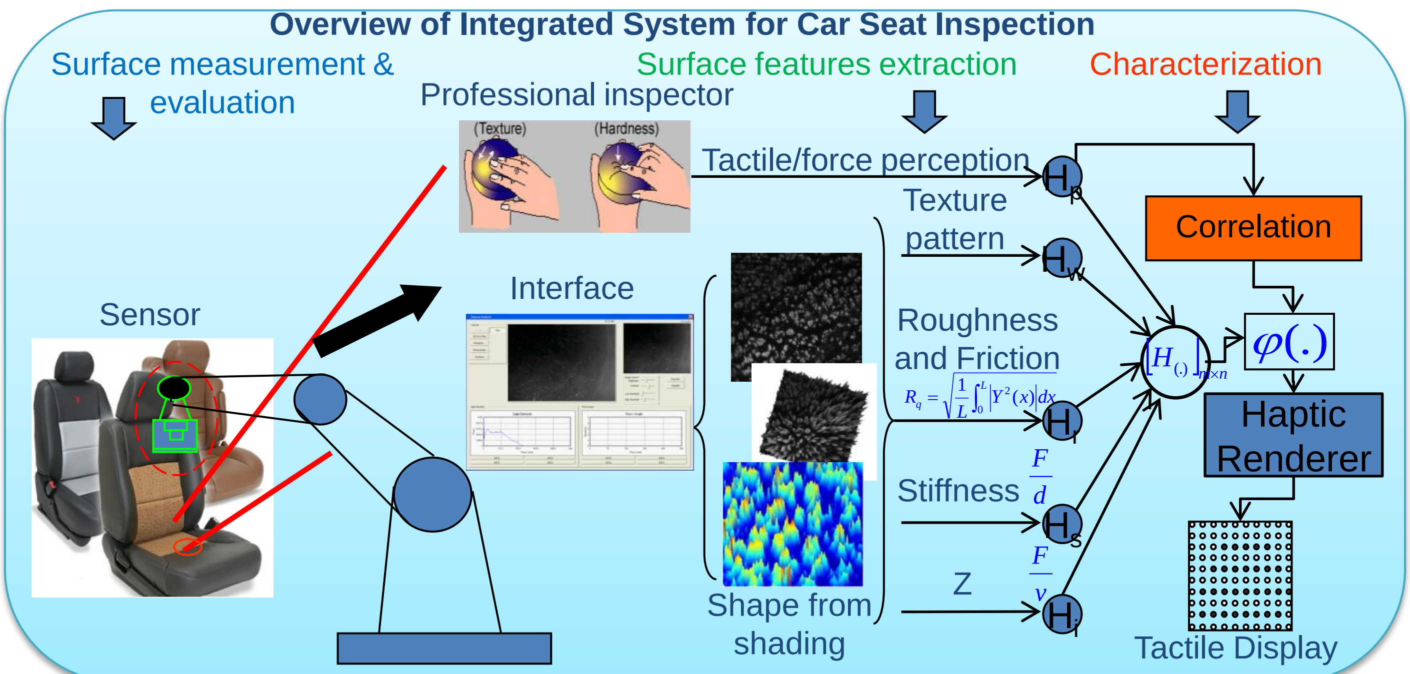
Tactile Stimulation Background





Some Examples

Electro Mechanical Actuator

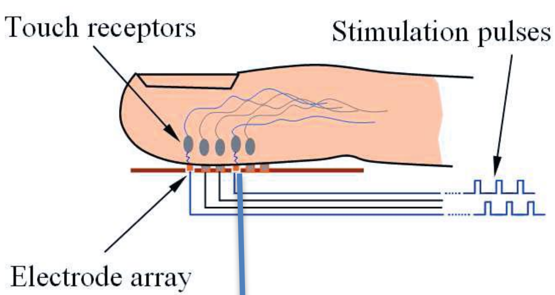
Electro tactile stimulation

Adapted from:

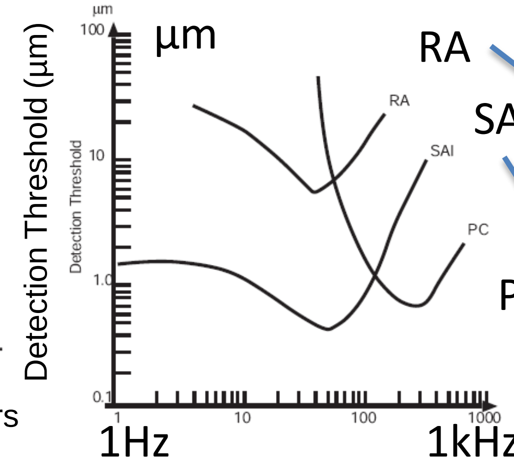
Benali-Khoudja ,et al., "Tactile interfaces: a state-of-the-art survey", ISR 2004, 35th International Symposium on Robotics, 23-26 March, Paris France

Principle of Electronic Tactile Sensing

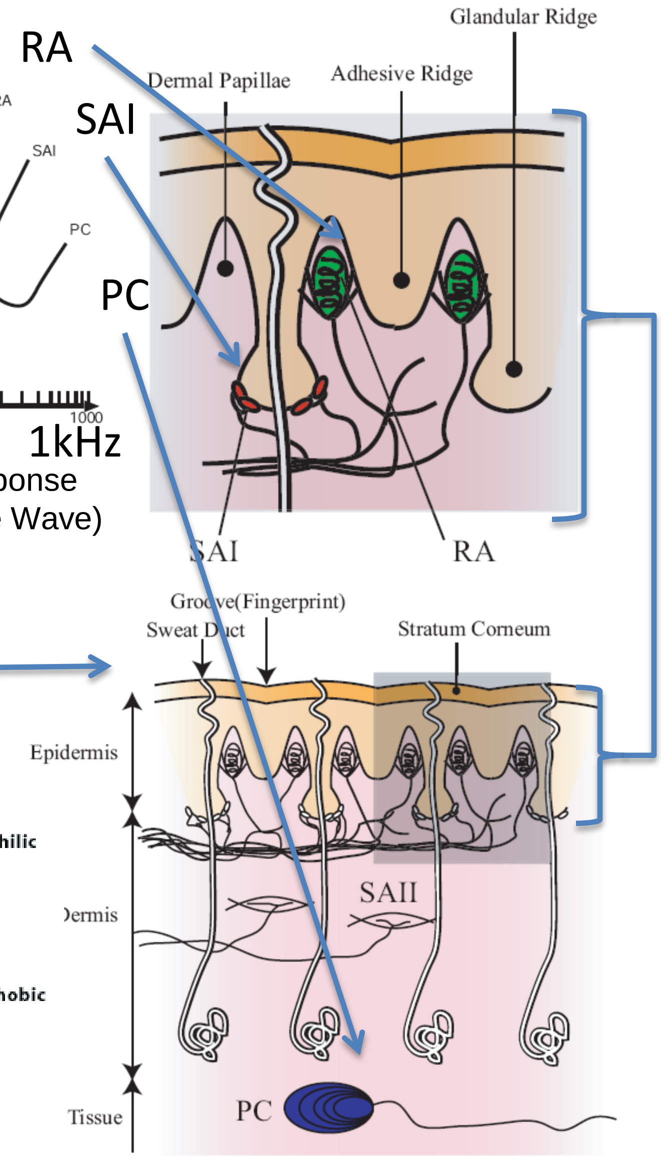
Illustration of fingertip electro-tactile through electrode arrays.



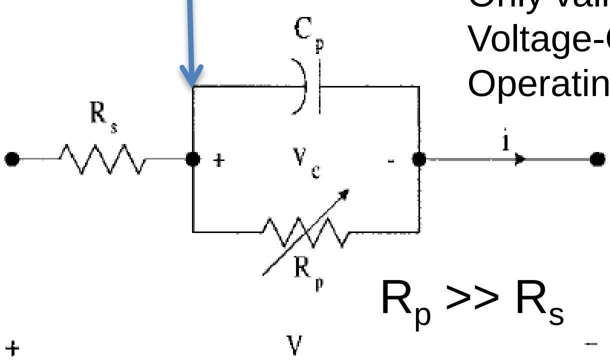
mechanoreceptors



Frequency Response
(mechanical Sine Wave)



Only valid at a set Voltage-Current Operating Point



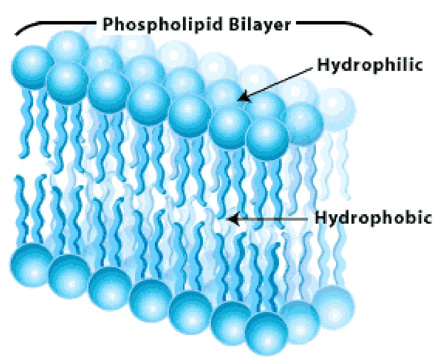
$R_p >> R_s$

Simple Electronic Impedance Model of Skin

R_s = models deep tissue

R_p = S.C. Impedance (non linear and time variant)

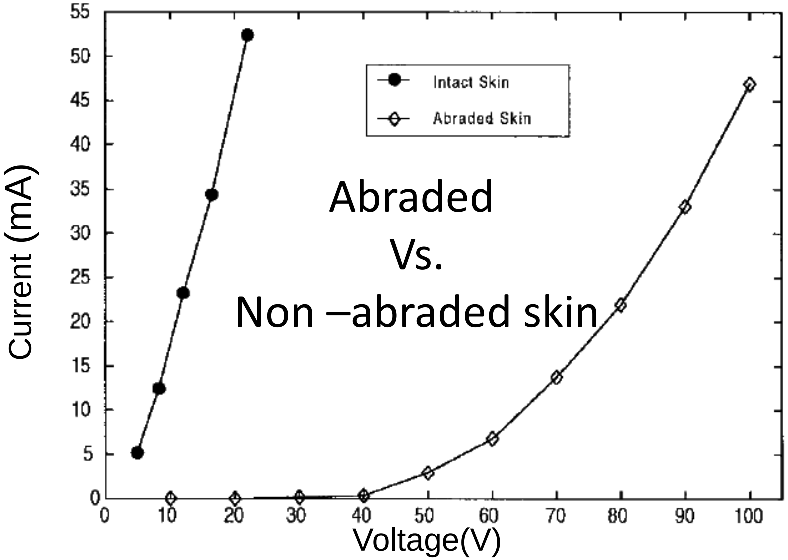
C_p = cell membrane (lipid bylaper that polarizes from a voltage potential)



Lipid-Bi-Layer
Cellular Membrane

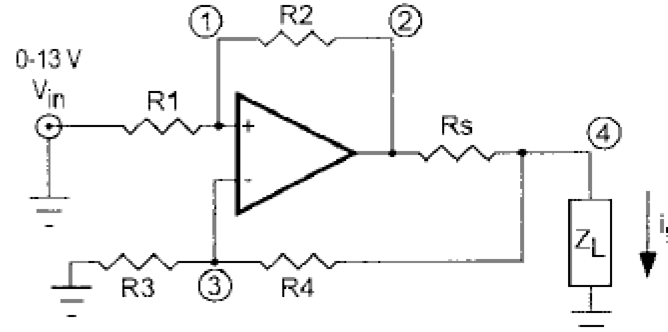
Adaptations from:
Hiroyuki Kajimoto ,et al., “Electro-Tactile Display with Tactile Primary Color Approach”, ISR 2004, 35th International Symposium on Robotics, 23-26 March, Paris France

Two Types of Electro-Tactile Stimulators



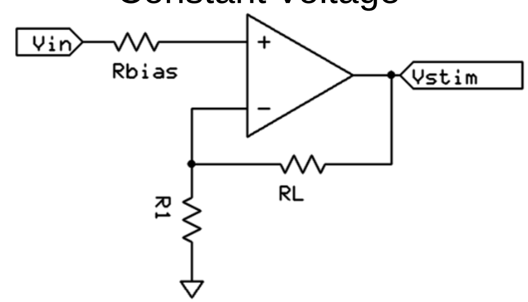
S.S. I-V characteristic for Abraded and Non-Abraded Skin
Measured using a CCD

The Two Classes of Tactile Display Drivers



Howand Current Pump Tactile Driver

Constant Current
VS
Constant Voltage



Non-Inverting OpAmp (Our Driver)

Both have been shown to mimic pressure or mechanical stimulation :
Constant Current Driver (CCD) (**popular method**)
➢Way of neglecting a model of skin electrical impedance (just set current level)

Constant Voltage Driver (CVD) (**our preferred method**) :
Attempt to set voltage pulse waveform at an operating point
➢Cannot be used in open loop system (cannot control painful or harmful current)

Ultimately the **skin is an obstacle** that must be overcome to stimulate the **axons of the mechanoreceptors** underneath so that they produce an action potential signal to the CNS

Removal of the S.C to make system appear LTI
Invasive because removal of S.C. or use of subcutaneous Implants needed to achieve stimulation

Why Using a CCD is not an optimal approach

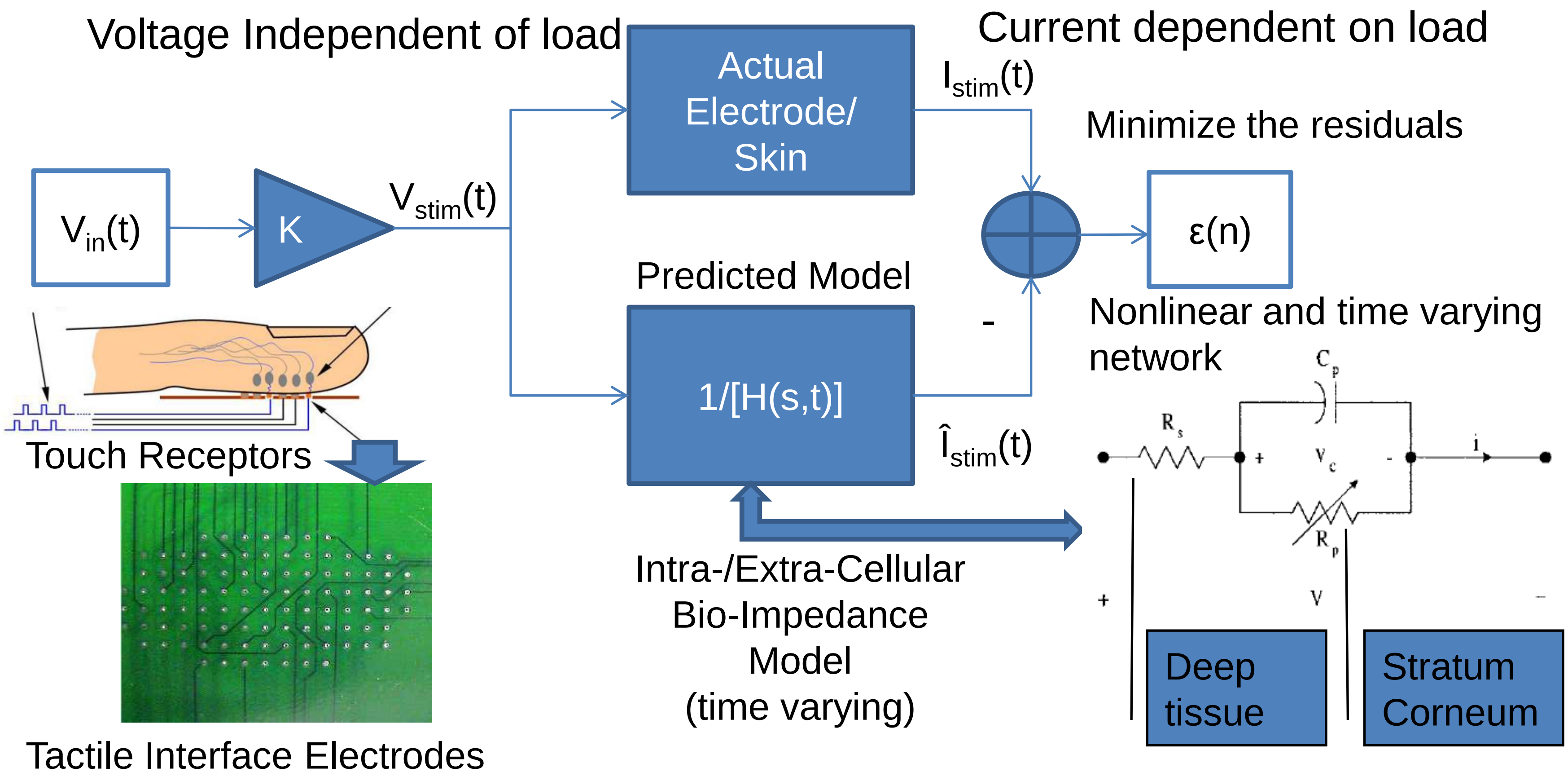
Table VI							
Identification of Parameters for 10 different subjects; Dry and Damp Finger Case. Under square wave stimulation **Operating point held at 75 volts or below sensation threshold**							
subject	**sex**	**age**	**finger condition**	**Rp (kΩ)**	**Cp (nF)**	**Rs (kΩ)**	**RRSE %**
1	M	30	DAMP	20.17	0.845	4.07	0.030
2	M	29	DAMP	44.49	0.379	90.29	0.033
3	M	26	DAMP	65.84	0.445	7.11	0.023
4	M	26	DAMP	23.21	0.847	3.93	0.042
5	M	28	DAMP	12.49	0.201	15.81	0.026
6	F	late 30's	DAMP	14.53	0.165	19.44	0.052
7	M	27	DAMP	16.48	0.160	19.81	0.022
8	F	28	DAMP	38.30	0.291	13.17	0.038
9	M	35	DAMP	30.96	0.344	11.30	0.056
10	M	30's	DAMP	61.89	0.382	8.410	0.020
1	M	30	**DRY**	194.00	0.165	19.00	0.031
2	M	29	**DRY**	272.67	0.104	30.45	0.024
3	M	26	**DRY**	258.19	0.085	38.39	0.032
4	M	26	**DRY**	195.04	0.012	26.18	0.025
5	M	28	**DRY**	236.34	0.115	27.55	0.022
6	F	late 30's	**DRY**	615.58	0.045	69.83	0.062
7	M	27	**DRY**	265.91	0.082	39.54	0.020
8	F	28	**DRY**	235.55	0.102	31.86	0.030
9	M	35	**DRY**	271.97	0.140	22.17	0.043
10	M	30's	**DRY**	258.80	0.075	44.72	0.028

Remarks

Incorporate ease of design and efficiency of CVD introduce and identify parameters of human bio-impedance in real-time to set current levels

Key:
Blue: largest R_p
Red: Smallest R_p
Orange: Largest C_p
Green: Smallest C_p

Overview: Using CVD with Parameter Identification to set stimulation current intelligently



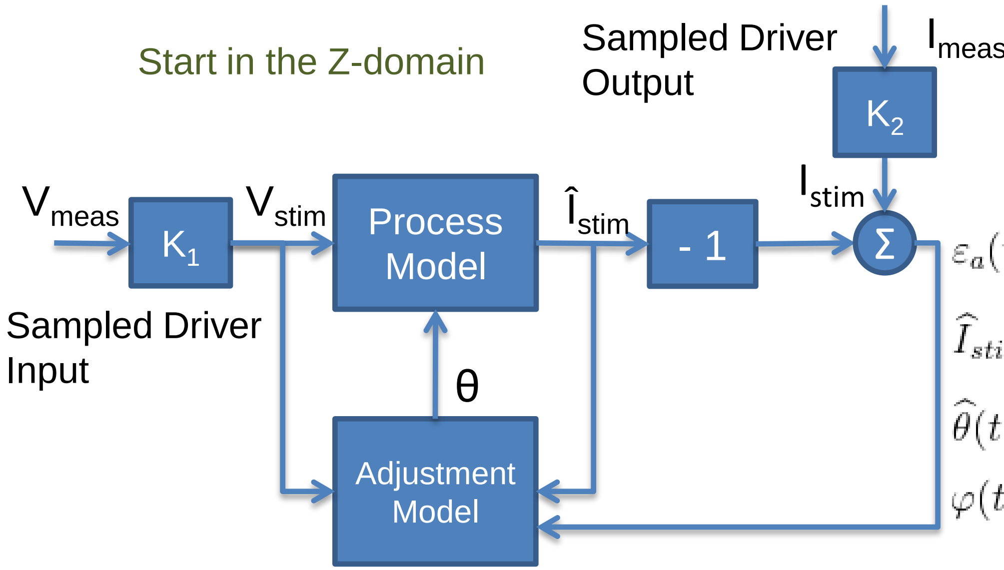
Future Goal

Model-Based Adaptive Control: use predicted H(s,t) to set V_{in} to match set I_{stim} for user

- H(s,t) is the Q-point-linearized, time varying finger impedance model calculated by iterative extended L.S. (with forgetting factor λ)
- Measurements of $V_{stim}(t)$ and $I_{stim}(t)$ are acquired from tactile interface electrodes to get $\hat{I}_{stim}(t)$

Real-Time Identification of unknown Z-Domain Parameters

Start in the Z-domain



$$\varepsilon_a(t) = I_{stim}(t) - \widehat{I}_{stim}(t)$$

$$\widehat{I}_{stim}(t) = \varphi^T(t-1)\widehat{\theta}(t-1)$$

$$\widehat{\theta}(t) = (\alpha_1, \beta_1, \beta_2, c_1)^T$$

$$\varphi(t-1) = (-\widehat{I}_{stim}(t-1), V_{stim}(t-1), V_{stim}(t), \epsilon_p(t))^T$$

Block Diagram of ELS Estimator In Z-Domain

Process Model (Z Domain Conductance Model):

$$\widehat{I}_{stim}(t) = \frac{\beta_2 + \beta_1 z^{-1}}{1+\alpha_1 z^{-1}} V_{stim}(t) + \frac{c_1}{1+\alpha_1 z^{-1}} e(t) \quad e(t) \approx \epsilon_p(t) = I_{stim}(t) - \varphi^T(t-1)\widehat{\theta}(t)$$

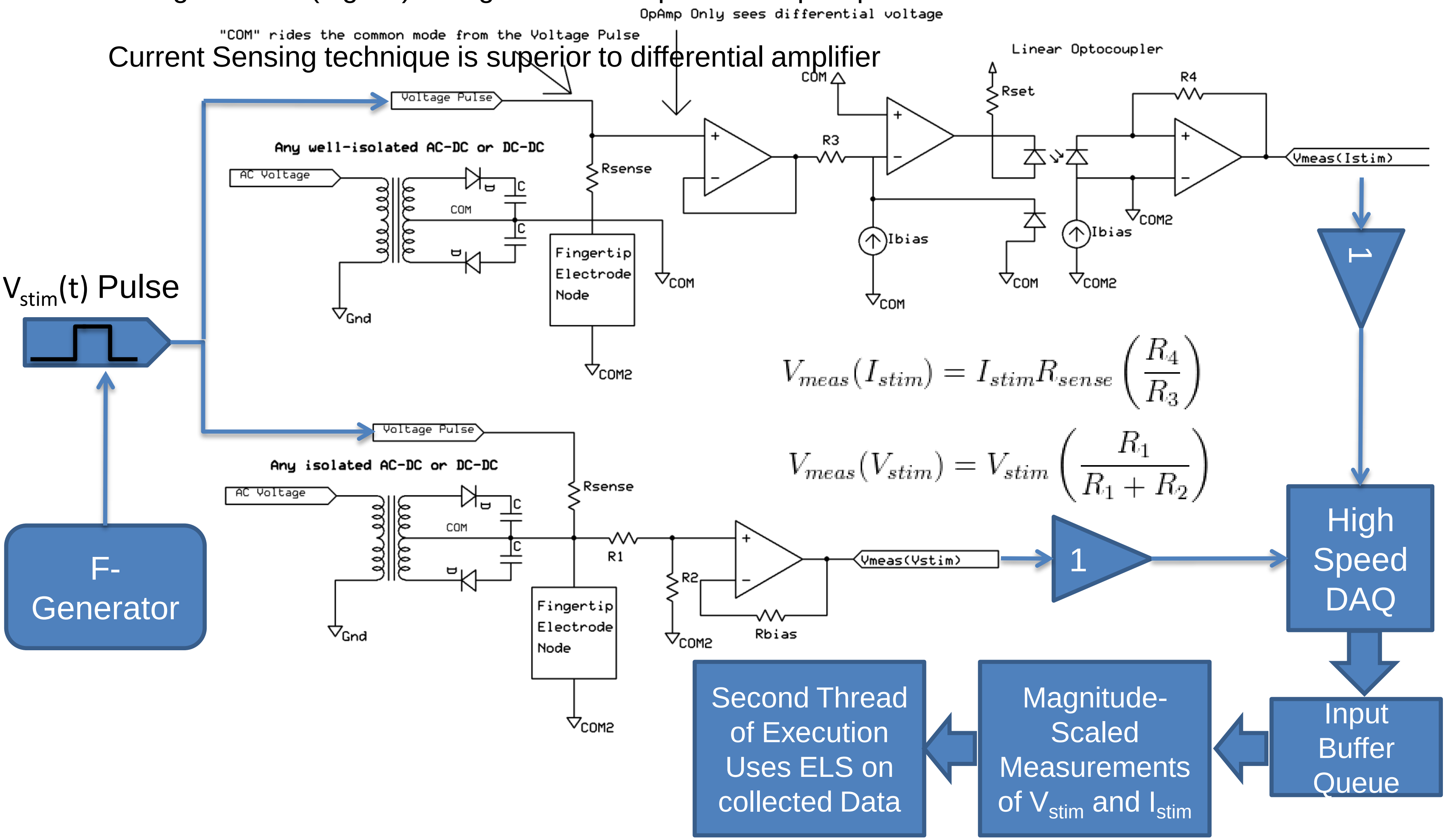
- Model consists of ideal first order model of electrical bio-impedance
- V_{stim} is the input and the calculated I_{stim} is the output of the system
- We use the stochastic error correlation coefficient **c_1** to model unknown nonlinearities in the ideal 1st order bio-impedance model as correlated noise from previous regressors
  - this is needed for stimulation waveforms that have slow rise time compared to square waves

Driving & Measuring the Voltage and Current: First Thread of Execution

Current Sensing by riding the Common Mode Voltage using Isolation Transformer

Voltage Divider (high-Z) w/ high bandwidth precision opAmp

Current Sensing technique is superior to differential amplifier



$$V_{meas}(I_{stim}) = I_{stim} R_{sense} \left(\frac{R_4}{R_3} \right)$$

$$V_{meas}(V_{stim}) = V_{stim} \left(\frac{R_1}{R_1 + R_2} \right)$$

Real Time Identification Algorithm: Second Thread of Execution

What we want Identified (at an operating point)

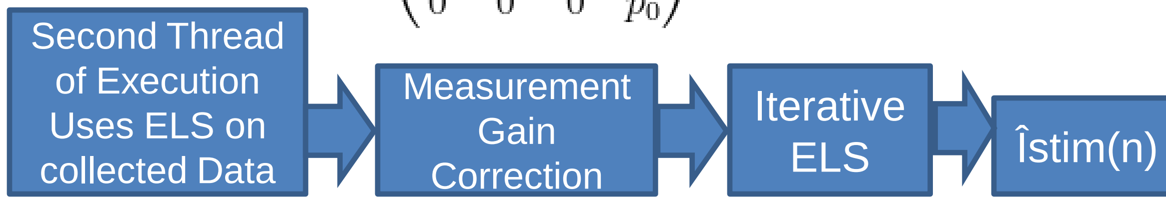
$$\widehat{I}_{stim}(t) = \frac{\beta_2 + \beta_1 z^{-1}}{1 + \alpha_1 z^{-1}} V_{stim}(t) + \frac{c_1}{1 + \alpha_1 z^{-1}} e(t)$$

$$\widehat{\theta}(t) = (\alpha_1, \beta_1, \beta_2, c_1)^T$$

Initial Conditions:

$$P_0 = \begin{pmatrix} p_0 & 0 & 0 & 0 \\ 0 & p_0 & 0 & 0 \\ 0 & 0 & p_0 & 0 \\ 0 & 0 & 0 & p_0 \end{pmatrix} > 0 \qquad \widehat{\Theta}_0 = (0,0,0,0)^T$$

Adjustment Model Algorithm (ELS)



For, t = 1…k, where k is a subset of the input buffer queue length for storing $V_{meas}(V_{stim})$ and $V_{meas}(I_{stim})$

$$P(t) = \frac{1}{\lambda} P(t-1)[1 - \varphi(t-1)\varphi^T(t-1)P(t-1)][\lambda + \varphi^T(t-1)P(t-1)\varphi(t-1)]^{-1}$$

$$K(t) = P(t)\varphi(t-1) \qquad \varepsilon_a(t) = I_{stim}(t) - \widehat{I}_{stim}(t)$$

$$\widehat{\Theta}(t) = \widehat{\Theta}(t-1) + K(t)\epsilon_a(t)$$

MSE goodness of fit criteria

$$E^2_{n+1} = (\epsilon^2_{a_{(n)}} + E^2_n mod(n,N))(mod(n,N) + 1)^{-1}$$

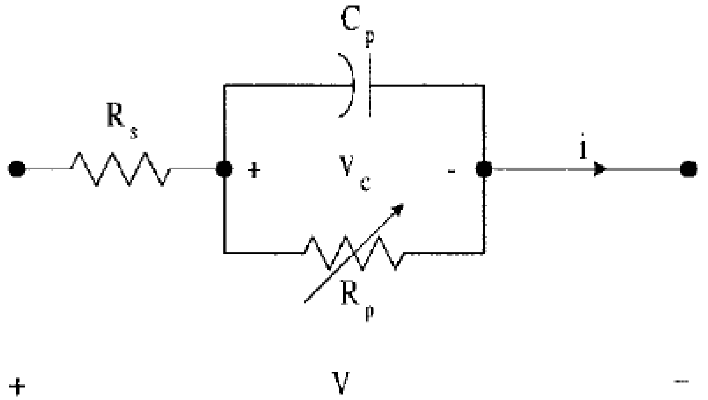
Repeat for n = j*k + 1…(j + 1)*k, for j=1,…(user stop)

Note: forgetting factor weight λ is included in the ELS minimization to account for the time varying $R_p(t)$

$$N \approx \frac{2}{1 - \lambda}$$

Extracting Physical Model from Z-Domain Model

S-Domain Model



$$\widehat{Z}_A(t) = \frac{R_s + R_p(t) + R_p(t)R_sC_ps}{1 + R_p(t)C_ps}$$

$$V_{stim} >> e(t) \Rightarrow \frac{1}{\widehat{Z}_D(z)} \approx \frac{\widehat{I}_{stim}}{V_{stim}} = \frac{\beta_2 + \beta_1 z^{-1}}{1 + \alpha_1 z^{-1}}$$

We use the Tustin Transform to take the above identified model in to the S domain:

$$z \approx \frac{1 + sT_s/2}{1 - sT_s/2}$$

Assuming:

- no frequency warping from sufficiently high sampling rate.
- First corner frequency << zero

$$R_p(t)R_SC_p >> R_p(t)C_p \Rightarrow \omega_c = \frac{1}{R_p(t)C_p}$$

$$w_D << \frac{2}{T_S} \Rightarrow w_D \approx \omega_A$$

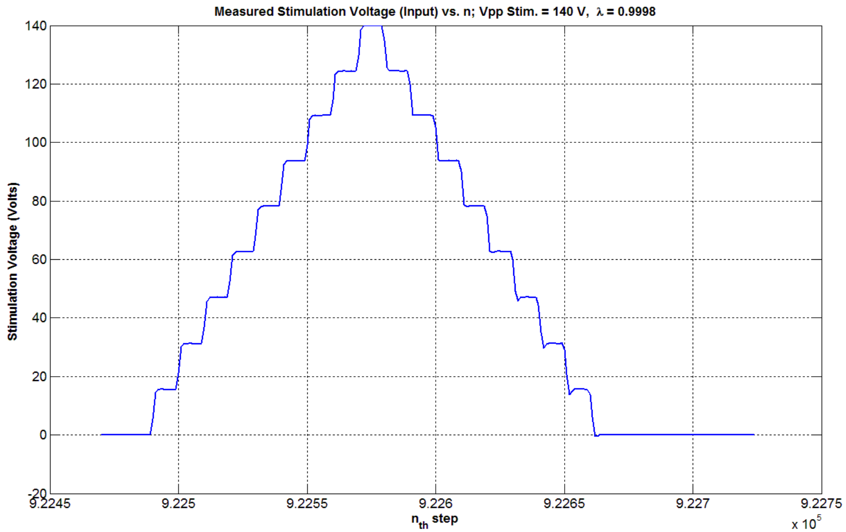
The physical bio-Impedance parameters can be Identified:

$$R_s = \frac{1 - \alpha_1}{\beta_2 - \beta_1}$$

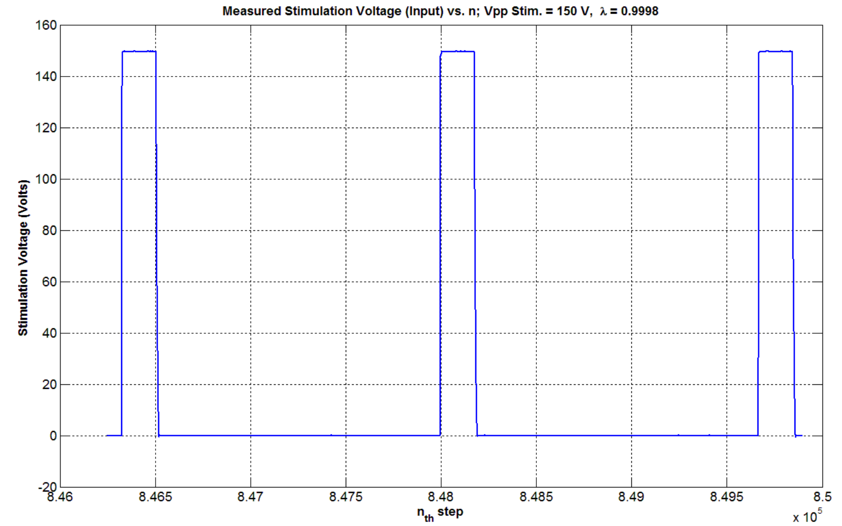
$$R_p = \frac{1 + \alpha_1}{\beta_1 + \beta_2} - R_s$$

$$C_p = \frac{T_s}{2}\left(\frac{\beta_2 - \beta_1}{\beta_2 + \beta_1}\right)\frac{1}{R_p(t)}$$

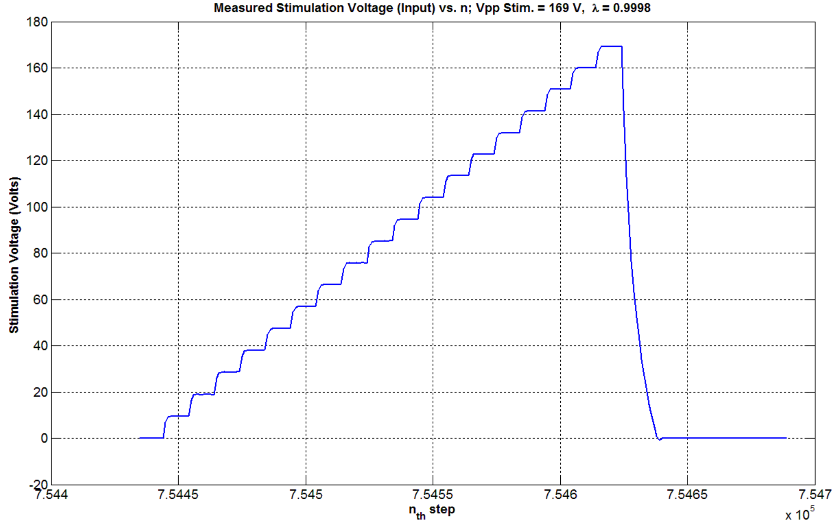
Stimulating Voltage Signal Primitives:



Triangle Waveform



Square Waveform

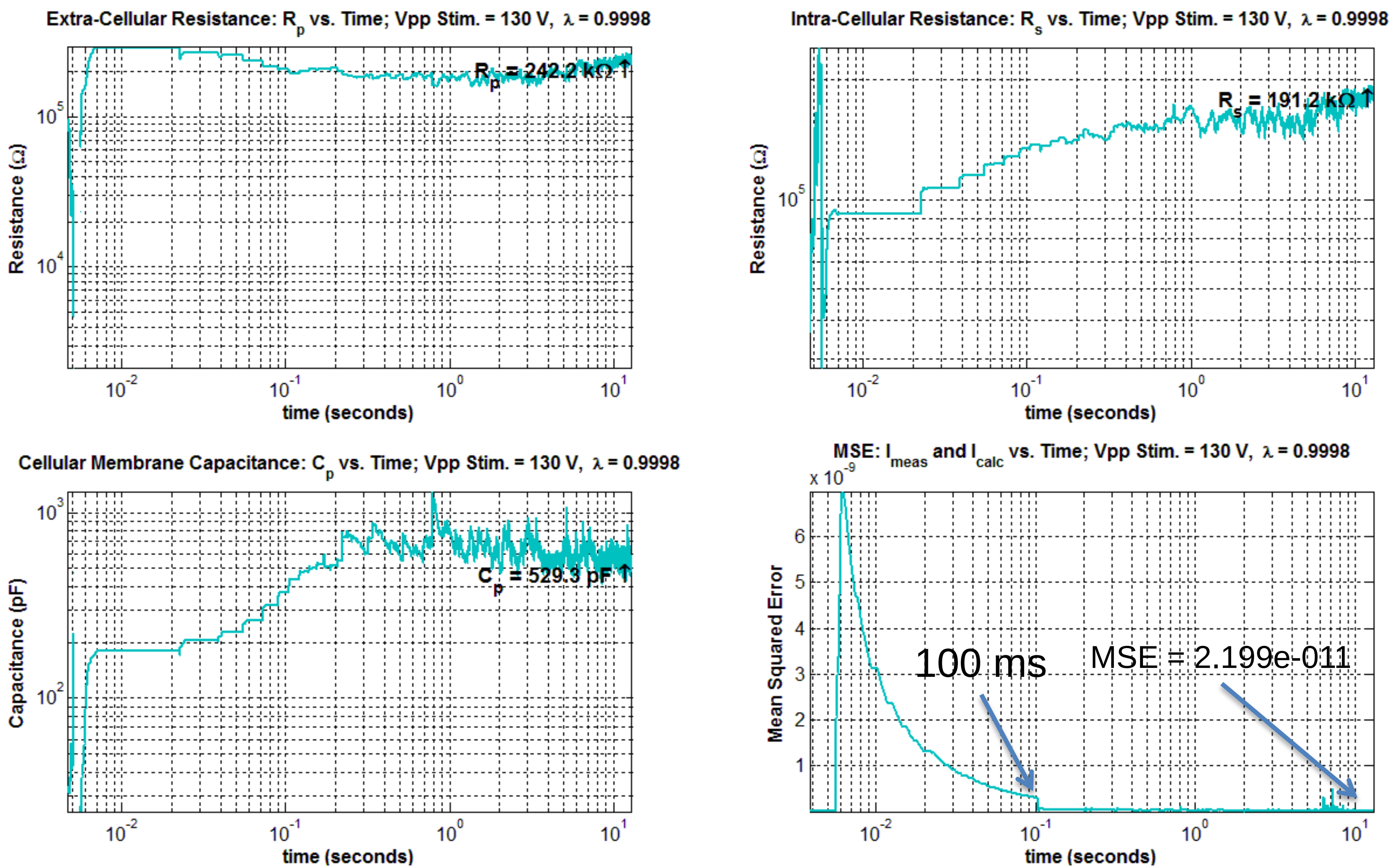


Saw Tooth Waveform

Configurations :Triangle, Saw Tooth or Square Wave Shape
V_{pp} : 50V – 250V
Frequency : 50 to 100 Hz
Duty Cycle : 5% - 11%
Features: Intra-Duty Cycle Modulation

Used for both stimulation and identification

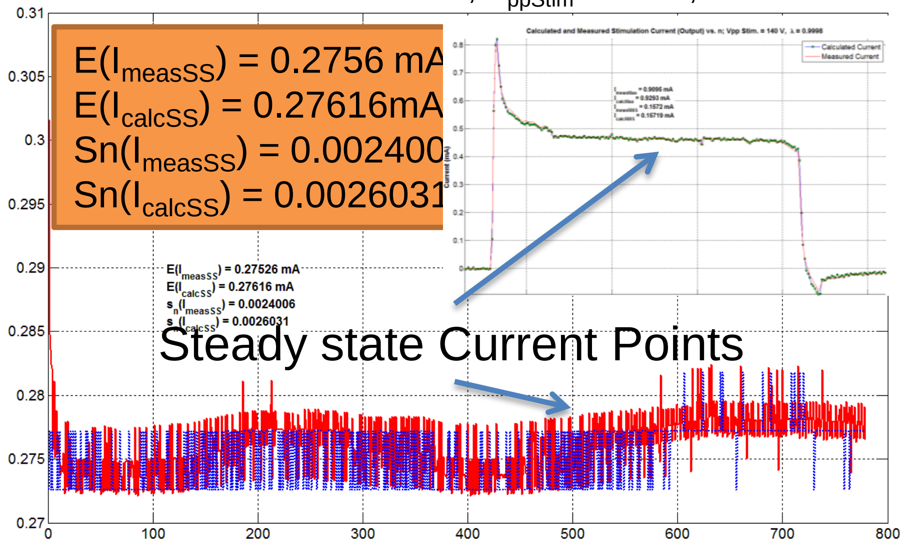
Results: ELS and Convergence (Typical)



Subject: Male, **Age:** 31, **Finger Condition:** Dry, **Finger Tested:** Index; **Finger Location**: kept const.
Test Condition: One-Subject Z_L at 130 Volts; successive measurement (no time lapse); no repeatability testing; const. pressing force;
Δtime: 0-13 sec. , **waveform:** square wave, no P.E.,**D.C. =** 11.0%, **Freq. =** 60 Hz **λ =** 0.9998, **Pressing Force:** 700grams

Results: Algorithm's ability to track with time variation

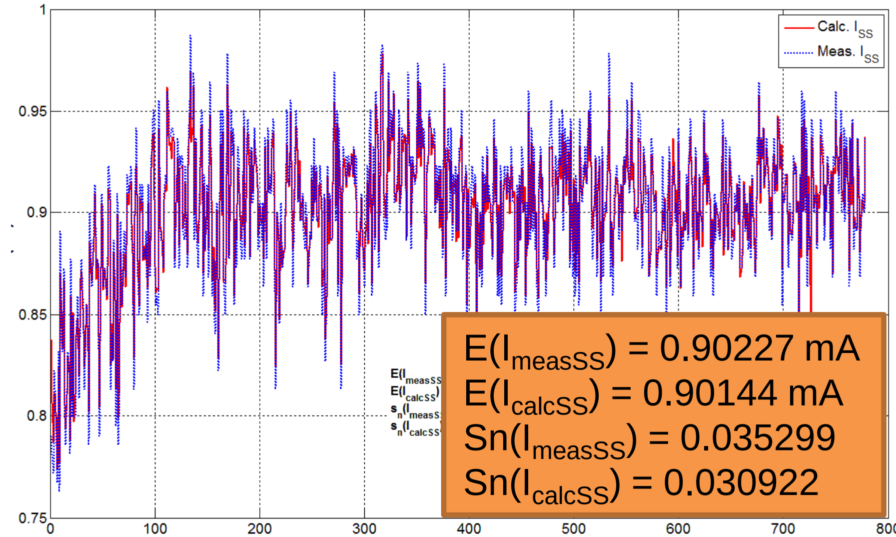
S.S Stim. Current all Active D.Cs; V_{ppStim} = 110 V, λ = 0.9998



Low stimulation voltage

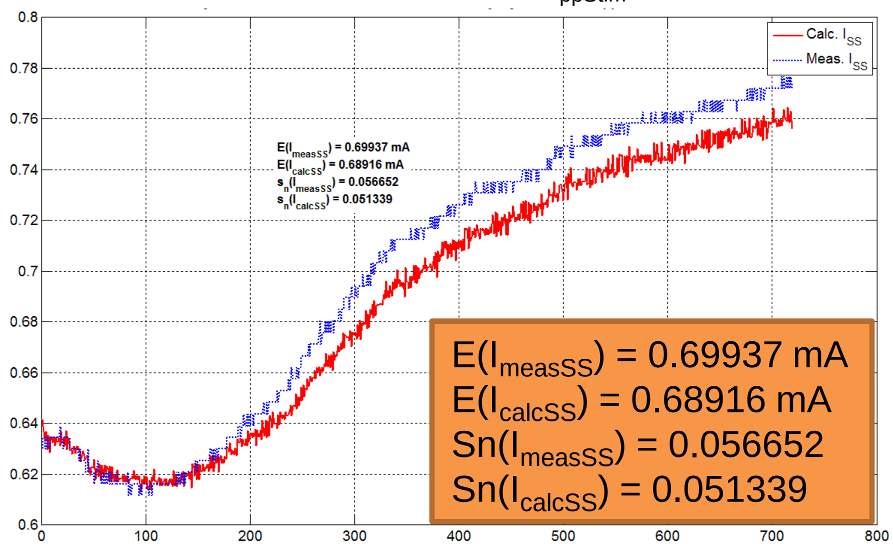
Current (mA)

S.S Stim. Current all Active D.Cs; V_{ppStim} = 160 V, λ = 0.9998



Tracking With Forgetting Factor

S.S Stim. Current all Active D.Cs; V_{ppStim} = 150 V, λ = 1



m_{th} value

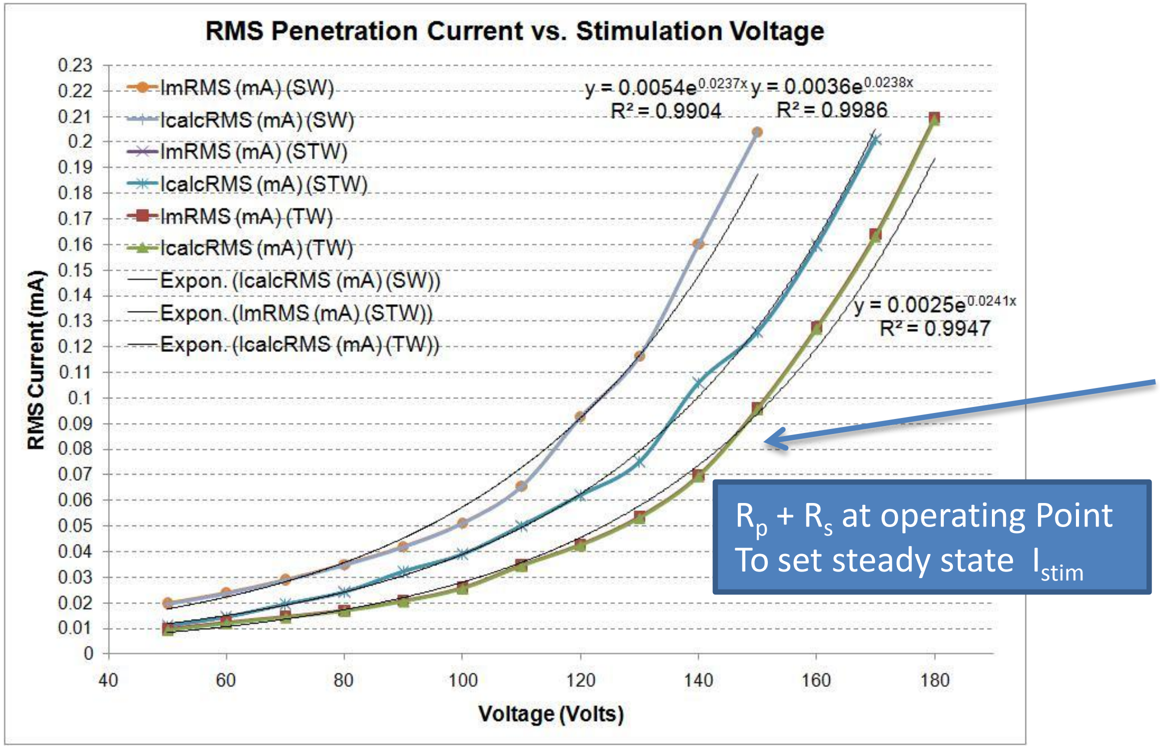
Tracking steady state I_{pp} of square wave voltage Stimulation from t = 0…13 sec :

In General :

- The standard deviation of measured steady state penetration current increases as stimulation voltage increases past a certain threshold

- requires fast tracking

Results: Identified R_p Dynamic Range



I-V DC characteristic with electrical skin impedance

Preliminary Remarks:

The steady state skin penetration current can be set by the identified Rp (and Rs) on-line

This is supported by:

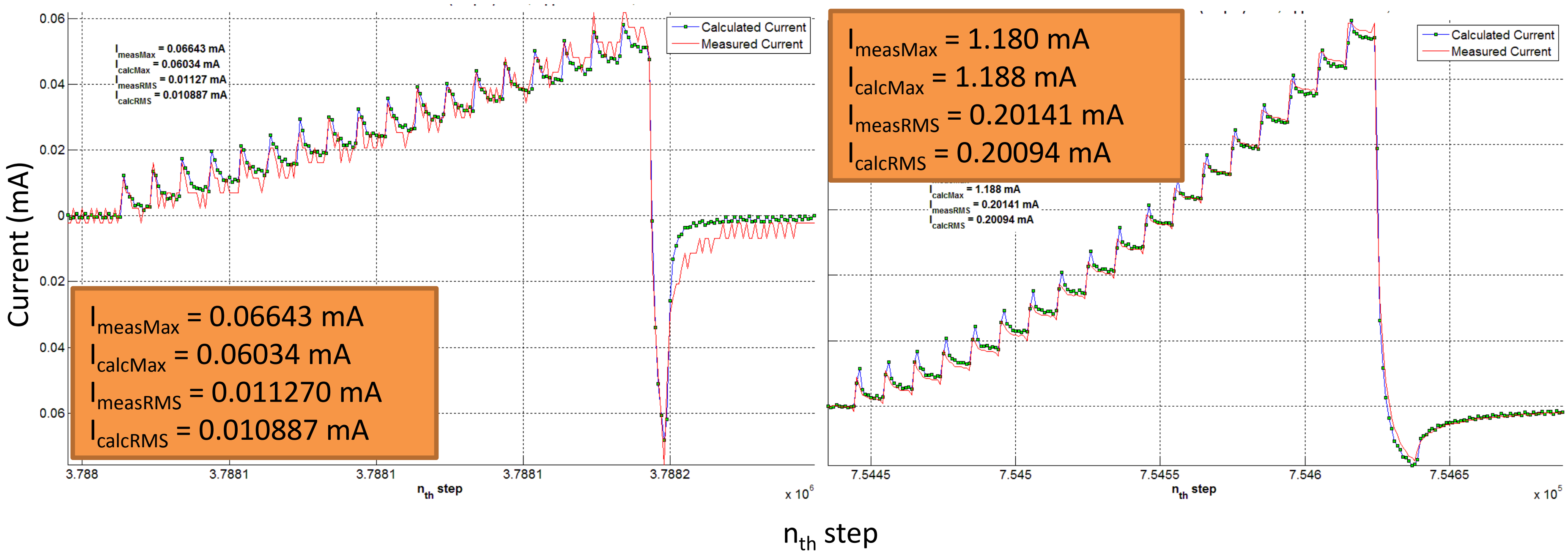
The ELS convergence time being less than the skins time variation (as seen in previous slide)

Algorithms ability to track the IV DC characteristic accurately

Subject: Male, **Age:** 31, **Finger Condition:** Dry, **Finger Tested:** Index; **Finger Location**: kept const.
Test Condition: One-Subject Z_L at multiple Q-Points; successive measurement (no time lapse); no repeatability testing; const. pressing force;
Δtime: 3 sec. assumed steady state interval, **waveform:** all no P.E.,**D.C. =** 11.0%, **Freq. =** 60 Hz **λ =** 0.9998, **Pressing Force:** 300 grams

Results: Advantage using ELS with slow Stimulation Voltage rise times

Calculated and Measured Current (Output) vs. n; V_{ppStim} = 50 V (left) and VppStim = 169 V (right), λ = 0.9998



$$\widehat{I}_{stim}(t) = \frac{\beta_2 + \beta_1 z^{-1}}{1 + \alpha_1 z^{-1}} V_{stim}(t) + \frac{c_1}{1 + \alpha_1 z^{-1}} e(t)$$

Saw Tooth Wave:

•As driving voltage Increases a notable exponential increase in skin penetration current is observed as a function of quantization level.

•By using the Extended least Squares, the regressor c_1 (error correlation term) characterizes the unknown signal nonlinearities as to enhance tracking at each delta step

Conclusion & Future Work

- Built versatile CVD, measurement and output current tracking system
- Plan to develop a feedback loop to set I_{pp} current levels based on identified model
- Developed high bandwidth current measuring technique
- Demonstrated ELS algorithm with forgetting factor can track non-linear and time varying current in real-time
- Future work will use the completed haptic render to investigate mimicking tactile sensation
- Currently Developing 200 point electro-tactile stimulator using arrays of multiplexed CVDs