OPTIMIZATION OF AN HEALTH MONITORING SYSTEM WITH PIEZOELECTRIC SENSOR

Team: Fellowship of the Ring

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Introduction

Background & Motivation

The medical industry has been focusing their research in developing non-invasive constant monitoring devices for in-patient's and out-patient's vital signs. Such a device could be an early warning system to identify problems with infections or medications, reduce cost and complications of invasive procedures, reduce in-patient length of stay and help doctors understand rare and complicated diseases by monitoring out-patient progress and emergency events.

The MEMs lab in the Mechanical Engineering department with the Michigan Center for integrative Research for Critical Care is currently developing an atrial pulse sensor made from a piezoelectric polymer and data collection module to meet this goal. The sensor is placed over an artery that is easy to access, like those in the wrist, finger, ankle, foot, temple and etc., with a ring or wrist band structure that can adjust the pressure applied to the sensor. The pulse wave propagated in the artery deforms the material creating a very detailed vital sign but it is very susceptible to noise and motion artifacts. This signal is collected, by a portable device, along with measurements from a pressure and temperature sensor and an accelerometer/ gyroscope, which will be used to develop methods to refine signal clarity and robustness. This device records the signals, powers the sensors, and send the information over Wi-Fi for monitoring and recording.

Device Overview

The portable device for this project will be one that is attached to the finger and contains the piezo electric sensor the capture the arterial pulse, send the electric output to a module in the wrist, which convert the pulse into heart rate, Blood pressure, breathing rate, arterial stiffness, and other figures that help identify critical health signals. It then send the information over wifi to local hospital where the information is recorded and monitored. The sensor itself is made up of a piezoelectric polymer PVdF that is laminated, attached to a plastic substrate and is held firmly against the finger with a strap

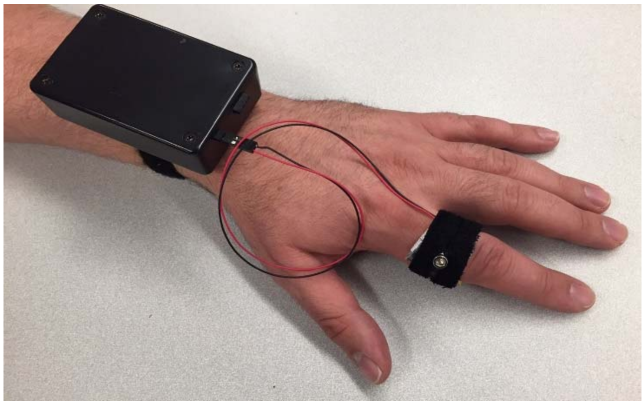

Figure 1 Prototype of continual health monitor device with ring containing piezoelectric sensor and module for data analysis and wireline communication

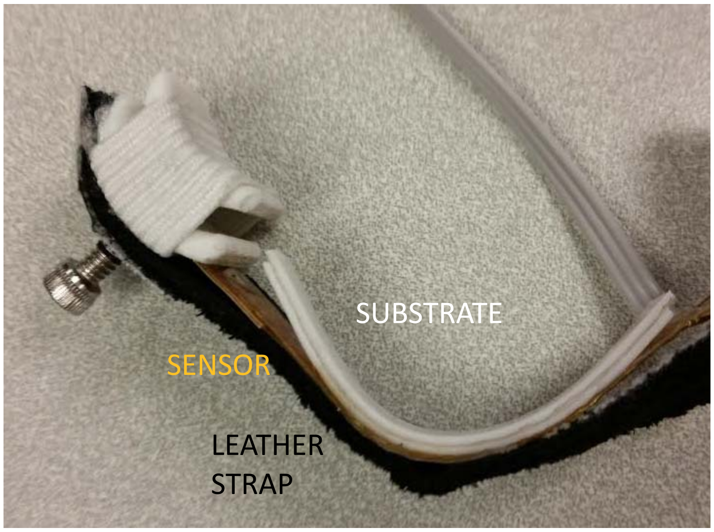

Figure 2 Close up side view at the ring, with critical components that affect signal output and user comfort, including the piezoelectric sensor, substrate backing, and finger strap.

Project Goal and Critical Subsystems

The goal of this project is to create a portable monitoring system that is robust and wearable. The device needs to process signal as well as larger devices currently used in intensive care units, and the signal quality needs to be balanced with an adequate level of comfort for the users. This helps our team focus in on two critical subsystems, sensor mechanical design and product comfort, for optimization. Obvious trade-off between comfort and signal quality were observed in earlier prototypes of the devices, where large ring devices that were able to accommodate large sensors output clear and high voltage signal, but were uncomfortable and inadequate as a portable device.

Subsystem 1: Sensor Optimization

The objective goal of this subsystem is to optimize the ring device by maximizing the sensor's voltage output while satisfying a number of geometrical constraints and engineering performance constraints.

Subsystem 1 Modeling

Two different modeling approaches were considered. The first was a physics based model of the sensor that captures the dynamics of the artery and that of the piezoelectric solid mechanics circuitry and the electrical structure of the sensor and the circuit. The second approach was data-based model created using experimental data from actual prototypes.

Physics Based model:

The sensor itself is made up of a piezoelectric polymer PVdF that is laminated, attached to a plastic substrate and is held firmly against the finger with a strap. This sensors is then connected to a circuit on the wrist module where the signal is processed and recorded.

This model breaks down into three different parts, first the dynamics portion that describes when the blood pressure pulse causes stresses in the ring that translate to the sensor, secondly a model for the piezo sensor converts these stresses into a voltage output and finally an electric circuit transforms the sensors' voltage output to what is actually read and recorded.

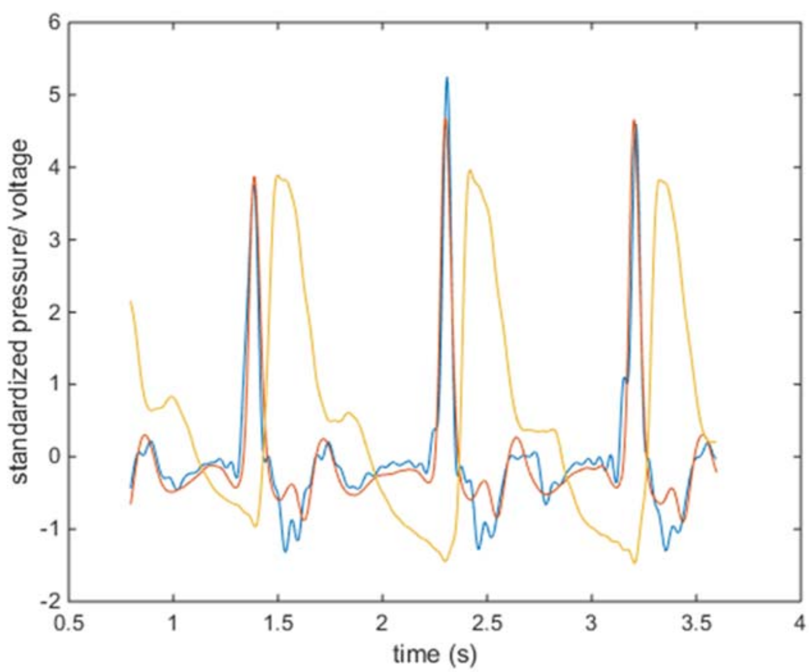

Figure 3 Comparison of model output (blue) with actual sensor output (red) and blood pressure input (yellow)

The dynamic model assumes that the radial and axial stresses of the ring are zero and calculates the tangential stress of a pressure vessel as if the laminate, sensor and substrate were the same vessel. It than calculated the bending stresses due to the pressure deforming the ring, as a beam made of two materials the substrate and a material with the combined properties of the sensors and laminate. The Bending stress for this second material is found and added to the tangential stresses. This stress then separated from the laminate to determine what the sensor is experiencing. These dynamic use all of the parameters described in Table 1.

Table 1 Parameters for sensor model

Variable	**Symbol**	**units**
Pressure	P	Pa
Radius of the Finger	r	mm
Thickness of the Sensor	t_{sen}	microns
Thickness of the laminate	t_{lam}	microns
Thinkness of the substrate	t_{sub}	mm
Area of sensor (Length x Width)	A	mm^2
Youngs Modulus of Sensor	E_{sen}	Gpa
Youngs Modulus of Laminate	E_{lam}	Gpa
Youngs Modulus of Substrate	E_{sub}	Gpa

These stresses are then used to find the voltage output of the piezo electric model, using the properties of the PVdF and electric constants found on Table 2. These properties along with the sensors geometry are also used to model the sensors maximum ability to pick up random noise. The maximum noise is then added to the output using MATLAB randomizer to try and capture the actual random noise and levels the sensor would pick up.

Table 2 Properties of PVdF

Property/constant	Symbol	Value	Units	Material
Boltzmann's Constant	K_B	1.3806e-23	m^2*Kg/s^2/K	--
Electric Constant	ε_0	8.854e-12	s^4A^2/m^3/Kg	--
Young's Modulus	E_p	8.3	GPa	PVdF
Piezo Strain Constant	D_{31}	22	pC/N	PVdF
Relative Dielectic Constant	ε_r	10e-12	--	PVdF

This new output is then processed by the simplest circuit used with the portable device, shown in Figure 4, it is also a good representation the more complex circuits the output signal gets processed through. Where sensor is represented as a current source and capacitor, this is an important because it interactions with the circuit causes a differentiation in the signal before it can be recorded.

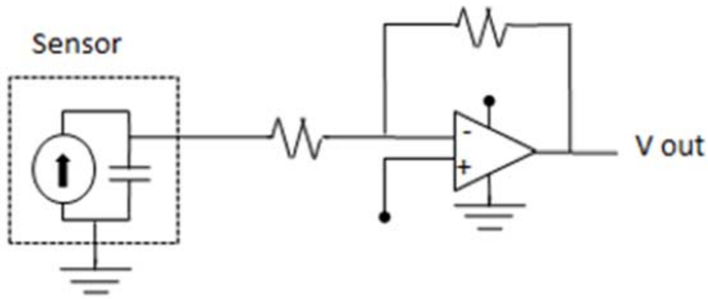

Figure 4 Circuit diagram of ring device

This model takes in actual time series data recorded in the lab, where the blood pressure input is from a pressure cuff on the arm and corresponding pulse is from a large PZT sensors recorded with Biopac machine. This allows for the direct comparison of the modeled data to the actual recorded pulse data.

Data-based Model

In order to find a data-based model, Table 3 relevant to the data-based model were varied to create 9 prototypes and collect 30 datasets from randomized experiments. The details of the design combinations and experiments are shown in the appendix B. The input data set include variables of sensor thickness, length, width, substrate thickness, and one parameter of material choice. The material choice, between cloth and leather, was treated as two Boolean variables for modeling purpose. The output data set include signal and device characteristics that were analyzed from the output signal data collected, including peak signal magnitude, noise levels, signal error, and current.

A neural network surrogate model, with one hidden layer and 10 nodes, was created from experimental data using MATLAB's neural network toolbox. A 60% - 20 % - 20% ratio was used for training, validation, and test data sets respectively. The result is shown below in Figure 5.

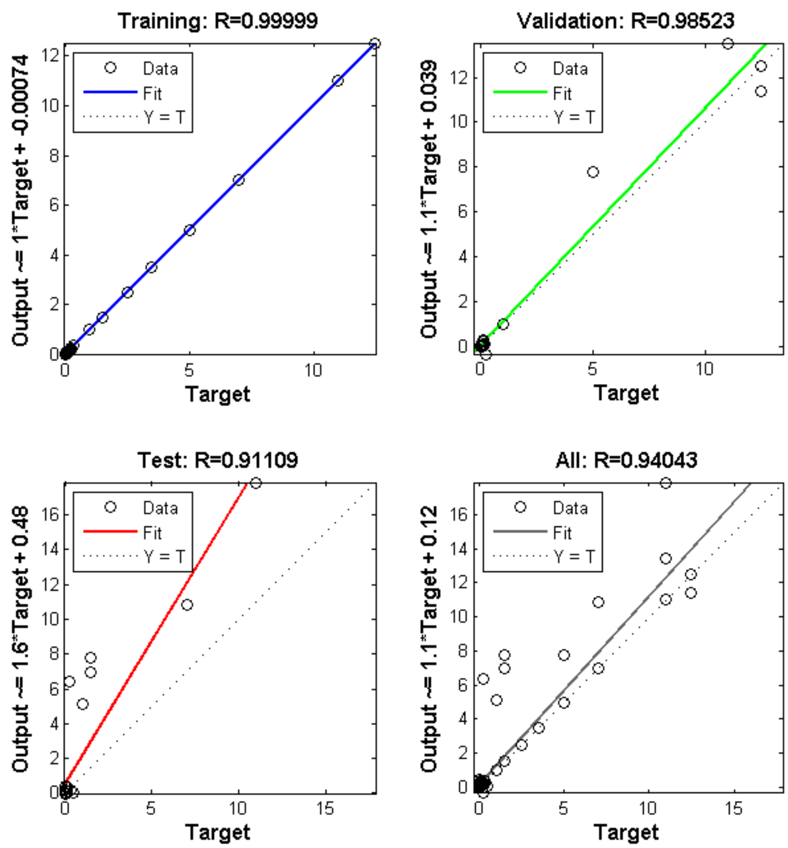

Figure 5 Result from neural network model for the sensor

Subsystem 1 Optimization

Subsystem 1 Optimization Problem

The objective function are the same for both the physics based and data based models and take the form of the equation below. They are not shown here because of their complexity.

$$\max_{\bar{x}} V = f(\bar{x})$$

The constraints of the optimization problem include inequality geometric constraints and engineering performance constraints. The variables and simple geometric constraints of upper and lower bounds are shown in Table 3 below.

Sensor thickness bounds are based on market availability of materials and manufacturing constraints. Sensor length and width upper bounds are determined with average human index finger circumference and segment length; the length wraps around the circumference and width covers up to the length of the finger segment. The lower bounds for the two variables are determined by manufacturing constraints. The bounds of substrate thickness, laminate thickness, laminate Young's Modulus were determined by available material. Those are in practice discrete variables but are treated as continuous variables for optimization simplicity.

Table 3 Variables used for subsystem 1 optimization

Variables	LB	UB	Model used
Sensor thickness (μm)	28	110	Physics and Data based
Sensor Length (mm)	8	50	Physics and Data based
Sensor Width (mm)	3	10	Physics and Data based
Substrate Thickness (mm)	0	3	Physics and Data based
Laminate Thickness (μm)	1000	50	Physics based
Laminate Young's Modulus (GPa)	10	0.01	Physics based
Material(cloth/leather) Discrete variable	0	1	Data based

Engineering performance constraints are shown below in Table 4.

Table 4 Engineering performance constraints

	Constraint
G1: Signal error	$\sum_{i=1}^{n}\left(\hat{f}(x_i) - y_i\right)^2/n \leq 0.1$
G2: Signal magnitude	$Signal\ magnitude\ \geq\ 60Hz\ noise\ magnitude$
G3: Signal to noise ratio (SNR)	$SNR\ \geq\ 15\ dB$
G4: Current level	$Current\ \geq 2\ nA$

Constraints were created for each of these models to increase the level of signal clarity and to be used with the circuity of the portable device. The most significate constrain was the error from the model to actual signal. Both the Physics and Data based model used the squared sum of error for each point to achieve maximum clarity. $\sum_{i=1}^{n}\left(\hat{f}(x_i) - y_{actual,i}\right)^2$/n. The data based model used the FFT results to set a signal to ration of 15 dB and a larger signal to 60 Hz noise. Both models used current constraint of 2 nA or larger. This came from experimental data. The Physics bases model also use an equation found from the linear fit of measured current to the sensors size.

Optimization Methodology

Optimization was performed with fmincon in MATLab. Two algorithms, Sequential Quadratic Programming (SQP) and Internal Point (IP), were used, and two solvers, Multi-Start (MS) (100 initial points) and Global Search (GS), were implemented for finding global minima. The different methods were tried to ensure robustness of results. Convergence rates and run time were further compared.

Table 5 below shows that while there is no significant difference between the performance of the two algorithms, GS solver performed better for the cloth model. All objective function results converged to 51 mV for cloth and 46 mV for leather, showing that the results are robust.

Table 5 Results and performances of optimization methods

Solver	Algorithm	Material	Obj [mV]	Convergence	Time [s]
MS	IP	cloth	51.2	0.2	132.288
MS	SQP	cloth	51.2	0.18	131.512
MS	IP	leather	45.7	0.89	54.793
MS	SQP	leather	45.7	0.89	48.250s
GS	IP	cloth	51.2	0.660377358	43.464
GS	SQP	cloth	51.2	0.32	110.816
GS	IP	leather	45.7	0.93220339	23.803
GS	SQP	leather	45.7	0.828571429	18.227

Results

Physics model

The optimization results for the physics based model are shown in Table 6, it is evident that the sensor with the 110 µm thickness had the better optimal point. There are several treads that can be seen from the table, most interesting is that the optimal length the increases as the as the thickness decreases becoming 3 times large for the thinnest sensor. The laminate Thickness stays relatively the same for the 110 µm and 52 µm but increases over three time for the 28 µm sensor. These results are even more surprising, since the optimal results for each sensor without constrains were the same, hitting the lower bound of all the variables except the substrate thickness hit the upper bound.

Table 6 Optimization of results of subsystem1, physics based model

Max Voltage (mV)	Sensor thickness (µm)	Sensor Length (mm)	Sensor Width (mm)	Substrate Thickness (mm)	Laminate Thickness (µm)	Laminate Young's Modulus (Gpa)
10.0	110	14.1	4.33	2.86	50	0.54
3.30	52	22.6	5.7	2.7	50	0.55
0.22	28	38.1	6.52	1.81	188	0.48

Sensitivity analysis

A sensitivity analysis was performed more the two engineering performance constrains given physics based model. Each of these inequality constraints were remove one at a time to determine if they were active or inactive. The ones determined to be active were relaxed to find their sensitivity, the results are shown in Table 7. G1, the error constraint was reality the same for each sensor thickness but the current constraint was only active for the thinnest sensor. Multi-Start with 50 initial conditions were used for these analysis.

Table 7 Sensitivity of the objective function of the physics mode; with respect to engineering performance constraints

Model	**g1: Error**	**g2: Current**
110	0.23	inactive
52	0.25	inactive
28	.28	.011

Parametric study

In the parametric study the physics based model was analyzed to determine if any of the constant parameters would affect the optimization. Six parameters were given small perturbations around the optimal point found above, the results are shown in Table 8

Table 8 Results of the parametrization study on the physics model

Radius of finger	Young's Modulus Substrate	Density Substrate	Relative Dielectic PVdF	Young's Modulus PVdF	Dielectric constant of PVdF
.5	-.00002	-.025	-.6	7.2	500

From the study it clear the properties of the piezoelectric polymer have the largest effect on the output voltage. The most dramatic is the Dielectric constant, this directly correlates the stress to on the sensor to it's voltage out, as it increases so does the output. The Young's Modulus of the polymer also increases the output, like due to the fact the stiffer it is the more stress it experiences. The Relative Dielectic constant decreases the output, this is due the fact that it is used to determine the sensors capacitance which is inversely related to the output. The radius of the finger has a middle change on the voltage output, this probably due to the why ring was modeled as a pressure vessel. Both the density and Young's Modulus of the substrate decrease the output by very little. This likely means that the material type change slightly without a significate change in output.

Data based model

The optimization results for subsystem 1 are shown in Table 9 below. It is clear that a device with cloth strap could perform better optimally compared to that with leather strap. It is interesting to note that the optimal sensor width are three times different between the two models, and that both of them require maximum substrate thickness for optimal performance.

Table 9 Optimization results for subsystem 1

Model	**Max Voltage [mV]**	**Sensor thickness [µm]**	**Sensor Length [mm]**	**Sensor Width [mm]**	**Substrate Thickness [mm]**
Cloth	51.2	46.8	44.3	3	3
Leather	45.7	44.4	46.6	9	3

Sensitivity analysis

Sensitivity analysis were performed for the four engineering performance constraints discussed under Subsystem 1 Optimization Problem. These inequality constraints were first removed one at a time to determine which constraints were active. The constraints that were active were loosened to numerically approximate the sensitivity of the objective function with respect to each constraint. Multi-Start with 50 initial conditions and SQP algorithm were used for these analysis.

The results are shown in Table 10 for the cloth model, G1 and G3 are similarly sensitive, while for the leather model G1 and G4 are active, with G1 much more active. This result aligns with idea that the error constraint is much stricter than the current constraint, an observation that was made from testing prototypes.

Table 10 Sensitivity of the objective function with respect to engineering performance constraints

Model	G1: Error	G2: Signal Mag	G3: SNR	G4: Current
Cloth	0.12	Inactive	0.12	Inactive
Leather	0.19	inactive	inactive	0.04

Conclusion

A comparison of the optimal results of the physics model and the data model were performed and a discrepancy was found, the optimal points for the physics based model linearly converged to the lower bound of the length and width of the sensor. Only the error constraint kept these optimal points from shrinking the sensor size more. This is not what is observes in the in the actual data collect for the data driven model.

The parameterization study for the physics model also showed that the Dielectric constant and Young's Modulus properties of the piezoelectric polymer dramatically effect that voltage output and a material with better properties my improve the overall design.

Both results show the significates of the substrate to the optimization and a further study on relaxing these constraints maybe help improve the optimization.

The results of the data-based model show that the length stayed relativity large, the thickness remained the width changed dramatically, this mean that the width maybe be as import for voltage as the length. Also the data driven model considers material types which would be more suitable to compare with the comfort model. Therefore the data driven model will be used in the system level optimization.

Subsystem 2: The sensors optimization from mechanical structure

Modeling

Conjoint analysis was used to create a comfort model because there is no existing model for ring device comfort. It is unreliable to determine comfort level from data collected based on methods such as surveying using questionnaires or images to represent the designs, thus prototypes were created to collect data from human subjects. The attributes and levels of the attributes for the prototypes were decided based observation of critical attributes that affect comfort and on the time constraint for our project.

The larger number of variables for subsystem 1, shown in the section Subsystem 1 Modeling, were considered and a few prototypes made and tested with subjects to determine that the comfort level of the ring is most sensitive to the width of the strap, thickness of the substrate backing on the piezoelectric, and the strap material.

From additionally considering the amount of time required for manufacturing and working with subjects, twelve prototypes were made based on two levels of strap with, three levels of substrate thickness, and two different strap materials (cloth vs. leather). Boolean choice data were collected from pairwise comparisons of designs, where the team conducted randomized experiments that included 10 subjects and collected 50 data points of different pair-wise comparisons, spanning 76% of the 66 possible pairs for comparison.

Figure 6 Components, sensor assemblies and ring straps, made for comfort data collection. Leather straps are darker in color. 3 levels of sensor assembly thickness and 2 levels of strap width shown.

A linear model for comfort, or utility U, was assumed and shown below in Equation 1.

Equation 1

$$U = \beta_1 w + \beta_2 t + \beta_3 m_1 + \beta_4 m_2$$

Table 11

Variable	Symbol
Width of Strap	w
Thickness of Substrate	t
Material (discrete boolean var.)	m_1 and m_2

The coefficients of the model were found by maximizing the objective function shown below in Equation 2.

Equation 2

$$\max_{\beta} f = \sum_{j=1}^{n} \log(P_j)$$

$$P_j = \frac{e^{-\bar{\beta}\,(\bar{x}_a - \bar{x}_b)\,*k}}{\sum_{i=1}^{N} e^{-\bar{\beta}\,(\bar{x}_{a,i} - \bar{x}_{b,i})}}$$

$$\bar{x}_a = [w_a\,, t_a\,, m_{1,a}\,, m_{2,a}], \qquad \bar{\beta} = [\beta_1\,, \beta_2\,, \beta_3\,, \beta_4]$$

$$k = \begin{cases} 1\,, & if\ choice\ 'a' was\ chosen \\ -1, & if\ choice\ 'b' was\ chosen \end{cases}$$

$$m_{1,a}\ \&\ m_{2,a}: Boolean\ variables.\ [1\ 0]\ for\ cloth\ and\ [0\ 1] for\ leather\ material$$

Fmincon with interior point algorithm in MATLAB was used to find the minimum of the optimization problem. Table 12 below show the results of the optimization.

Table 12 Optimization results for finding linear comfort model coefficients

f^*	β_1^*	β_2^*	β_3^*	β_4^*
83.89	-7.51	-3.24	1.69	0.3

Surface and contour plots were created to quickly check the validity of the minima. Examples where the minima is checked with respect to β_1 and β_2 are shown below.

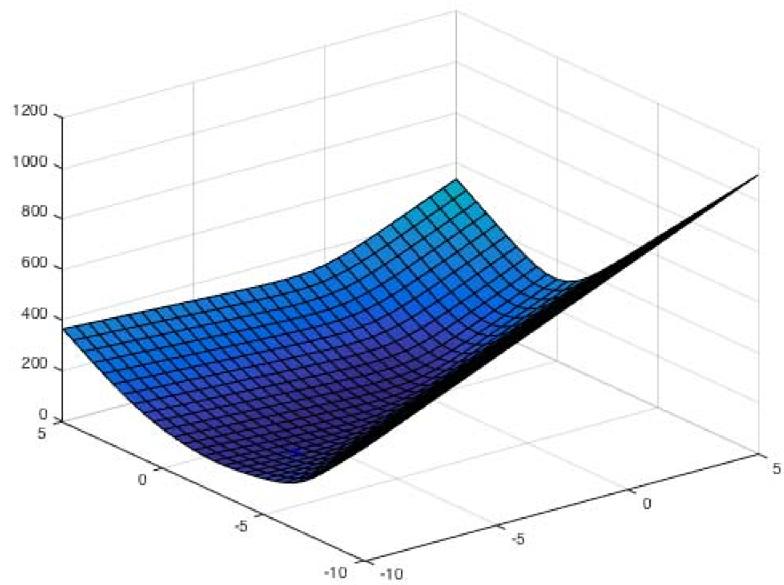

Figure 7 Example surface plot that was used to check validity of minima as a function of B_1 and B_2

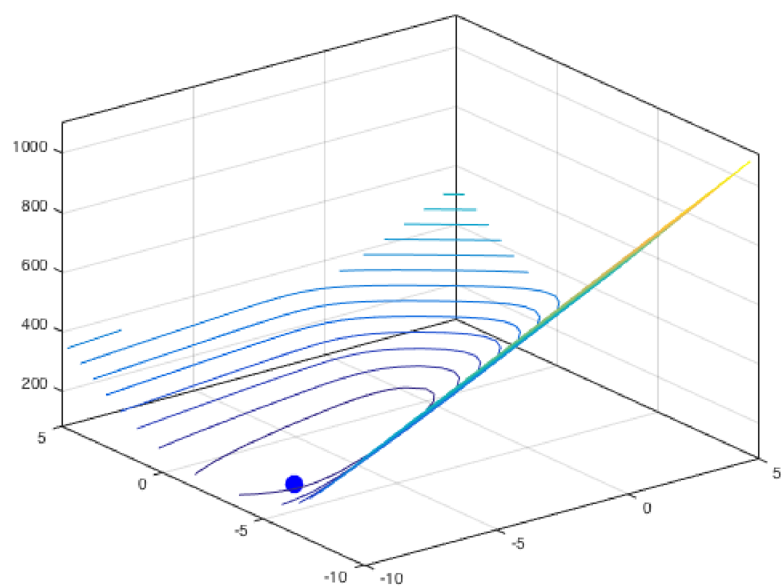

Figure 8 Example surface plot that was used to check validity of minima as a function of B_1 and B_2

Optimization

Optimization Problem

The objective function for optimizing comfort is shown in Equation 3 below.

Equation 3

$$\max_{\bar{x}} U \ = -7.51w \ + -3.24t \ + \ 1.69m_1 \ + \ 0.3m_2$$

$$\bar{x} = [w, t, m_1, m_2]^T$$

The constraints for the subsystem are independent upper and lower bounds of the variables explained in Subsystem 1 Optimization Problem and under Equation 2 . The values are stated again below in Table 13 below.

Table 13 Constraints for subsystem 2 variables

Variables	LB	UB
Strap/Sensor Width (mm)	3	10
Substrate Thickness (mm)	0	3
m_1 & m_2 (discrete variables)	0	1

Optimization Methodology

For optimizing the device made of leather, $[m_1, m_2] = [1, 0]$ and for a device made of cloth , $[m_1, m_2] = [0, 1]$.

Since the problem objective function is linear and the variables are limited only by their respective independent upper and lower bounds, solving this optimization problem is trivial and can be done by simply plugging in maximum values for variables corresponding to a positive coefficient and minimum values for a variable corresponding to a negative coefficient.

Results

The results from optimization shown in Table 14 Optimization results for comfort subsystem below shows that a ring device created with cloth material has a better optimal than a ring device with leather material. In fact, since the only difference between the models are constant offsets from coefficients for the material choice, it could be concluded that in general devices would be more comfortable with cloth material.

Table 14 Optimization results for comfort subsystem

Model	U^* (max)	w [mm]	T [mm]	m_1	m_2
Cloth	-20.84	3	0	1	0
Leather	-22.23	3	0	0	1

Sensitivity analysis

Since model is linear, the sensitivity of the objective with respective to each variable could be easily determined by inspecting their respective coefficients. The -7.51 coefficient for the strap width and the -3.24 coefficient for the substrate thickness show that the model predicts larger comfort with smaller width and thickness values, and that the comfort is twice as sensitive to strap width as it is to substrate thickness.

Conclusion

A ring device created with cloth material in general is more comfortable than a ring device with leather material, width and thickness are to be minimized for comfort, and width is twice as strong as thickness in influencing comfort. Note that these are results derived from a linear model, where all the variables are assumed to be independent. Observations from comments recorded during experiments with subjects, shown in Appendix A. Comments from Comfort Testing, reveal that while the linear model captures the general trend for comfort, there is some level of interaction of the variables that affects comfort.

System Level Optimization

Optimization

In order to optimize the whole system that include the sensor subsystem and the comfort subsystem, the option of having a linear cost function that link the two subsystem was first considered. However, the team decided against that option because since manufacturing and overall product design for the device is not mature yet, there is no accurate way to determine cost as a function of geometry, material, performance, and utility. A new system level optimization problem was ultimately formulated by including an acceptable, assumed 90%, of maximum utility from the comfort model, as an additional inequality constraint to the sensor model. The new constraint is shown in Equation 4 below, where $U(\bar{x})$ is the utility function shown in Equation 3.

Equation 4

$$g_5 = U(\bar{x}) \geq (U_{min} + 0.9 * (U_{max} - U_{min})$$

Table 15 90% of the maximum utility value in the utility range of the two models

Model	U max	U min	90% Max U
Cloth	-20.84	-71.6	-28
Leather	-22.23	-67.7	-29

Optimization Methodology

For the objective function and constraints, refer to Subsystem 1 Optimization Problem, Table 3, Table 4, and Equation 4.

Results

The results of system level optimization is shown in Table 16 below. Overall a device with cloth strap can achieve more optimal voltage performance even with the additional utility constraint. It can also be observed that the objective value of the leather model is much more sensitive to the additional constraint by its drastic loss of 75% voltage value.

Table 16 System level optimization results and % change from sub system optimal values

Model	Max Voltage [mV]	% Change from Sub System 1 optimal	Max Utility	% Change from Sub System 2 optimal
Cloth	41.0	-38 %	-28	-10 %
Leather	18.0	-75 %	-29	-10 %

Comparison of the results of optimization before and after adding the utility constraint, however, a significant shift in the sensor size could be seen from the change in optimal sensor length and substrate thickness. The sensitivity of the optimal attribute values indicates that it is important to determine what is an acceptable value of utility constraint is, otherwise these physical values may not be near a real optimal for design purpose. The comparison is shown below in Table 17.

Table 17 Comparison of optimization results of cloth model with and without 90% max utility constraint

Model	Max Voltage [mV]	Sensor Thickness [µm]	Sensor Length [mm]	Sensor Width [mm]	Substrate Thickness [mm]
Cloth w/o utility constraint	51.2	46.8	44.3	3.0	3.0
Cloth w/ utility constraint	41.0	34.6	8.0	3.0	1.3

Sensitivity Analysis

Sensitivity analysis revealed that for the cloth model G2 and G4 are inactive, with sensitivity levels doubled of what was seen prior in Table 10. For the leather model, the sensitivity level for all the engineering performance constraints are consistently around 0.55 across the board. The optimal of the leather model is much more sensitive to shifts in constraints.

Table 18 Sensitivity of the objective function with respect to engineering performance constraints

Model	G1: Error	G2: Signal Mag	G3: SNR	G4: Current	G5: Comfort
Cloth	0.22	Inactive	0.13	Inactive	0.18
Leather	0.56	0.55	0.55	0.55	0.55

Conclusion

Currently a 90% level from maximum utility previously determined is used as an inequality constraint. Knowing that the optimal variable values are sensitive to the utility constraint, the correct level of utility is required to achieve a practical design. Further work with subjects could be done to set a realistic value for utility. A nonlinear model, for instance from neural network modeling, that not only captures the general trend while assuming the variables for utility model are independent could perhaps also serve to get better results for system level optimization.

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Appendix

Appendix A. Comments from Comfort Testing

	Age	Occupation	Test	Pair	Comments
Subject 1	24	Student	1	28	It's kind of hard to feel pulse. The leather is tight but can't feel pulse. Feel the plastic piece in the cloth one is smaller, more comfortable.
			2	48	The survey is very thoughtful. Can't move finger as much with wider strap, less comfortable.
			3	1	if I am a patiient, might be hard to wrap strap around. Eslatic rubber band that is slip on might be better. Leather is more comfortable than cloth
			4	20	My finger is numb. Middle finger works well with wider strap.
			5	10	Thin one can move finger more easily, but wide strap give you less pressure so more comfortable that sense. But if I have to wear for an hour, I'd prefer one which I can do more things with.
Subject 2	24	Student	6	7	My fingers turn red really quickly. I'm not sure if I can wear this ring for an extended period of time. The thin cloth pinches my finger even when I'm not moving.
			7	13	For obvious reasons the one having no backing is more comfortable, but it seems that the one with backing can feel pulse faster.
			8	23	Opposed from expectation, I liked the thicker sensor with leather rather than thinner sensor with cloth.
Subject 3	26	Working	11	28	Could feel with the latter leather prototype, but not the cloth one. Like wider leather one bc. Don't have to tighten as much.
			12	16	Don't have the thin leather, bc it constraints finger. Like the more distributed force. Might have personal bias against felt material.
			13	14	The sensor thick is very uncomfortable. Feels like c-clamp on finger.
			14	58	The wide geather is favorite so far. User not as pleased with thicker sensor.
			15	2	User is visuallybiased. Feel repulsive upon seeing thicker sensor. Says its not too bad though
Subject 4	26	Working	16	45	Like the leather , its pretty soft.
			17	28	Like the latter one because it feels less obstrusive. The thin strap cuts into the skin, which also was cloth
			18	37	Don't like the thicker sesnro
			19	10	1st one softer
Subject 5	24	Working	21	53	The latter feel better. The former felt pinching.The strap cut less into skin bc. Sensor stiffner

			23	21	The former felt more breathable. Felt like the cool side of pillow. Latter very constricting
			24	46	Like the leather, but the sensor thinner felt so much better.
			25	58	Almost felt no difference
Subject 6	29	PhD	27	6	Prefer softer leather material
			29	12	Like thinner because easier to move
			30	58	Like thicker sensor because force more evenly distributed.
Subject 7	25	PhD	31	8	The latter is ichy
			32	28	Like the leather
			33	64	Thicker sensor too sick.

Appendix B. Data Sets Collected for Data-based Modeling

Test	Sensor Thickness (micron)	Sensor Length (mm)	Sensor Width (mm)	Substrate Thickness (mm)	Peak to Peak Voltage (mV)	Maximum Signal frequency (dB)
1	28	25	5	1	0.013266	0.001185
2	28	25	5	0	0.017261	0.000926
3	28	25	5	2	0.012839	0.000588
4	28	25	9	1	0.020452	0.000779
5	28	25	9	2	0.015653	0.000658
6	28	50	9	1	0.017688	0.001556
7	28	50	9	2	0.015251	0.001425
8	52	25	9	0	0.059497	0.008179
9	52	25	9	1	0.048593	0.007673
10	52	25	9	2	0.042563	0.004323
11	52	50	5	1	0.045779	0.004376
12	52	50	9	1	0.033543	0.005555
13	52	50	9	2	0.04299	0.005254
14	110	25	5	1	0.029347	0.00268
15	110	25	5	2	0.027688	0.001883
16	110	50	5	0	0.05505	0.006116
17	110	50	5	1	0.037337	0.002642
18	110	50	5	2	0.02892	0.002183
19	110	50	9	1	0.04299	0.004907
20	110	50	9	2	0.058241	0.004967
21	28	25	9	0	0.012045	0.000777
22	28	25	9	0	0.008427	0.000541
23	28	50	9	0	0.012286	0.001524
24	52	50	5	0	0.029121	0.005009
25	52	50	9	0	0.054623	0.007223
26	52	50	9	0	0.029523	0.004905
27	110	25	5	0	0.01892	0.00113
28	110	25	5	0	0.01892	0.00113
29	110	50	9	0	0.051809	0.004983

Test	60 Hz noise (dB)	Maximum Noise (dB)	Error (mV)	Current (nA)	Cloth	Leather
1	0.003212	0.000104	0.08342	0.25	1	0
2	0.003641	0.000169	0.462083	0.25	0	1
3	0.003369	0.000179	0.14504	0.25	0	1
4	0.004777	0.000155	0.207811	1	0	1
5	0.004027	0.000182	0.339822	1	1	0
6	0.00287	0.000336	0.159975	2.5	1	0
7	0.002895	0.000217	0.099555	2.5	0	1
8	0.003803	0.001303	0.046104	1.5	0	1
9	0.002925	0.001378	0.097319	1.5	0	1
10	0.003012	0.000489	0.208237	1.5	0	1
11	0.004869	0.000634	0.096634	5	1	0
12	0.001383	0.000526	0.139089	12.5	1	0
13	0.002139	0.001099	0.142226	12.5	0	1
14	0.00405	0.000522	0.203871	3.5	1	0
15	0.004592	0.00048	0.360925	3.5	0	1
16	0.004542	0.000722	0.108527	7	0	1
17	0.004184	0.00042	0.050398	7	0	1
18	0.004247	0.00029	0.091901	7	1	0
19	0.003726	0.000985	0.115994	11	0	1
20	0.003035	0.000937	0.139159	11	1	0
21	0.002396	0.000204	0.088593	1	1	0
22	0.001751	0.000126	0.219687	1	1	0
23	0.001611	8.88E-05	0.043475	2.5	1	0
24	0.001719	0.000614	0.076457	5	0	0
25	0.002562	0.001152	0.098204	12.5	1	0
26	0.00291	0.00053	0.21605	12.5	1	0
27	0.001942	0.000165	0.133582	3.5	1	0
28	0.001942	0.000165	0.133582	3.5	1	0
29	0.003718	0.000378	0.0556	11	1	0