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Design of Disposable Paper-based Piezoelectric Devices for Multi-functionality

Introduction:

The focus of this study lies in Piezoelectric devices, which in our case, are used as force sensors. Reviewing the role of force sensors in modern day, a single sensor device can allow for structural analysis of structural elements, the use of touch screens to navigate through computer interfaces, characterization of materials properties and forces, and much more. However, most sensors and electronic devices call for specific materials, sophisticated fabrication techniques, and exorbitant equipment in product manufacturing. As prices escalate[5], high efficiency (i.e. performance/cost ratio) becomes harder to maintain. In contrast to the inflation and increasing complexity of technologies, these inexpensive sensors are a disposable green technology that call for everyday materials that can be fabricated without the need of costly equipment or highly specialized human resources. Throughout the study, frugal innovation was central theme while a "Nature does it best" and "The simpler, the better" approach was principal.

Background:

The Soft Materials and Matter Transport (SMMT) research group in the Materials Science and Engineering Department at ISU introduced me to their work of undercooled liquid metal core-shell particles (FM Particles) which offer a heat-free pathway for metal processing on any heat-sensitive substrates, heat-free soldering, and are inexpensive to synthesize (Figure 1a). By exploiting the benefits of these undercooled core-shell particles in association with piezoresistive micro electromechanical systems (MEMS), the presented design creates an elegant high efficiency, frugal sensor technology. In comparison to intricate electronics designs, piezoresistive MEMS devices simply create connections between mechanical stimuli and resistivity via the piezoresistive effect.[1] Note that the main argument of this paper lies in exploiting the differences between paper-based MEMS utilizing silver paste (Standard), and emphasizing the benefits of introducing this research group's FM particles into a new MEMS Design.

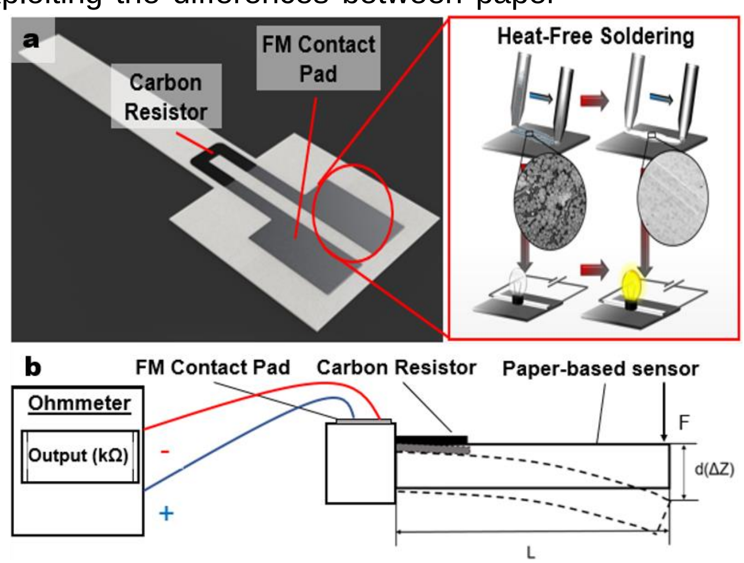

Figure 1. (a) Design of paper-based sensor & heat-free soldering. (b) Method of calibration. Dotted line = Deflected cantilever arm. d(ΔZ) = Deflection.

MEMS Sensors Fabrication:

Work on this project started with creating a sensor design and subsequently fabricating a working model. In fabricating a paper-based sensor, a precise, programmable paper cutter was used to make various sensor architectures (and shapes) and then bonded the piezoresistor and FM contact pads to the paper substrate via a laser cut stencil (Figure 1a). To introduce the mechanism of piezoresistive effects, a simple cantilever arm architecture was employed (Figure 1b). For materials, I chose low-cost elements such as various types of paper, carbon ink, and FM particles. While the principle of operation is conceptually simple, I explored the wide range of tunability (of sensor features) within the control space. I did this by varying the features of the paper substrate (cantilever base), piezoresistor (carbon ink resistor), circuit connection points (contact pads), and recording the relative changes in sensor sensitivity (Figure 3). In Figure 2, you can see the systematic decomposition of the MEMS Design, which I will be referring to as the control

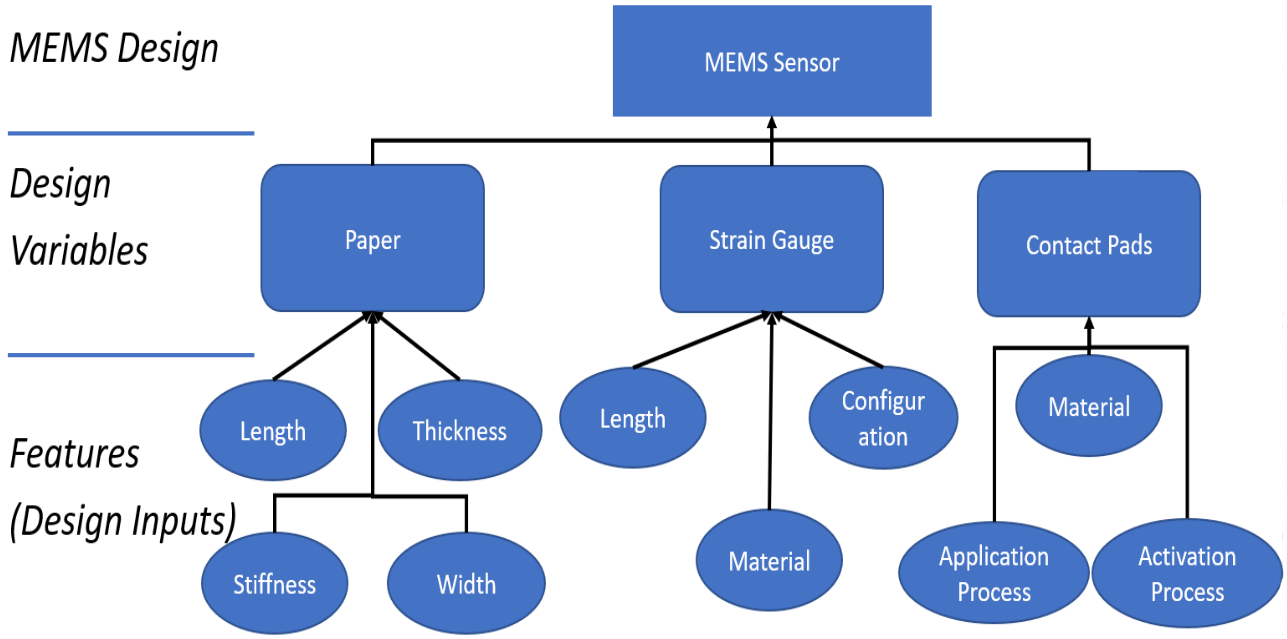

Figure 2. MEMS Sensor Design System Decomposition. Also referred to as "MEMS Control Space"

space.

<u>Design of Experiments Methodology:</u>

Next, a series of calibrations and experiments for various sensor configurations were conducted to investigate piezoresistance, MEMS sensor tunability, as well as the sensor's functionality and utility. I employed a structured systems engineering approach and focused on a single Design Variable or subsystem at a time (Figure 2), while varying design features iteratively and recording the changes in sensor sensitivity (resistance/deflection). The general framework of this investigation can be summarized as a hierarchal structure. Working down the hierarchal tree: A "set of experiments" refers to a group of experiments conducted within a Design Variable or subsystem, an "experiment" refers to sample (sensor configuration) where the features are varied, and "experimental runs" are a series of measurements conducted on a sample where the deflection is varied (Figure 2). Some terms I will use interchangeably working down the hierarchal tree include global sensitivity (i.e. MEMS Design sensitivity), sensor sensitivity calibration or impact (i.e. Design Variable calibration), and sensor sensitivity (specific response of Design Features configuration). At each level of this experimental framework, we investigate the overall responses of these experiments and gain understanding of this MEMS Design holistically.

Paper Tunability:

Firstly, investigation into the piezoresistive effect and explored tunability of the MEMS sensor with relation to the Paper Subsystem (Design Variable). I connected the sensor in series with an ohmmeter and then applied force at the end of the beam causing the piezo-resistor to elongate (strain). Behind the sensor, a ruler was placed the record the position of the cantilever beams free end. For each sample and set of experiments, the initial position of the free end was set as the datum. Throughout these experiments, a micro-manager was used to apply a precise deflection to the beam, and the deflection experienced (dΔZ) was recorded as a function of position initialized at the datum previously set. Each time the deformation was changed, the resistance reading was recorded via the ohmmeter. Data analysis revealed a linear relationship between deflection experienced by the cantilever beam from constant force applied, and relative change in electrical resistance, the piezoresistive effect (Figure 1b).[2] This relationship (slope) we define as the **sensor sensitivity (ΔR/ΔZ).** In Figure 3, we observe two experiments of higher impact (on sensor sensitivity) which we will be focusing on in this study. These are change in beam length and change in beam thickness.

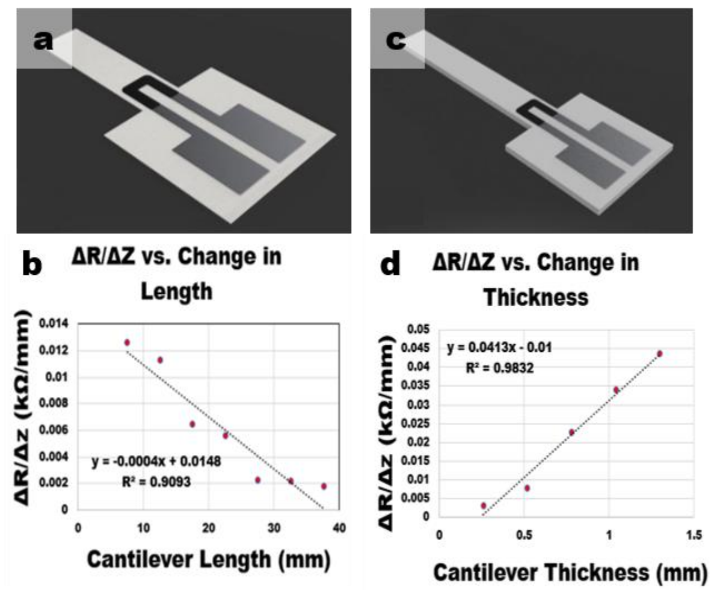

Figure 3. (a-b) Experiment 1: sensor length is varied. (c-d) Experiment 2: sensor thickness is varied. Slope = sensitivity of sensor related to change in beam dimensions.

Strain Gauge Tunability:

While investigating the tunability of the Strain Gauge Design Variable, the same procedure and experimental set-up as the paper sensitivity calibration in the section above was used. Instead of varying beam dimensions, strain gauge length was varied. Generally, this had low impact in the subsystem calibration and global sensitivity. The only noticeable results concluded that increasing the length increased the surface area of the "sensing control surface" which assists in capturing the mechanical responses more accurately. Further investigation was halted as a result and the strain gauge was held constant throughout the remainder of this study. It is worth mentioning that configuring the strain gauge subsystem can lead to many other sensing capabilities and applications, but this investigation is outside the scope of this study.

Contact Pads Tunability:

If you recall from the background section, the main argument of this study is to exploit the benefits of using FM Particle contact pads in MEMS in place of Silver Paste contact pads (Standard). In the Contact Pads subsystem, we focused on the material feature and conducted the exact same series of experiments as described in the Paper Tunability section (Figure 3). From this, we derived the same sensor calibration curves, but with Silver Paste instead of FM contact pads (Figure 4 (b-d)).

Once these tunability calibrations curves were done, further investigation was conducted into the intrinsic properties of the FM Particles and contact pads. The application process was kept constant throughout the study. Utilizing the heat-free metal processing capabilities of the FM Particles[3], an ink was synthesized for ease of "painting" contact pads onto the paper-base. The same standard ink-stencil application process was employed[1]. Considering the contact pads as a bed of core-shell metal particles, their micro-structure when solidified influences the transference of electrons. This phenomenon is yet to be studied. The solidification or "Activation Process" (Figure 2) of these meta-stable particles (phase-change particles) is simply applying a normal force to the bed of particles[3]. In this study, we have two different methods of doing this, applying differential point forces across the bed (Scratching Method) and applying a constant normal force (Rolling Method). To test the influences of these methods, an experiment was conducted to record the resolution of the sensor with each activation method. While moving up through different

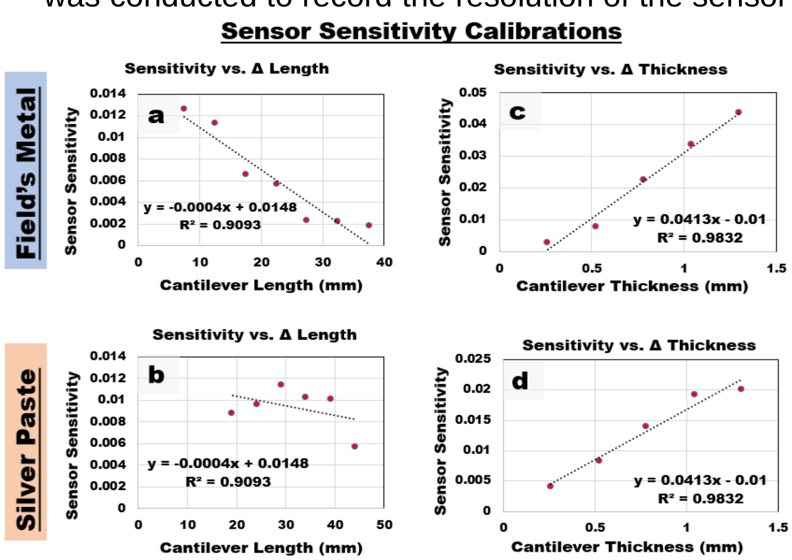

Figure 4. Sensor Sensitivity Calibrations,

FM Contact Pads vs. Silver Paste Contact Pads.

(a-c) Sensor Calibration 1: Field's Metal Results.

(b-d) Sensor Calibration 2: Silver Paste Results.

Slope (y) = Global Sensitivity Parameter.

R^2 = Global Sensitivity Parameter

resolution ranges, the low and highest values were recorded and studied. The results are revealed in Figure 5.

Resolution Setting	Rolled Method	Scratched Method
	Resolution Readings Range (min – max)	
200Ω	130.00 - N/A	2.53 - 25.53
2000Ω	81.33 – 1549.00	3.66 – 27.00
20kΩ	0.12 - 2.14	0.00 – 0.40
200kΩ	0.00 - 2.03	0.00 – 0.00
20MΩ	N/A - N/A	0.00 – 0.00

Figure 5. FM Contact Pads Resolution Study,

Rolled Solidification Method vs. Scratched Solidification Method.

Resolution Readings Range =

[Min resistance reading recorded] – [Max resistance reading recorded]

Force Calibration and Sensor Functionality:

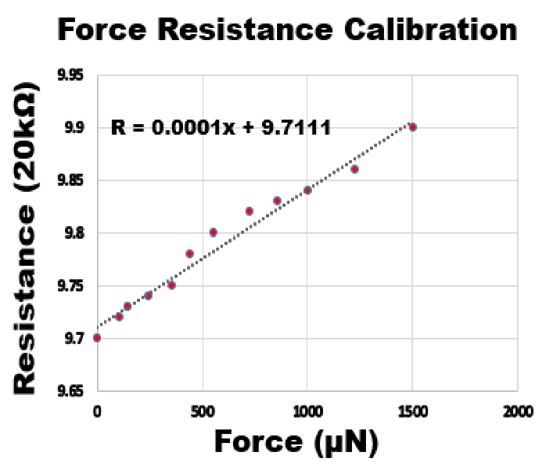

Figure 6. Sensor Force Resistance Calibration

After results from tunability calibrations, force calibrations where completed. Utilizing a similar experimental set-up as Figure 1.b, the sensor free end was placed on a high precision balance. Pre-measured weights were placed on the sensor free end, then the resistance and force readings were recorded from the multi-meter and force balance respectively. Figure 6 showcases the relationship between force applied and change in resistance, revealing a linear relationship. force calibration with Chromatography Paper-base was also conducted (Stiffer Paper). Applying skills in computer science, circuitry, and engineering, efficient sensor signal processing [ΔR/ΔV] was accomplished by employing an inexpensive, micro-computer configuration. Furthermore, a Self-Automated Force Calibration System was developed, fitted with code to calculate resistance based on a force input (force applied to sensor) and display precise, live, raw data on a computer screen. By fitting the code and interface calibration system further, force mapping of the sensor surface is accomplishable, along with many other data collection, representation, and analytical methods. Integration of the sensors with computer interfaces opens many possibilities for sensor functionality, some of these possibilities were explored to showcase the utility of the MEMS Sensor Design.

Keithley Data (Is it Ohmic?):

To showcase consistency of our Paper-Bases MEMS sensors relative to ohmic behavior, mass data sets of I-V curves for various sensor samples were done. The set-up for this series (YSR-1-25A Series) is shown by Figure 7 below. A Table of the sensor samples used are also below in the table (Figure 8). This set of experiments utilized a voltmeter (Keithley) connected to a sensor sample (refer to Figure 7). On the free end of the sensor, a micro-manager and reference ruler were placed to consistently measure deflection. Throughout this set of experiments, the sensor sample was varied where each sample had one or two features changed as described in Figure 8. For each experiment, a series of five runs (with 10 sweeps) where collected measuring the current as the voltage was varied from -0.5V to 0.5 V through the connected sensor sample. Throughout the 5 runs, the beam was deflection was varied from 0mm to 20 mm in 5 mm increments. The experimental control was the ohmic response (I-V curve data) a reference 100kohm resistor. Essentially, the test was to see how well the sensors' response from the voltmeter matched that of the reference resistor. In other words, "Is it ohmic?". Results revealed responses relating to consistency and reliability of sensors. In some results, it seemed that capacitance build up in some section of the sensor. In some other cases with samples utilizing Silver Paste Contact Pads, there was high inconsistency with signal processing and almost no relation to the experimental control. Generally, almost all of the samples utilizing FM Contact Pads mimicked the exact ohmic behavior as the experimental control. Therefore, revealing that our sensors abide by the ohmic law, and are more consistent and reliable in comparison to the standard utilizing Silver Paste Contact Pads.

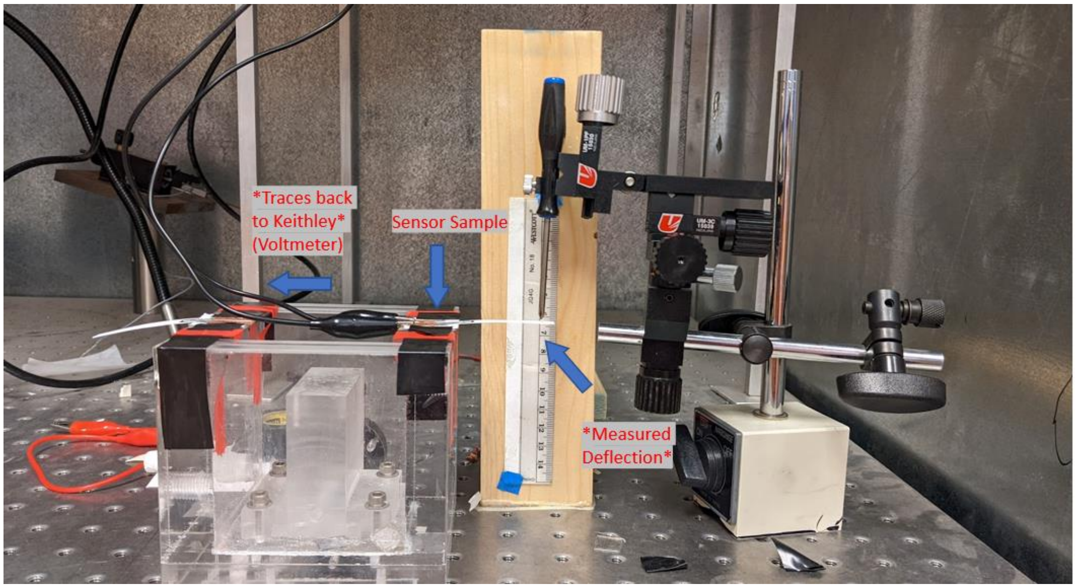

Figure 7. Voltmeter "Is it Ohmic" experimental set-up.

Sensor sample connected to Voltmeter, Micro-manager and Ruler placed to control & measure deflection.

Sample	**Contact Pads**	**Resistor Length**	**Beam Thickness**	**Beam Width**	**Beam Length**	**Quality (Age)**	**Quality (Integrity + Connection)**
YSR-1-25A	FM Particles (Scratched = Default)	8 mm	0.2 mm (1 layer)	9.5 mm	45 mm	Oldest	Lower
YSR-1-25B	Silver Paste	8 mm	1 layer	8 mm	45 mm	Oldest	Lower
YSR-1-25C	FM Particles	13 mm	1 layer	8 mm	45 mm	Old	Mediocre
YSR-1-25D	FM Particles	8 mm	1 layer	12.5 mm	45 mm	Fresh	Higher
YSR-1-25E	FM Particles	8 mm	0.60 mm (3 layers)	10.5 mm	45 mm	Old	Lower
YSR-1-25F	Silver Paste	8 mm	1 mm (5 layers)	8 mm	45 mm	Old	Mediocre
YSR-1-25G	FM Particles (Rolled)	8 mm	1 layer	8 mm	45 mm	Fresh	Lower

Figure 8. Sensor Sample Classifications used in Voltmeter experiments.

Utility Analysis and System Analysis:

Viewing the Design of Paper-Based MEMS through a holistic lens, a general utility analysis and system optimization was completed. Below in Figure 9, a Hybrid-hierarchal decomposition of the DOE system reveals the interfaces between various sub-systems (Red = Behavior Variable; Green = Coupled Behavior Variable). In the scope of this study, global sensitivity is defined as the impact of a change (or behavior) on the overall MEMS Design and Utility of Sensor.

While this study focuses on Paper-Based sensors, a focus was placed upon exploring paper's tunability with the cantilever beam dimensions, and their respective effect on sensor sensitivity. Since our Paper-Based MEMS used FM Particles, a true metal processing, instead of Silver Paste, a silver flakes and epoxy mix, there was noticeable benefits and higher utility for this MEMS Design. These investigations revealed many benefits to introducing FM Particles into a MEMS Design. Such as high tunability of sensors, heightened sensitivity with FM contact pads, addition of attributes and capability, as well as higher reliability and robustness. The highly efficient, standardized, heat-free manufacturing technique for these sensors is also a design strength supplementing the design's utility as a low-cost, green, disposable technology. Certain attributes of the FM Particles and application methods, also opens conversation about bulk systems as well.

Furthermore, literature review of the current state of MEMS and Piezo-resistor applications[2] revealed many pathways for highly efficient MEMS, each with a different focus and function. Inspired from modern MEMS applications, many designs for multi-functional and three-dimensional (3-D) force sensors were developed to showcase the versatility of this green technology. While developing a multitude of designs, the Paper-Base, Strain Gauge Configuration, and Sensor Architecture were the main components of the design optimization space. Optimization parameters included capability, risk, cost, time, and plausibility. For each approach, a rating scale of 1-10 for the optimization parameters was applied, evaluated, and assigned a value describing its utility and strength as a design. [More info on this can be found in "Review of MEMS Project" Ppt.]

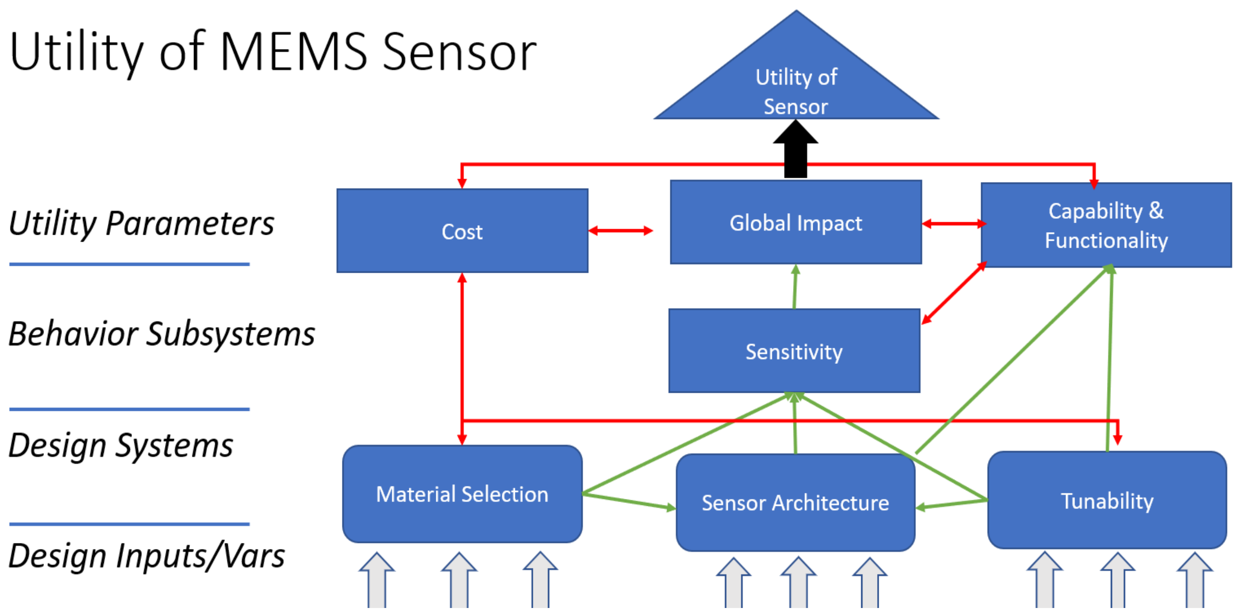

Figure 9. MEMS Sensor Utility Decomposition. Also referred to as "MEMS Design Space"

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Discussion/Conclusion:

In this study, various sensor configurations were investigated to showcase the high tunability of the MEMS Design and paper-based sensors. Paper's tunable features (folding/cutting/stacking), in culmination with FM particles, allows for endless possibilities in the design space for modern applicability and functionality. As Joseph Doll[2] summarized in his work, piezo-resistors is a natural mechanism that finds use in many micro-applications. Xinyu Lui's Paper-Based Piezoresistor's[1], is an example of simply designed MEMS that is as functional as many modern force sensors, while being low-cost to manufacture and low environmental-impact. Generally, piezoelectric devices are used to support a larger mechanism with single, high precision, micro-operations such as micro-biotics, micro-actuators, and torque sensing. They are also used as micro-sensors to detect specific chemical contents in applications like micro-fluidics and small-scale biosensors. The proposed paper-based MEMS design attempts to revive an old technology of piezoresistive cantilevers and other piezoelectric devices, and bring it into modern-day, up-scaled, applications. As proved in this study, the sensor design can be manipulated in various ways within the design space to achieve a variety of broad and specific uses. The paper-based MEMS design may also interface with other piezoelectric device applications for a single, multi-functional, device. An example of a proposed design: a paper-based, 3-D, multi-surface, force sensor with chemical sensing (micro-fluidics) capabilities, able to characterize the force surface interactions of field, as well as its chemical contents.

Throughout this project, skills in experimental design, collecting and applying deep knowledge of diverse fields of study, systems thinking, and other engineering techniques guided the delivery of an attainable product. By employing the intrinsic solidification ability of undercooled FM Particles, via external mechanical or chemical stress, a heat-free manufacturing technique was developed for fabricating highly-tunable, multi-dimensional, multi-functional, paper-based sensors[3]. These disposable paper-based piezoelectric devices attempt to challenge the status quo of over-complicated and expensive technology systems. An interdisciplinary perspective was employed while, conceptually, sustaining an affordable and simplified approach with materials, manufacturing methods, and simplified systems. These affordances offer lower-cost and "greener" alternatives to current technology's carbon footprint and inflation in the STEM technological industry.

Future Work:

Future research includes integrating this MEMS design with other fields of study and technological capabilities for a robust, elegant device. For example, training a Machine Learning model with calibration data sets, of tunable sensor features and respective effect on sensitivity, would allow for ease in optimization of sensor design and design of experiments toward a desired sensor design. As well as many data extrapolative methods. For aeronautical application, designing a small lightweight three-dimensional force sensor (or gyroscope) could characterize aerodynamic forces and flow. In addition, Micro-fluidics (chemical sensing) capabilities could characterize the chemical nature (of fluid or gas) of a flow of an environment. This path has applicability for low-cost geospatial assessment methods, small scale performance testing, automated flight path corrections of drones, etc.

Implementing triboelectric generators or piezoelectricity as a flexible power source is a pathway toward achieving self-sustainability for smaller carbon and chip footprints. This would lower waste impact on the environment. An example of a integrating the MEMS design into a modern day-to-day use includes attaching a sensor at the base of a shoe to extrapolate dynamic and kinematic data about an individual's walking and posture. This path can offer applicability in kinesiology, health, and any other studies of motion and forces of a body or element. As you can see, the proposed MEMS design has endless possibilities for modern-day utility.

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