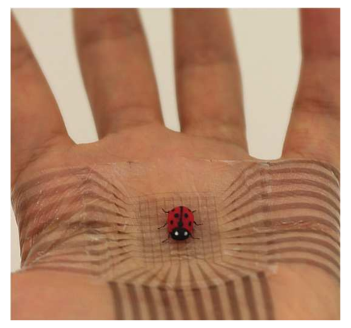
Optimization Methods for Designing Wearable Devices

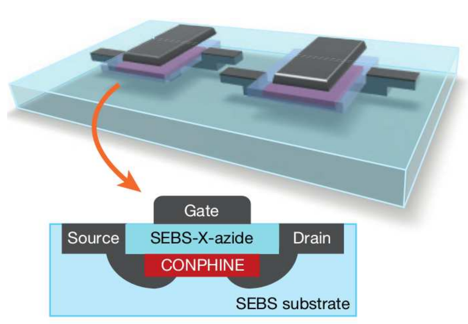
Reza Rastak & Christian Linder

Introduction

Researchers around the world are creating the technologies to produce efficient and robust stretchable and wearable electronics. For example, a new method is recently developed to create stretchable transistor arrays for wearable applications [1].

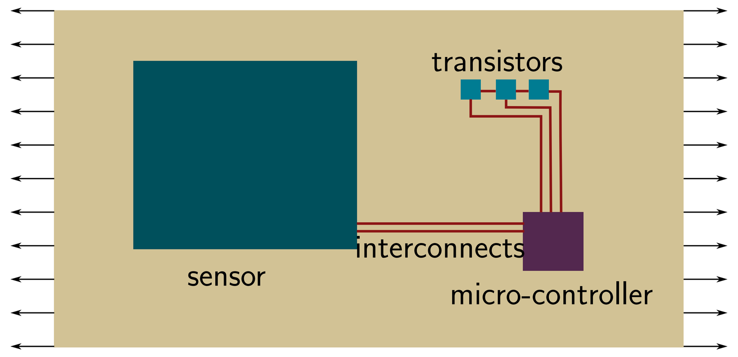

transistor array attached to bent wrist


stretchable sensor attached to human palm

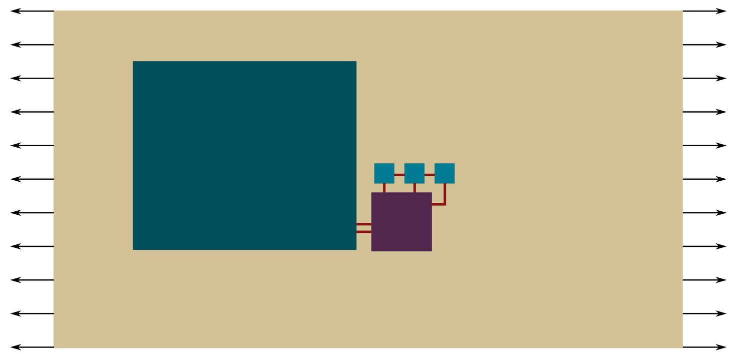


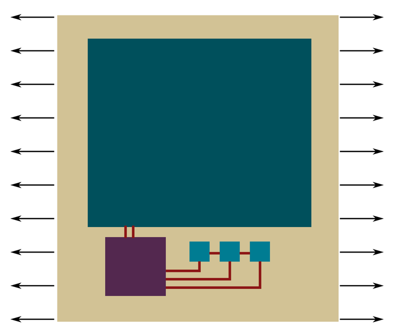
Intrinsically stretchable transistor

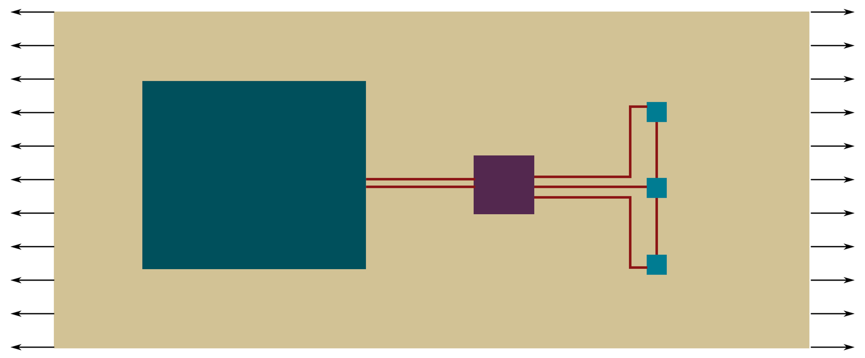
Still, many aspects of designing a fully stretchable circuit are challenging. For example, conductors and semi-conductors are usually much stiffer than the substrate and have lower stretchability. This means that the elastic substrate has to absorb most of the mechanical strain in order to protect electronic components. The location of the components and their distance has a big effect on the performance of the device. In general, large substrate and greater distance between electronic components would result in better stretchability of the whole system. However, electronic circuits need to be compact and space efficient. Also large distance between component increase the length of the interconnects and increases internal resistance of the device. It is generally hard to balance the need for stretchability, space-efficiency, and better electrical properties.



Original simple design

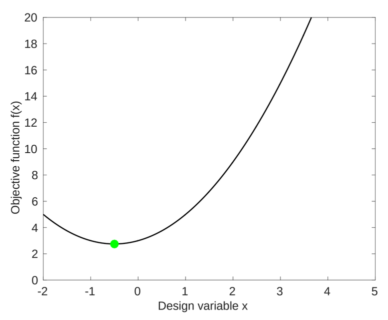

Minimize interconnect length

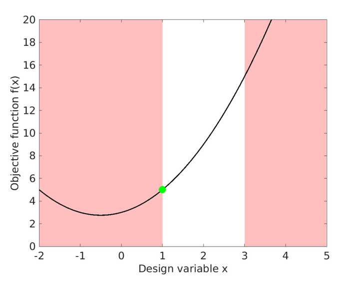

Minimize overal device size

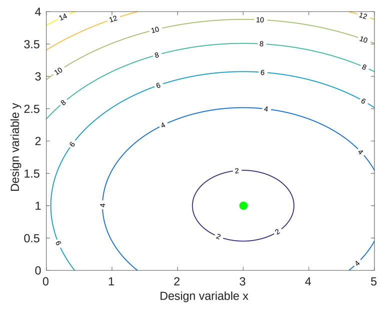

Minimize stress localization

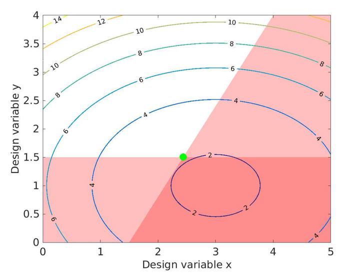
Optimization using particle swarm

In general, optimization refers to the methods for finding design variable that minimize a give function, called the objective function. In addition to the objective function, the optimization can restrict the possible values of the design variables. These restrictions are called constraints. The concept of the objective function and the constraints can be seen for one dimensional and two dimensional cases.

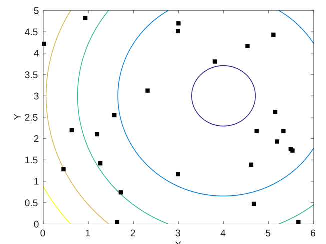

one-dimensional objective function

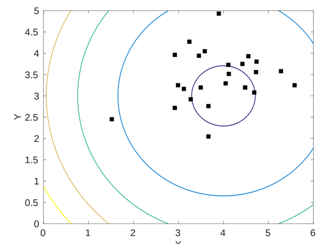

one-dimensional objective function with constraints

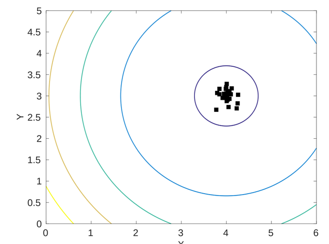

two-dimensional objective function

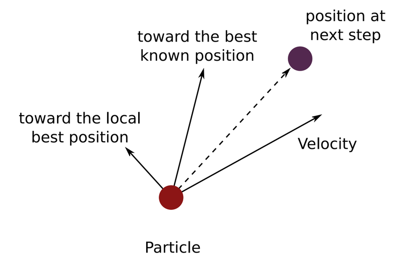

two-dimensional objective function with constraints

Particle swarm optimization is well-known general optimization methods. It has inspired from the collective brain of small insects such as ants and bees. A swarm of particle are chosen each represent a design. The particles compute the objective function and check for the constraints. At each step, the particle that finds the best response communicates this information to other particles. Each particle uses the swarm information and the information from its memory at previous step to calculate its next trajectory. The particles eventually converge to the global optimal point of the domain even if there are multiple local minima.


particle swarm iteration 1


particle swarm iteration 5


particle swarm iteration 10



calculation for next step

In this study:

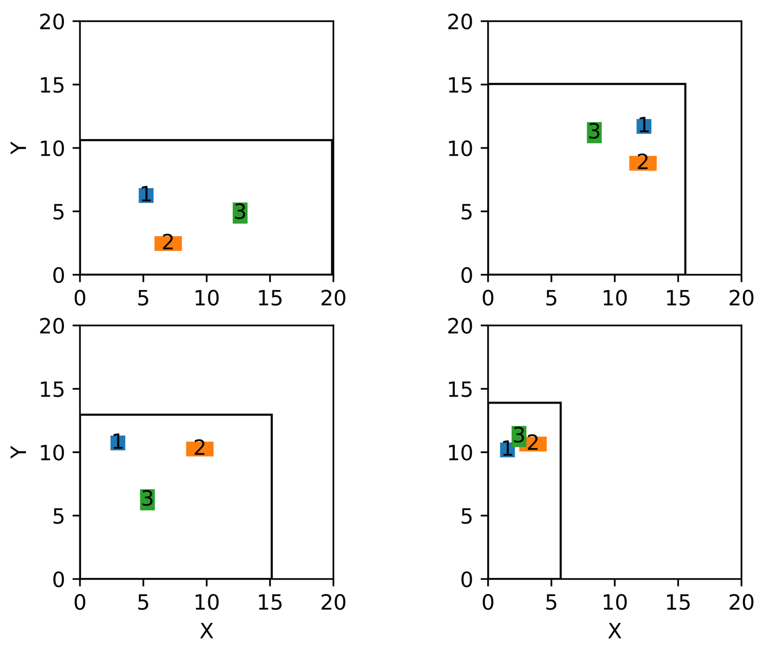
- **Design variables**: The dimensions of the circuit board and the location of every component.
- **Objective function**: We optimize the circuits to have the minimum surface area.
- **constraints**: We ensure that each component does not exceed its mechanical damage limit and they don't physically overlap

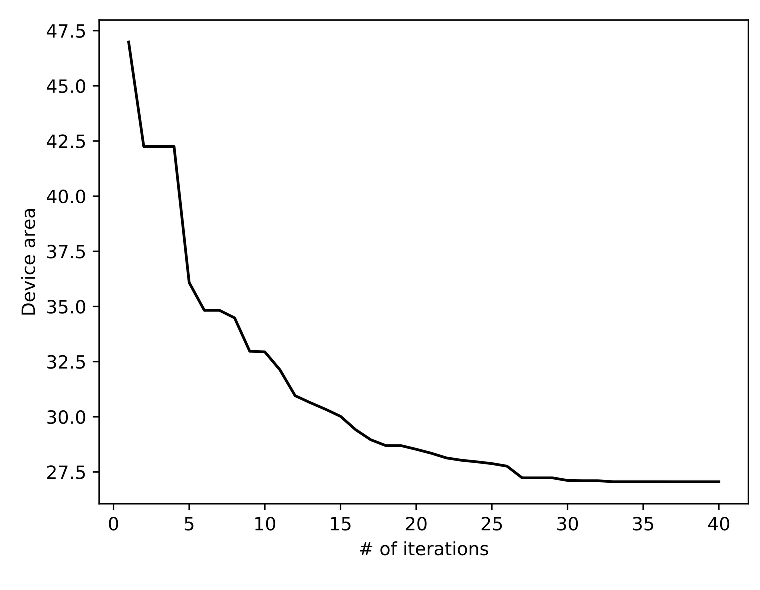
Results

To demonstrate the capabilities of the optimization method we chose three components with the following properties.

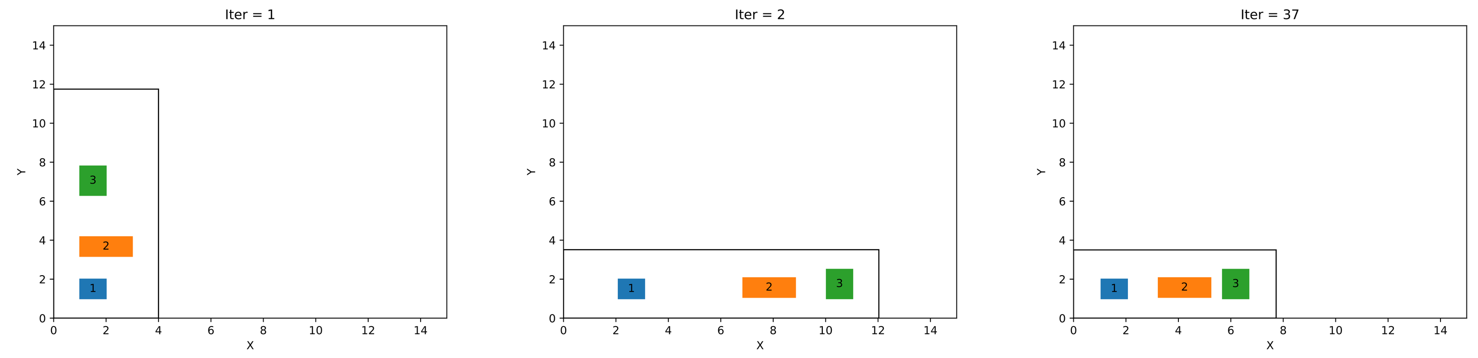
component #	width	height	Young's Modulus (E)	Max. strain	color
1	1 mm	1 mm	0.5 MPa	10 %	blue
2	2 mm	1 mm	1.0 MPa	20 %	orange
3	1 mm	1.5 mm	0.6 MPa	20 %	green

The results show that the algorithm is able to move components to their optimal location and gradually reduce the size of the total device. The objective function (area) decreases continuously until it becomes stable. As seen in the figures, individual designs may be faulty for having component overlap, but the best designs always perform good. The finite element simulation is only run for the components without any overlap.


Four random initial designs



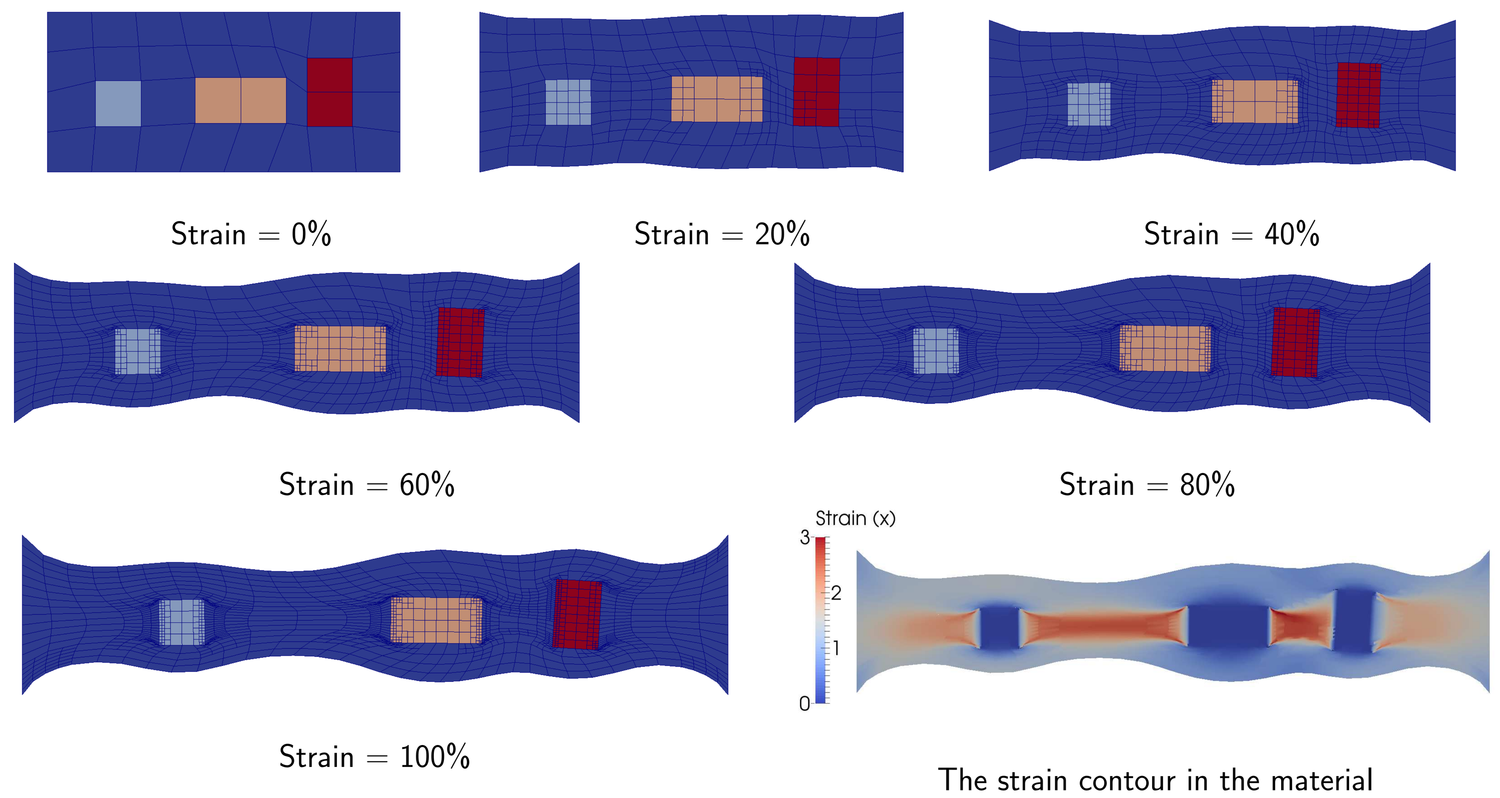
The area goes down as the simulation continues



The evolution of the best design for (from left to right) iteration 1, iteration 2, and iteration 37

Finite element simulation

During optimization, at every step and for each particle, a two dimensional finite element simulation is performed. Using the geometry of the device, a quadrilateral mesh is create with the software **CUBIT**. The resulting mesh is then supplied to the finite element code **DealFEM**. This program is able to produce accurate simulations with local mesh refinement as seen in the next figures. The **neo-hookean** material model is used to produce these results.



The strain contour in the material

Future work

There are many future directions for this optimization study.

- Test the optimized designed with real materials.
- Improve the efficiency of the optimization algorithm
- Develop a analytical theory about stretchability optimization.
- Extend to three dimensional geometries.

References

[1] S. Wang et al. (2018). *Nature* 555(7694):83-88.
[2] J. Kennedy & R. Eberhart (1995). *Proc. Int. Jt. Conf. Neural Netw. IEEE* 4:1942-1948.
[3] C. H. Li et al. (2016). *Nat. Chem.* 8:618-624.
[4] J. Xu et al. (2017). *Science* 355(6320):59-64.
[5] Y. Wang et al. (2017). *Sci. Adv.* 3(3):e1602076.
[6] L. Jin et al. (2018). *Proc. Natl. Acad. Sci. U.S.A.* 115(9):1986-1991.
[7] W. Wang et al. (2021). *Nat. Electron.* 4(2):143-150.
[8] G. Chen et al. (2019). *Matter* 1(1):205-218.

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