Design for manufacturability of soft sensors with discretized stiffness gradients.

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Summary: Sophisticated and mechanically robust soft sensor must be created through a combination of manufacturing methods, including laser machining, chemical etching, 3D printing, hot embossing, and material casting. As such, the design of soft devices is, by necessity, the design for manufacturability (DFM).

Our specific goal is the creation of soft sensors for wearable motion capture [1], but the design approach is generally instructive for the spectrum of manufacturing approaches in soft biomimetic robots [2]. We introduced the use of different materials in what we call ”discretized stiffness gradients” to mechanically interface the extensible elastomer to inextensible electronics and textiles. Mechanical gradients are a salient feature connecting tissues of vastly different elastic modulus, such as in cephalopod beaks [3]. Ultimately, the design philosophy is to approach the problem in two phases: first, generate a sensor in CAD software; second, deconstruct the sensor to generate the molds.

The soft sensor we use here is a liquid-metal-in-elastomer type, Fig. 1A. The sensing element is a microchannel formed internally to an elastomer matrix via casting and laminating two halves of the device. We realize the discretized stiffness gradient by including four distinct materials spanning seven orders of magnitude in elastic modulus: from soft silicone ($E \approx 10^4$ Pa) to stiff silicone (10^6 Pa) to velcro (nylon, 10^9 Pa) and finally to electrical wiring (copper, 10^{11} Pa).

The molding approach generates the desired features as 3D printed molds, casts silicone rubber in the 3D printed molds, and laminates layers of cured silicone rubber with a thin layer of uncured rubber as the adherent. Mold design features include polyester films to ensure consistently flat and smooth rubber surfaces, alignment features for accurate placement of layers during lamination, separate molds for stiff and soft silicone parts, molding lips to ensure clean edges in the cast parts, a vacuum chuck interface feature used to enable spin-spreading of a consistent thin layer of uncured rubber for lamination, and a top press used to evenly load the molds during curing to ensure consistent thickness of rubber layers, Fig. 1B. The design process flow is outlined in Fig. 2.

Future directions of design for manufacturability approaches to soft devices will require formalized rules and the addition of new manufacturing techniques. Each new manufacturing technique will require iteration of device design as well as manufacturing design. Ultimately, the design of soft devices is a practice in design of manufacturing.

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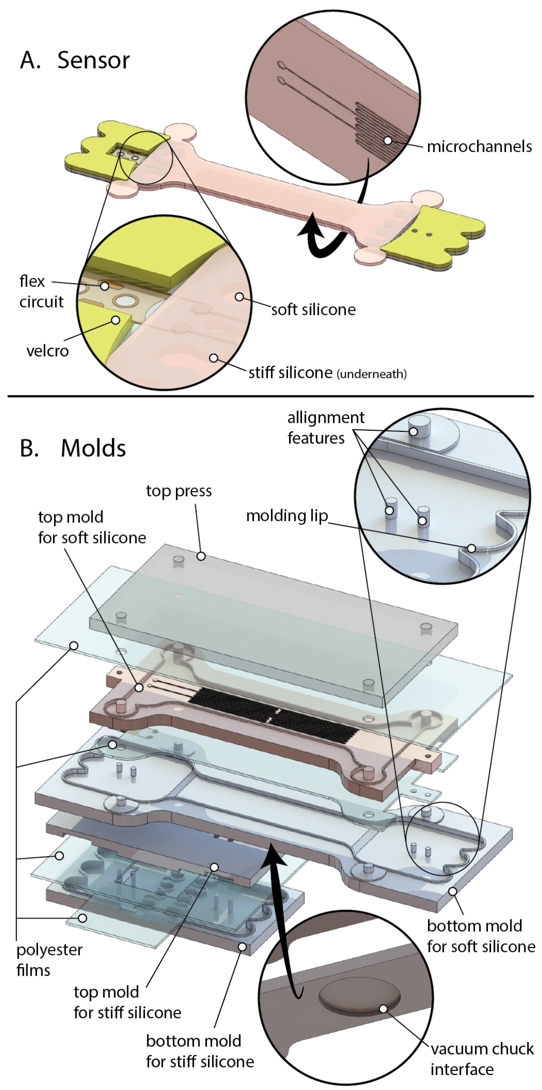

Fig. 1. Renderings of the soft sensor, A, and the set of molds used to make the sensor, B.

[1] Yigit Mengüç and et al. Wearable Soft Sensing Suit for Human Gait Measurement. *under review*, 2014.

[2] Kyu-Jin Cho and et al. Review of manufacturing processes for soft biomimetic robots. *International Journal of Precision Engineering and Manufacturing*, 10(3):171–181, 2009.

[3] Ali Miserez and et al. The transition from stiff to compliant materials in squid beaks. *Science*, 319(5871): 1816–9, 2008.

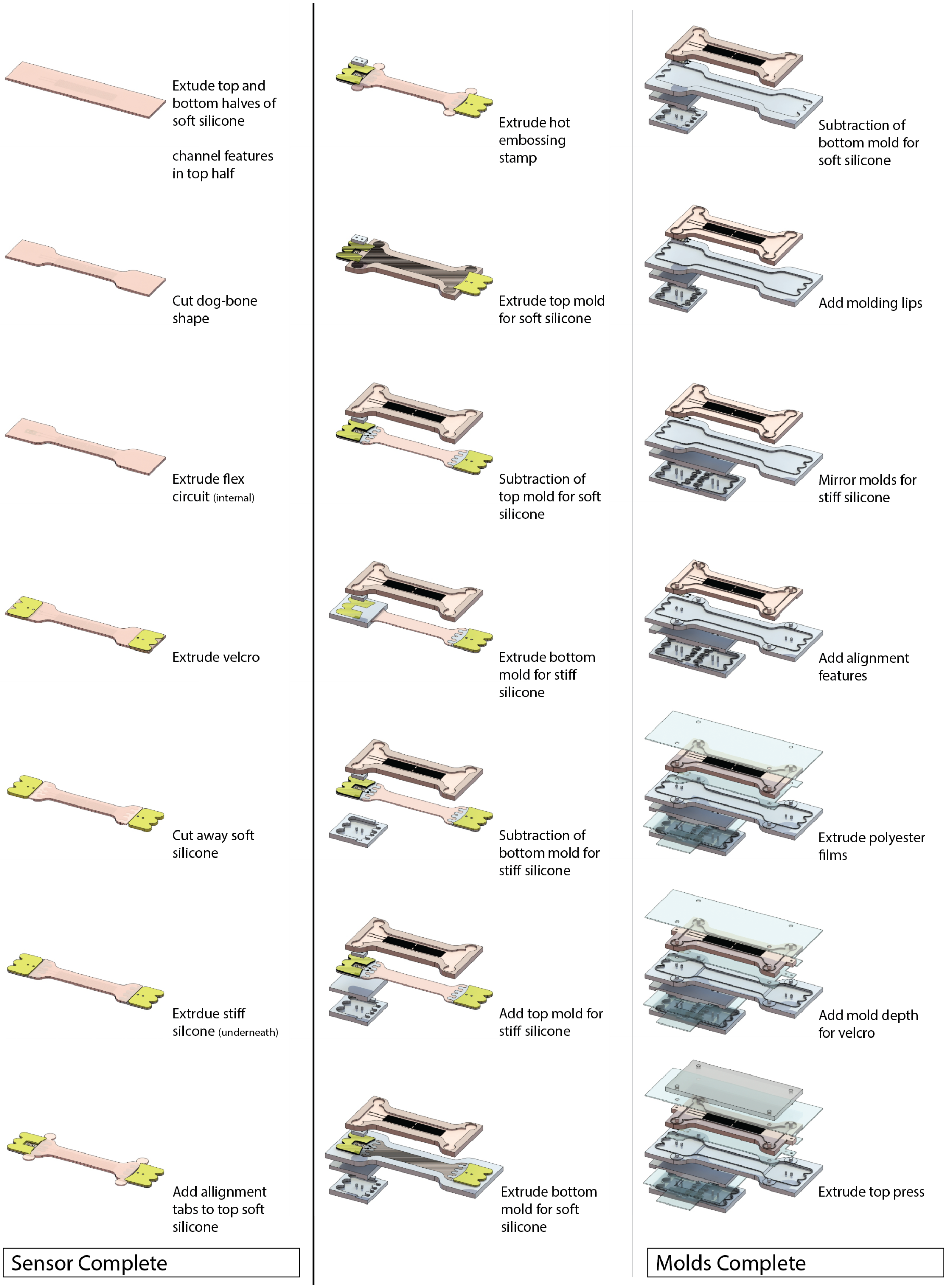

Fig. 2. The design process generates the sensor in full, then deconstructs it to generate the mold parts.