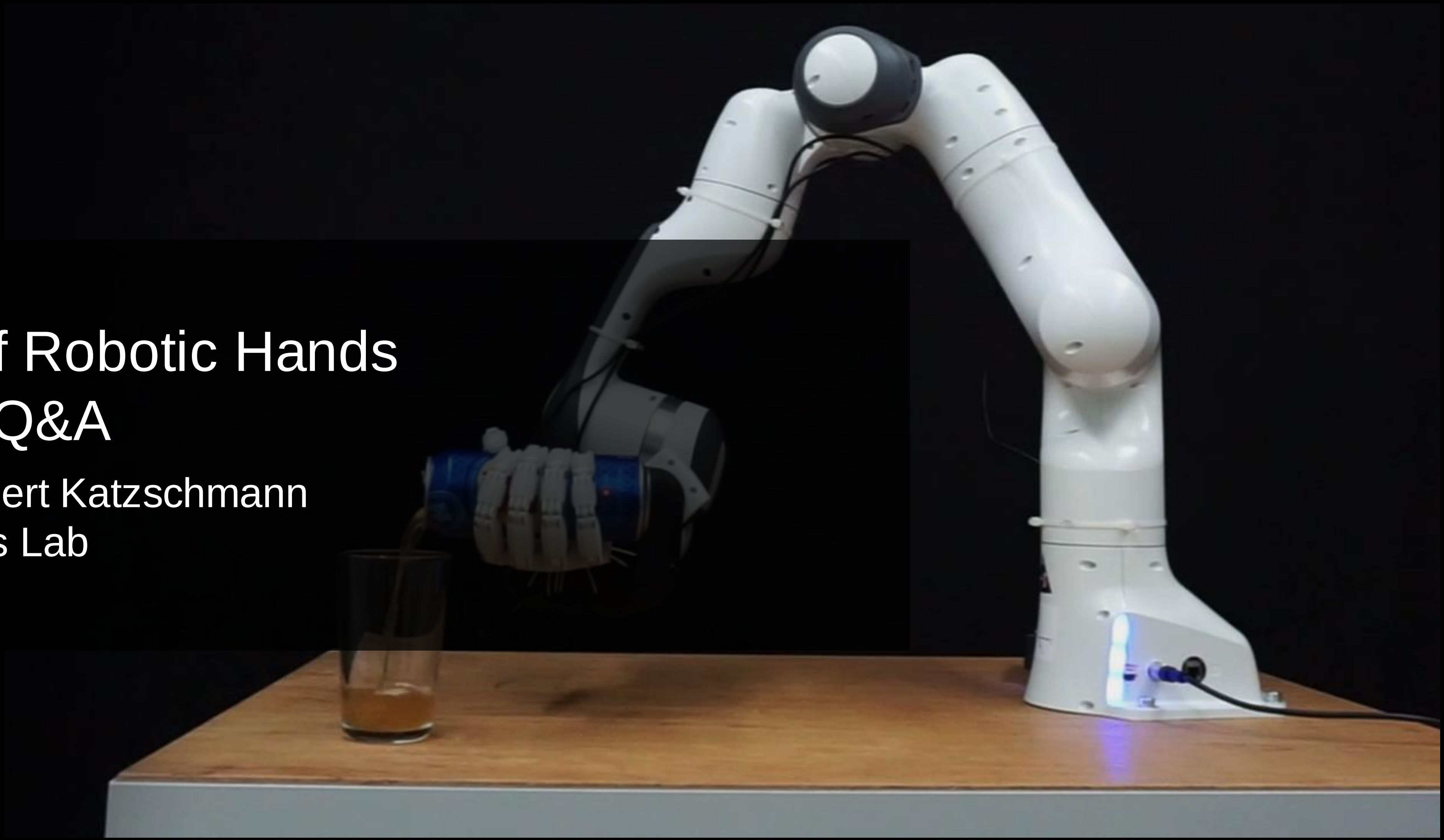


Design of Robotic Hands
Focus & Q&A

Prof. Dr. Robert Katzschmann
Soft Robotics Lab
ETH Zurich

External Design Constraints

Task

- Flight
- Locomotion
- Manipulation
- Medical

Scale

- um (Micro robots)
- mm
- cm
- dm
- m (Elephant-like)

Environment

- Air
  - Low density
  - Gusts of wind
- On ground
  - Power density
  - Rough terrain
- Water
  - Watertightness
  - Density of water
- On or inside a living being
  - Small size
  - Compatibility

Dexterous manipulation task at dm-scale in air or on ground

Swift coordination

Multi-tasking

Fast chopping

Internal Design Constraints

Actuation Modality

- Environment
- Power density
- Power source

Power Source

- Onboard / Tethered
- Energy density

Sensors

- Materials
- Deformations
- Soft / Rigid

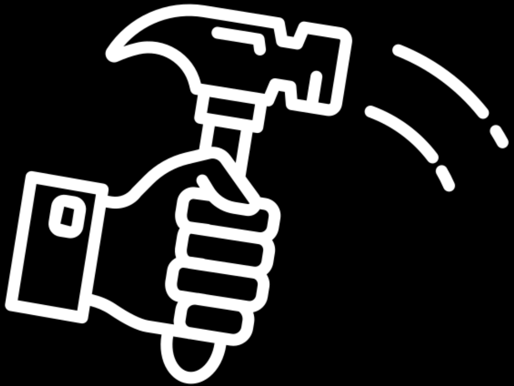
Data + Energy delivery

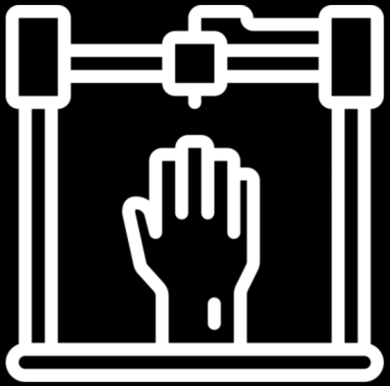
- Routing
- Materials

Fabrication Technique

- Cavities
- Composite
- Integrative or Additive

Example Design Constraints for a Robotic Gripper





Anthropomorphic

- Proportions
- Trajectories
- Proprioception

Robust

- Durable
- Strong
- Reliable

Low-Cost Fabrication

- Reduced number of parts
- 3D Printable
- Simple injection-molding
- Off-the shelf components

Image sources from left to right:
https://ceti.one/wp-content/uploads/2018/09/human-hand_960.png
https://thenounproject.com/icon/construction-3997459/
https://thenounproject.com/icon/3d-hand-print-3511765/

Example: Actuation Modality for a Robotic Gripper

At joint

- Inflating bellows introduce bending motion
- Highly integrated
- Intrinsic compliance
- Bulky

Away from joint

- Move joint with tendons
- Modularity
- Shown to be stronger
- More anthropomorphic

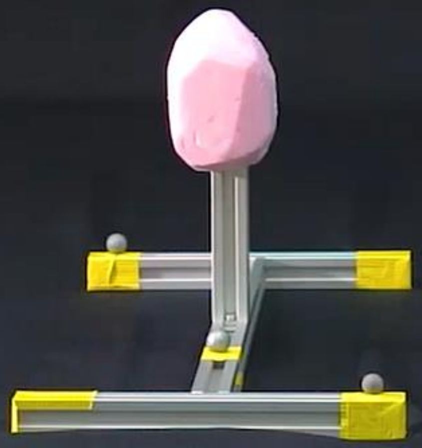
---

1. Images source (from left to right):
2. https://cdn0.tnwcdn.com/wp-content/blogs.dir/1/files/2017/10/SoftRobotics_Picking_Tomato.jpg
3. Tavakoli, M., Batista, R., & Sgrigna, L. (2016). The UC softhand: Light weight adaptive bionic hand with a compact twisted string actuation system. Actuators, 5(1). https://doi.org/10.3390/ACT5010001

Simple Linkage Designs

1. https://www.bostondynamics.com/products/spot/arm
2. https://www.businesswire.com/news/home/20200305005216/en/Dexai-Robotics-Announces-Oversubscribed-Funding-Round-to-Launch-Alfred-a-Robotic-Sous-chef
3. https://everydayrobots.com/technology

Simple Soft Gripper in Air



Appius, Aurel X., et al. "Raptor: Rapid aerial pickup and transport of objects by robots." *2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2022.

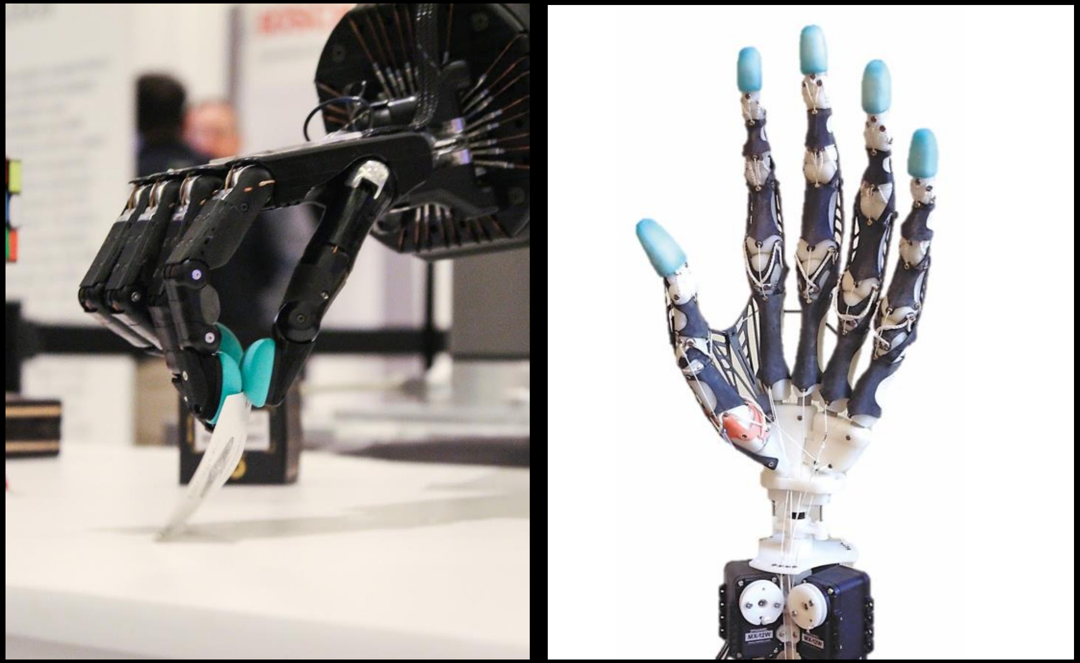
Bauer, Erik, Barnabas Gavin Cangan, and Robert K. Katzschmann. "Autonomous Vision-based Rapid Aerial Grasping." *arXiv preprint arXiv:2211.13093* (2022).

Commercial Gripper Choices: Robust or Dexterous

Robust (and simple)

- Simple design
- Limited capabilities

Image source (from left to right):
- Hand-E Adaptive Gripper, https://www.universal-robots.com/media/1808165/product-picture.jpg
- Franka Emika Hand: https://wiredworkers.io/product/franka-emika-hand/

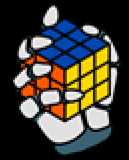


Dexterous

- Highly biomimetic
- Fragile

Image source (from left to right):
- Shadow Dexterous Hand : https://www.shadowrobot.com/dexterous-hand-series/
- Xu, Z., & Todorov, E. (2016). Design of a highly biomimetic anthropomorphic robotic hand towards artificial limb regeneration. *Proceedings - IEEE International Conference on Robotics and Automation*, *2016-June*, 3485–3492. https://doi.org/10.1109/ICRA.2016.7487528

The challenge for an anthropomorphic hand



The Problem

Conventional robotic grippers **lack versatility**

Humanoid robotic hands are **expensive** and complex

Humanoid robotic hands are **complicated** and require programming expertise

The Desired Solution

Versatile & Dexterous
One universal robotic hand for a large range of use-cases with different grasp types and re-orientation motions

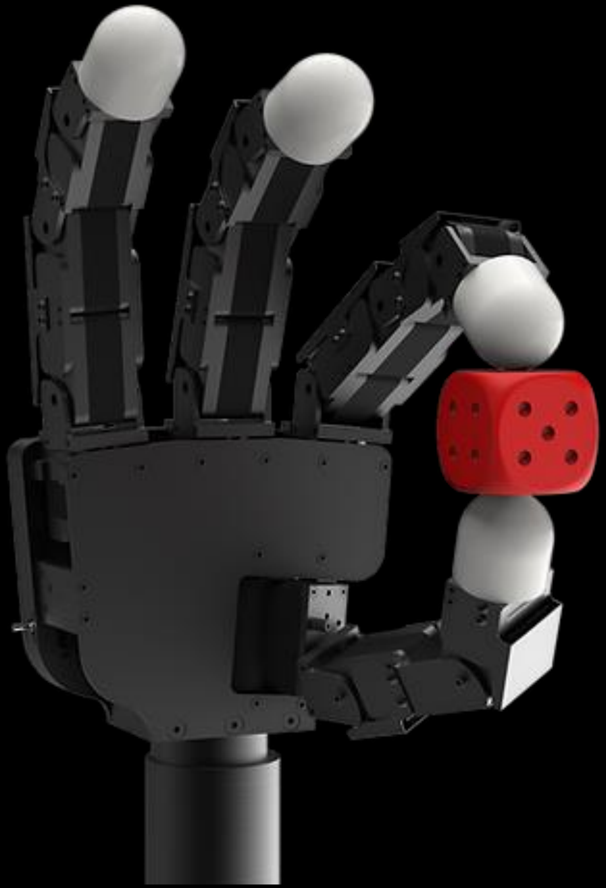
Cost-Efficient
Simplified joint design optimized for easy and cost-effective fabrication

Easy-to-use
Reduced programming effort by using gesture-based control

SoftRobotics Laboratory

Motors in Joints

Allegro Hand

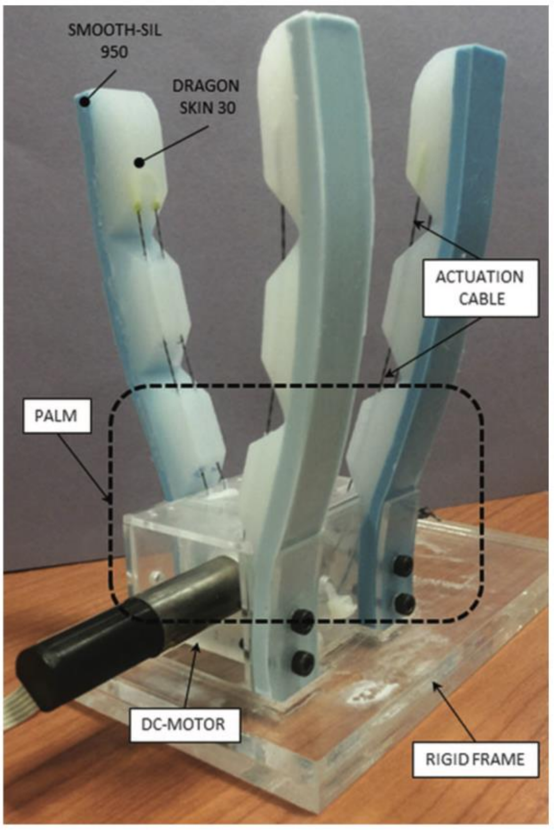


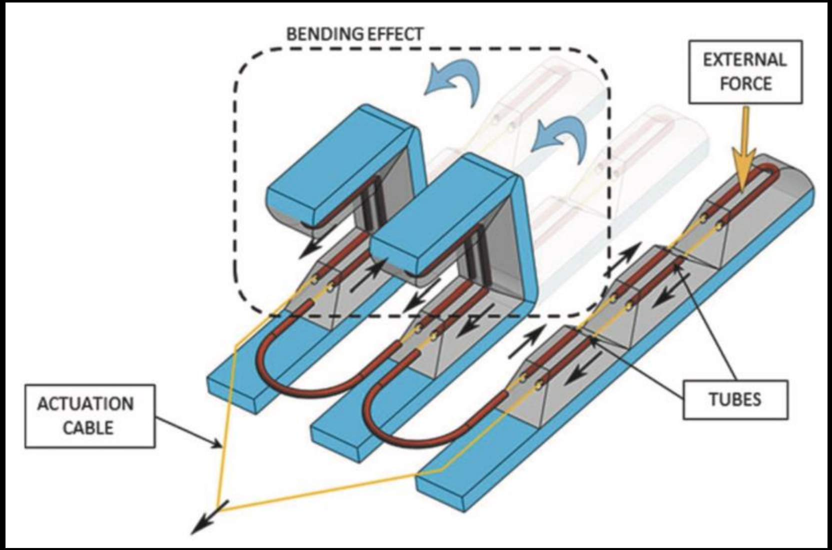
https://www.wonikrobotics.com/research-robot-hand

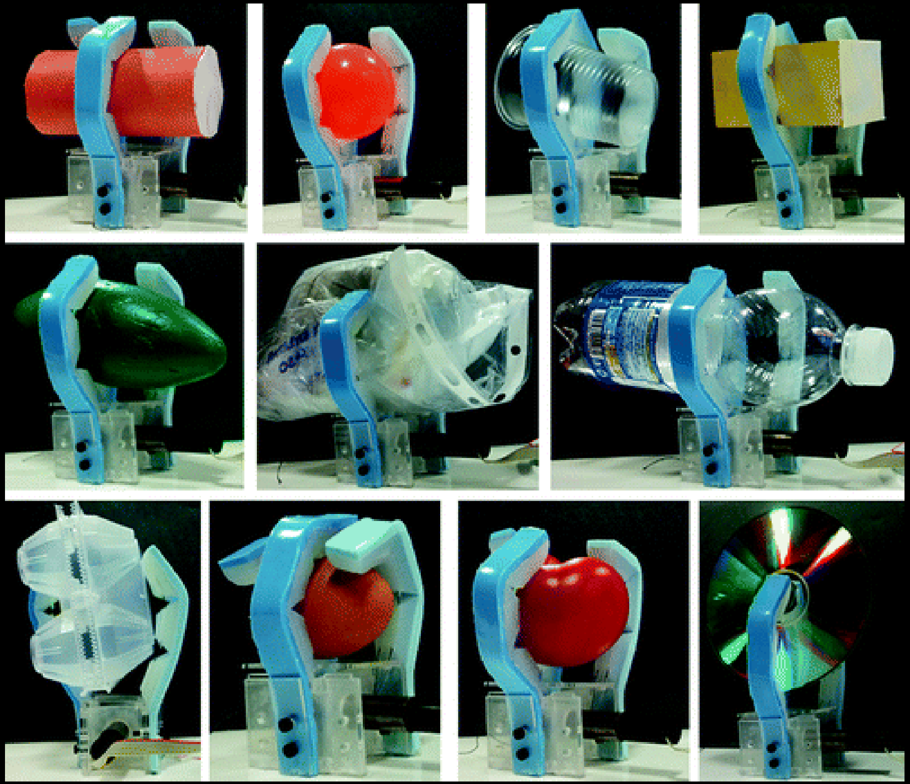
Schunk SVH Hand

https://schunk.com/us/en/gripping-systems/special-gripper/svh/c/PGR_3161

Tendon Driven – Grasping



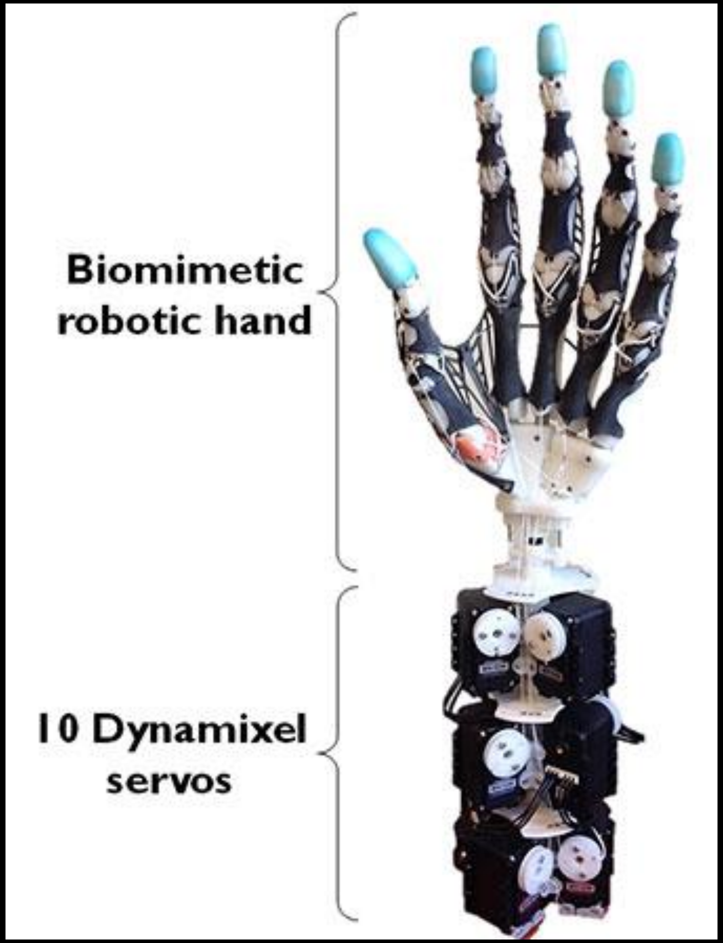




M. Manti, T. Hassan, G. Passetti, N. D’Elia, C. Laschi, and M. Cianchetti, “A Bioinspired Soft Robotic Gripper for Adaptable and Effective Grasping,” *Soft Robotics*, vol. 2, no. 3, pp. 107–116, Sep. 2015, doi: 10.1089/soro.2015.0009.

Tendon Driven Actuation – Design Principles

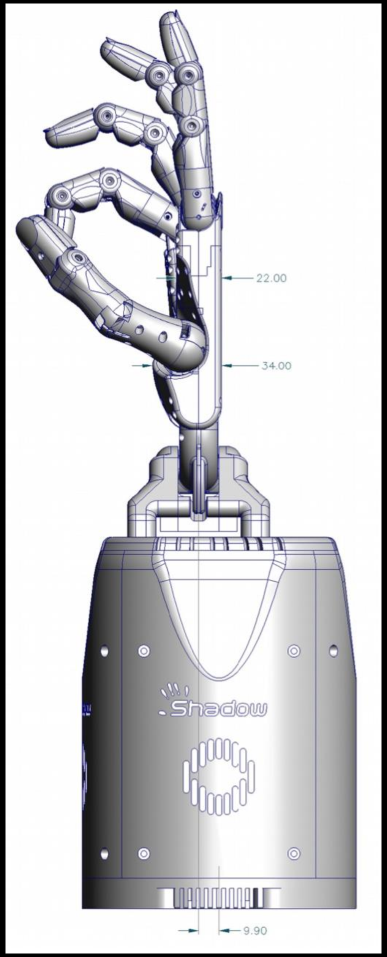
- Tendon
  - Extensible or in-extensible
- Routing
  - Channels guiding the tendon
- Power source
  - Electric motor
    - Battery
    - Tethered



Zhe Xu and E. Todorov, "Design of a highly biomimetic anthropomorphic robotic hand towards artificial limb regeneration," 2016 IEEE International Conference on Robotics and Automation (ICRA), Stockholm, Sweden, 2016, pp. 3485-3492, doi: 10.1109/ICRA.2016.7487528

Pin Joint Type

Weiner, P., Starke, J., Hundhausen, F., Beil, J., & Asfour, T. (2018). The KIT Prosthetic Hand: Design and Control. *IEEE International Conference on Intelligent Robots and Systems*, 3328–3334. https://doi.org/10.1109/IROS.2018.8593851

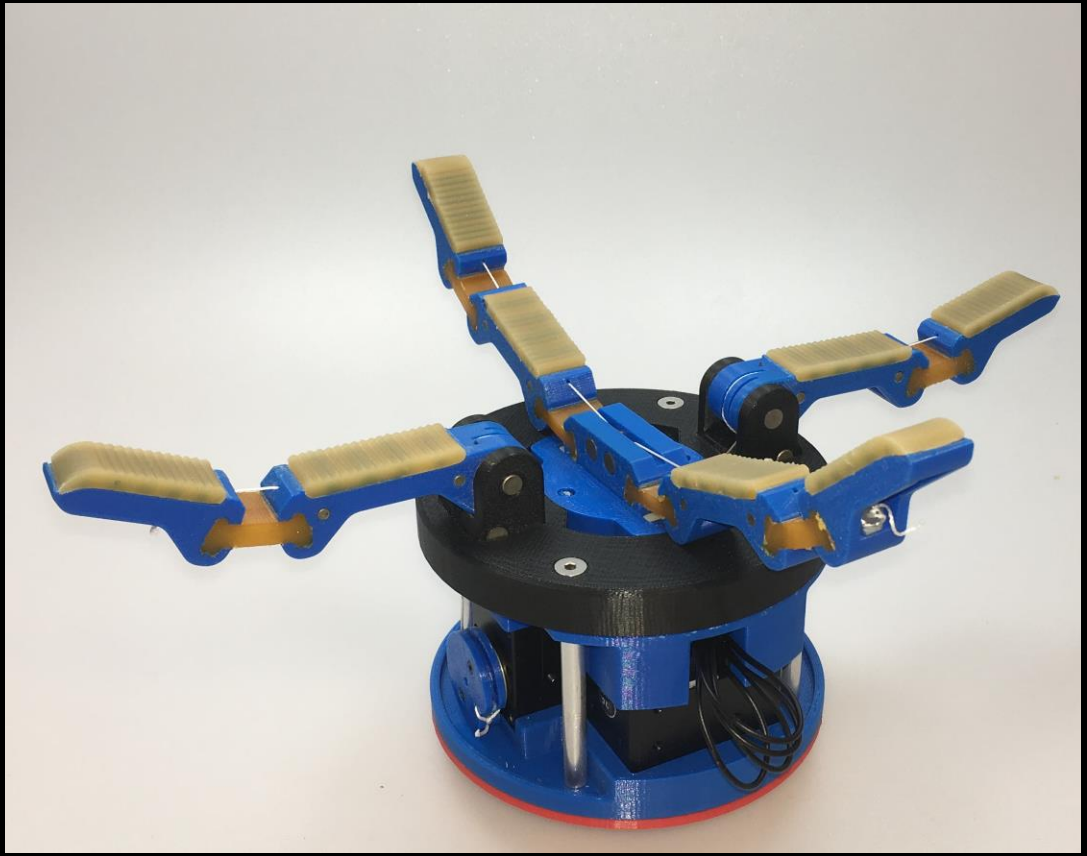


Shadow Dexterous Hand : https://www.shadowrobot.com/dexterous-hand-series/

Pin

- Classical approach
- Breaks on overstress
- Difficult manufacturing

Flexure Joint Type



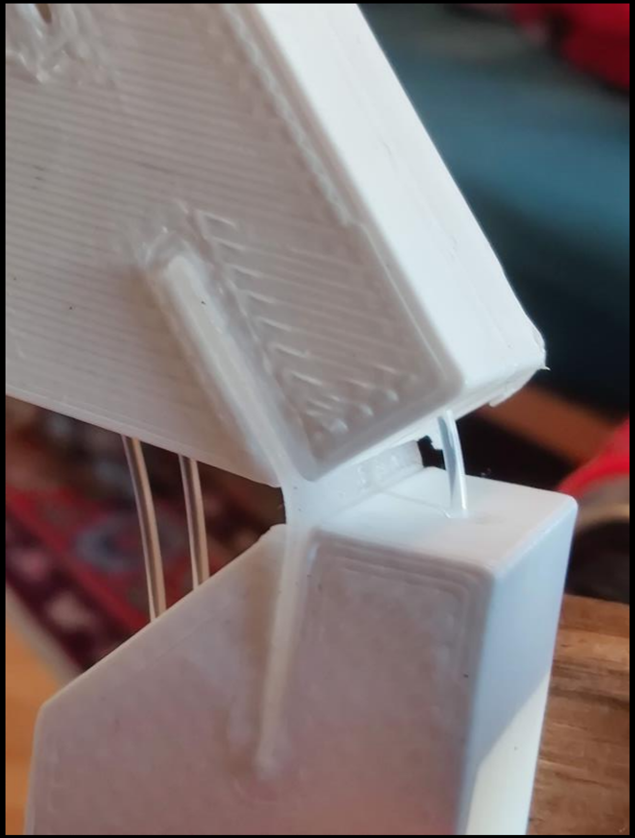
Flexure

- Simple manufacturing
- Low Friction
- Prone to wear
- Low cost if injection molded

Images source (from left to right):

- Tavakoli, M., Batista, R., & Sgrigna, L. (2016). The UC softhand: Light weight adaptive bionic hand with a compact twisted string actuation system. *Actuators*, *5*(1). https://doi.org/10.3390/ACT5010001
- Yale OpenHand Model Q, https://www.eng.yale.edu/grablab/openhand/images/hand%20-%20q.png

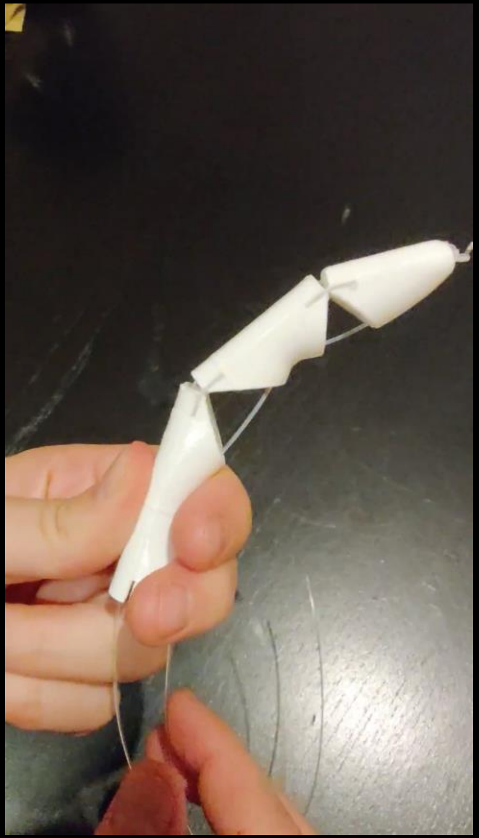
Examples of Flexure-based Joint Designs for Fingers



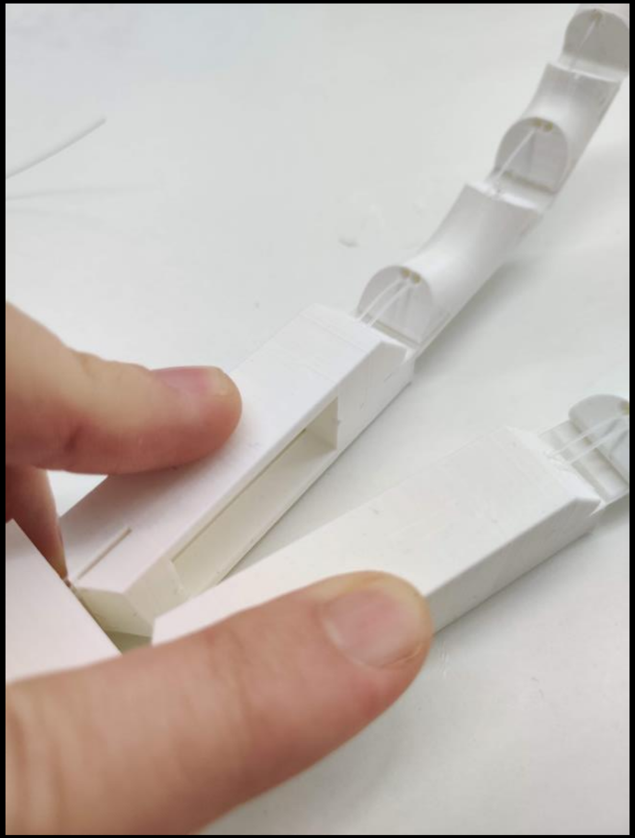
Flexure joint using polypropylene sheets

Lauener et al. 2022

Individual finger design

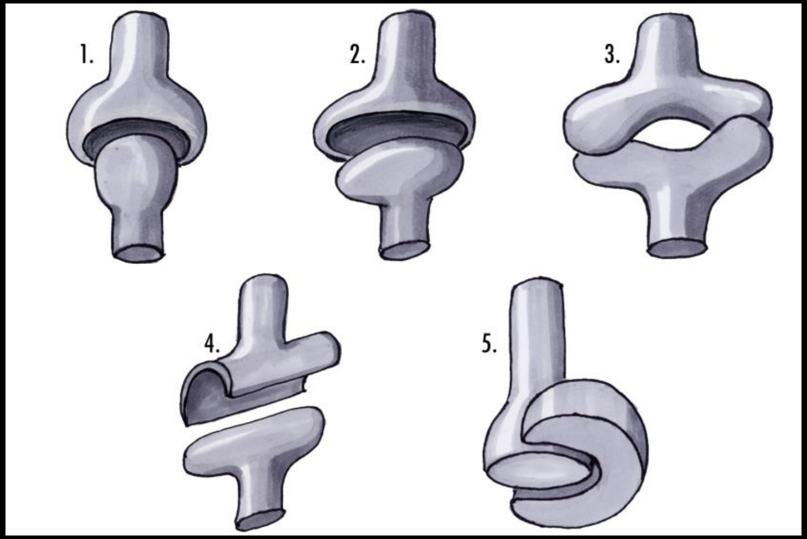


Refined geometries



Two finger gripper with added adduction/abduction

Joint Type: Synovial



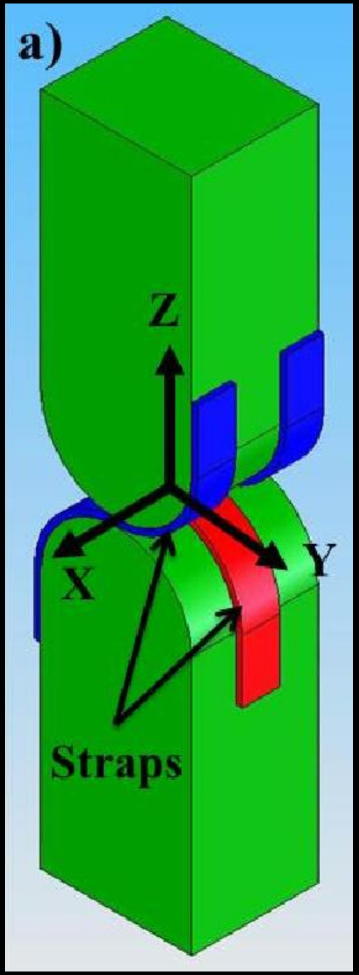
https://en.wikipedia.org/wiki/Ball-and-socket_joint#/media/File:Gelenke_Zeichnung01.jpg

Synovial

- Difficult to build
- Biomimetic
- Dislocate instead of breaking
- Potentially high cost

Xu, Z., & Todorov, E. (2016). Design of a highly biomimetic anthropomorphic robotic hand towards artificial limb regeneration. *Proceedings - IEEE International Conference on Robotics and Automation*, *2016-June*, 3485–3492. https://doi.org/10.1109/ICRA.2016.7487528

Joint Type: Rolling Contact



Slocum, A.H. (2013). Rolling contact orthopaedic joint design.

Kim, Y.-J., Yoon, J., & Sim, Y.-W. (2019). Fluid Lubricated Dexterous Finger Mechanism for Human-Like Impact Absorbing Capability. *IEEE Robotics and Automation Letters*, *4*(4), 3971–3978. https://doi.org/10.1109/LRA.2019.2929988

Rolling Contact

- Low friction
- Dislocates instead of breaking

Contact Rolling Joint: Existing design

FLLEX Hand Ver. 2 : Robustness and Payload Test, https://www.youtube.com/watch?v=cZuzXdMyJsA

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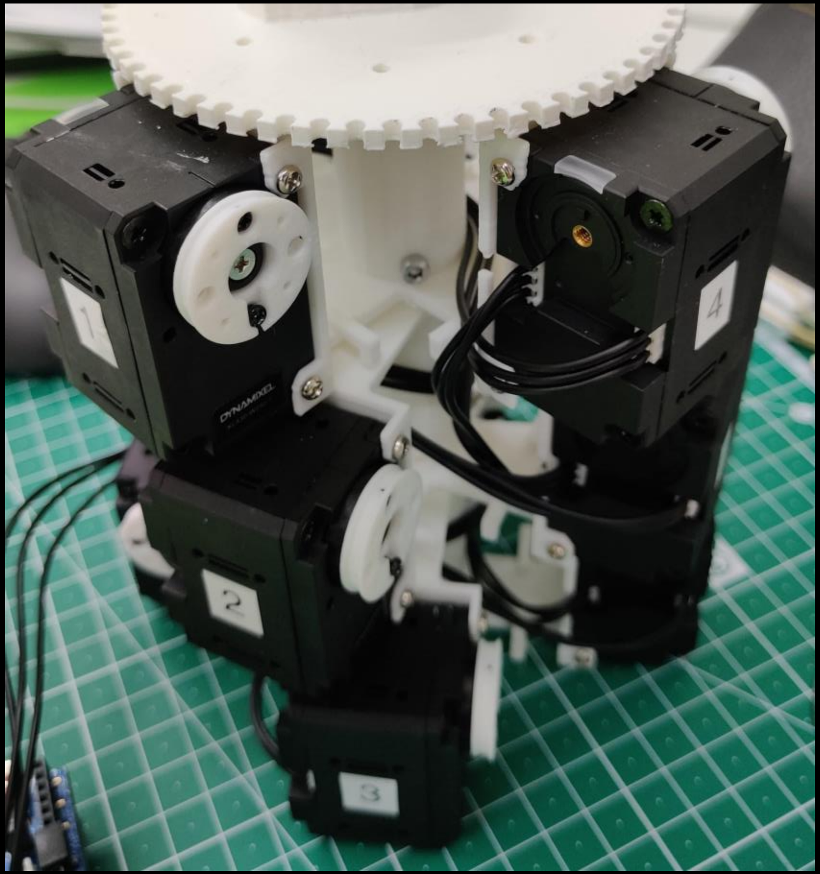
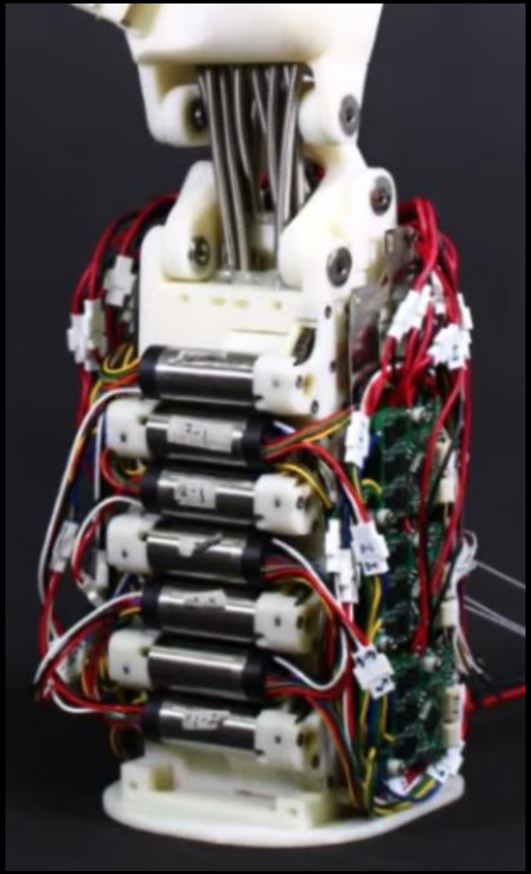
Electromagnetic Motor-based Actuation



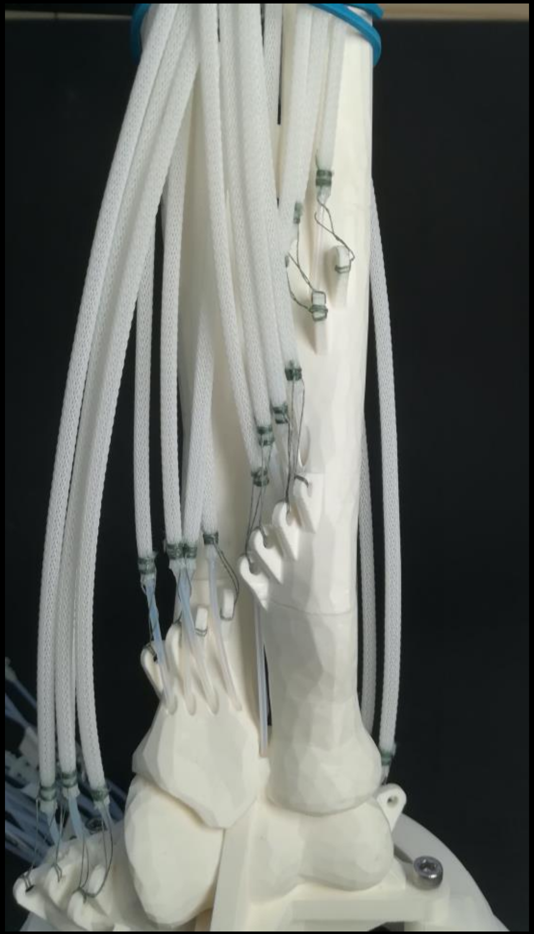


Servo Motor

- Controlling easier
- Inexpensive
- Efficient
- Bulky for actuating many DOF

1. SRL's test bench
2. FLLEX Hand Ver. 2 : Robustness and Payload Test, https://www.youtube.com/watch?v=cZuzXdMyJsA

Fluidic Actuation Types



Stefan Weirich, Development of a Biomimetic, Soft Actuator System for a Tendon-driven Hand, 2021 (at SRL)

Artificial Muscles Robotic Arm, Real Copy of Human Arm, https://www.youtube.com/watch?v=gd9d_BAXWvg

Pneumatic

- Compliance by compressible air
- Equipment intensive

Hydraulic

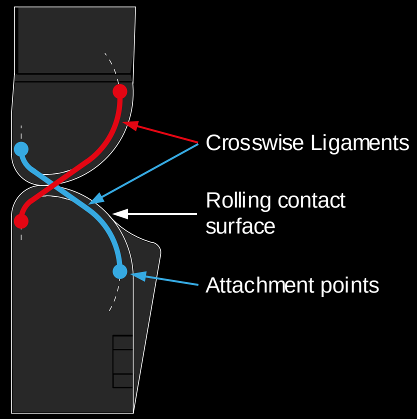
- Stronger than pneumatic
- Difficult plumbing

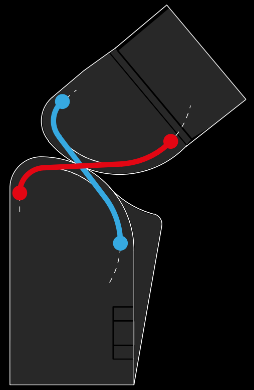
SoftRobotics Laboratory

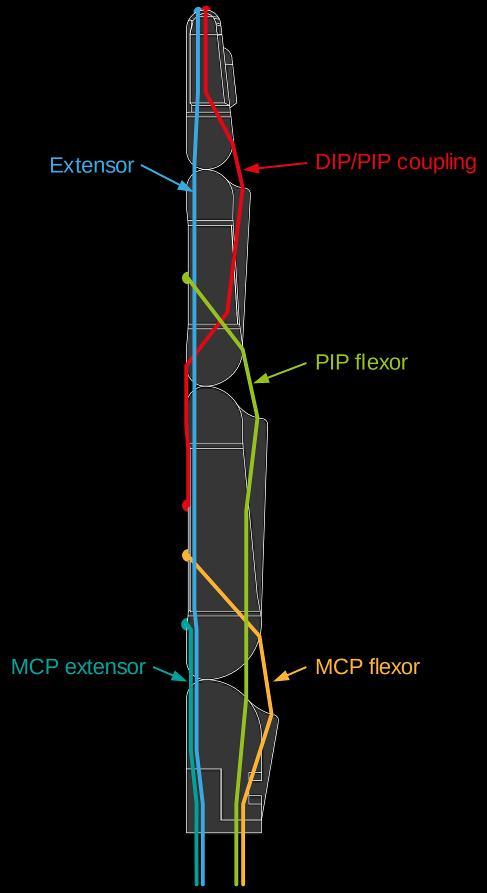
Finger Design

Dexterity

Ligaments & Tendons



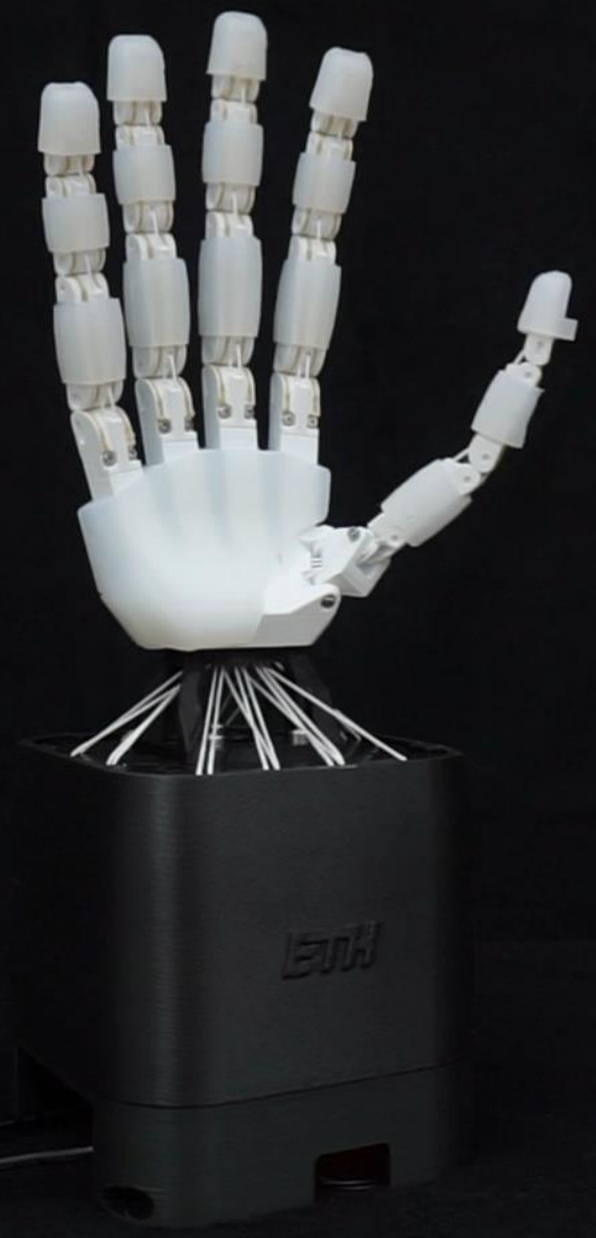


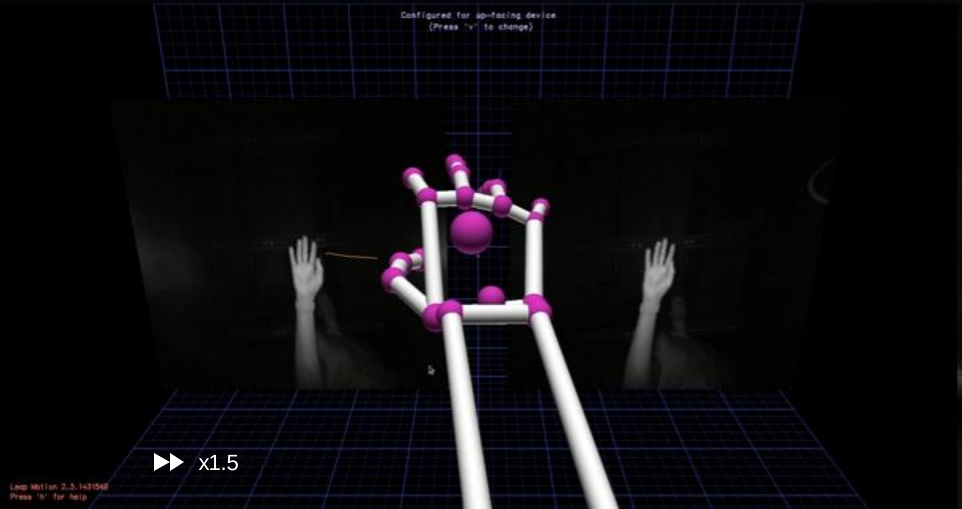


1. Schüunke, M., Schulte, E., Schumacher, U., Voll, M., and Wesker, K. (2005). Prometheus: Allgemeine Anatomie und Bewegungssystem. LernAtlas der Anatomie. Thieme, Stuttgart, 4 edition.

Actuation, Sensing and Control

- Dexterous 16-20 DoF
- High Payload 10 kg
- Lightweight 1 kg
- Compliance
- Integrated Sensing





▶▶ x1.5

Potential Applications of an Anthropomorphic Hand

▶▶ x2

Detailed Comparison of Anthropomorphic Hands

Product	ShadowRobot (UK) [1]	Schunk SVH (Germany) [2]	Clone Inc. (Poland) [3]	QB SoftHand (Italy) [4]	Allegro Hand (Korea) [5]	Robotiq 3-finger Gripper (Canada) [6]	faive robotics [7]
Cost-Efficient	72.000 – 190.000 €	56,000 €	?	7.500 – 9.000 €	?	15.000 €	20.000 €
Versatility /Dexterity (DoF, actuators)	20 Electric motors	9 DC motors	27 hydraulic McKibben actuators	2 Electric motors	16 DC motors	3 Electric motors	21 DoF 17 DC Motors
Compliance	No	No	Not yet demonstrated	Yes	No	No	Yes
Payload	4 kg	?	7 kg	2 kg	5 kg	10 kg	10 kg
Weight	4.3 kg	1.3 kg	?	0.77 kg	1.09 kg	2.3 kg	1 kg
Limitations	Highly dexterous but very expensive, High weight Low Usability Entirely rigid	Dexterous but very expensive, Only produced on demand (4 Months lead time) System complexity	Develops entire torso system, Limited mobility due to hydraulics Aims to be commercially available in 2023	No independent finger control, No complex motions or in-hand manipulation	Bulky dimensions, Unreliable, No compliance	Limited grasping motions and functionality	

1. https://www.shadowrobot.com/
2. https://schunk.com/us/en/gripping-systems/special-gripper/svh/c/PGR_3161
3. https://clonerobotics.com/

3. https://qbrobotics.com/
4. https://www.wonikrobotics.com/research-robot-hand
5. https://robotiq.com/de/produkte/adaptiver-3-finger-robotergreifer
6. aive-robotics.com

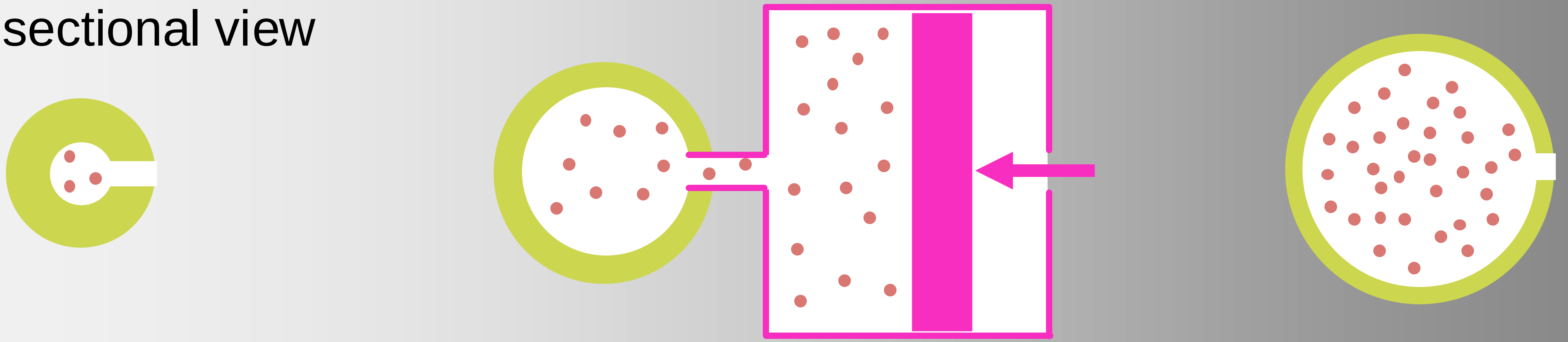
Tendon Driven – Key Takeaways

Advantages:
- High force transmission
- Electromagnetic motors are efficient
- Volume of force generation and action do not need to be the same
- Mimics biological musculoskeletal systems

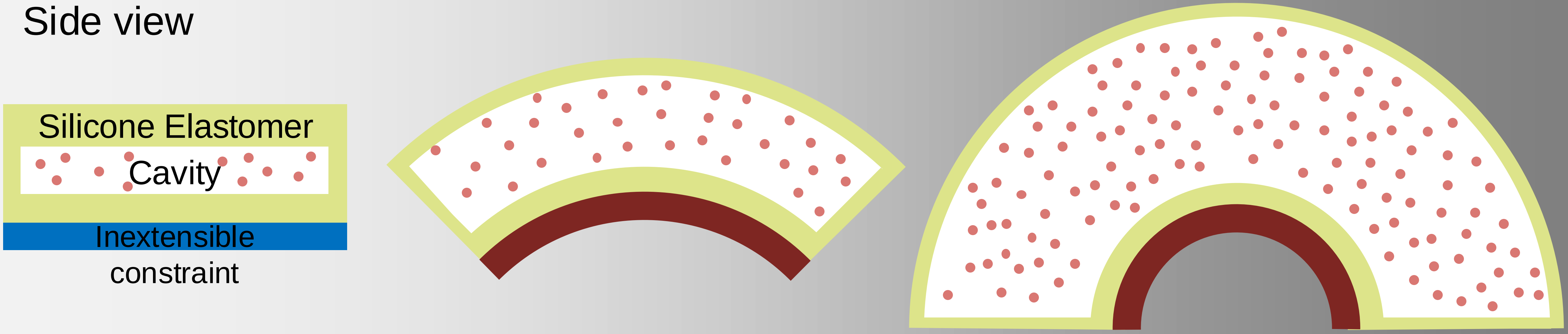
Disadvantages:
- Friction at joints
- Routing difficult for complex systems
- Rigid attachment points in soft structure
- Rigid motor needed

Working principle of a fluidic-powered soft actuator: constraints and pressurization

Cross-sectional view

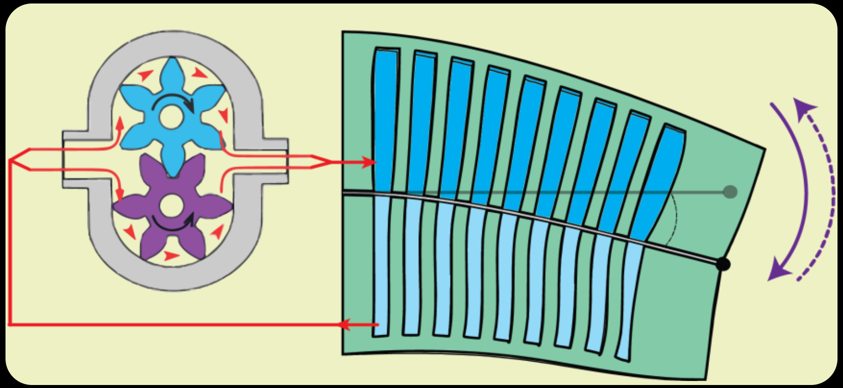


Side view



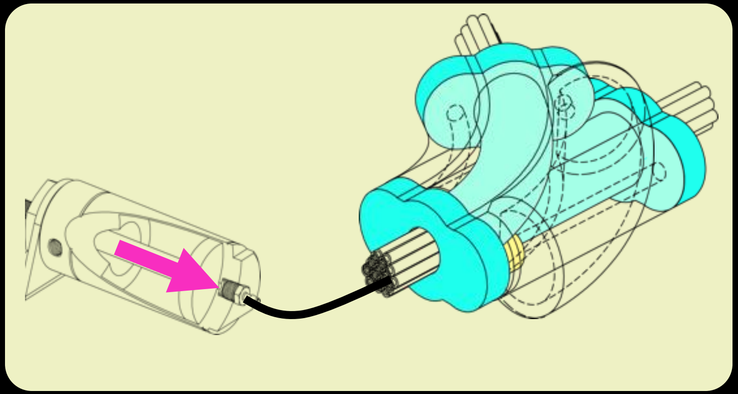
Soft actuators can be powered by displacement pumps, pneumatic cylinders, or valve arrays

Displacement pump



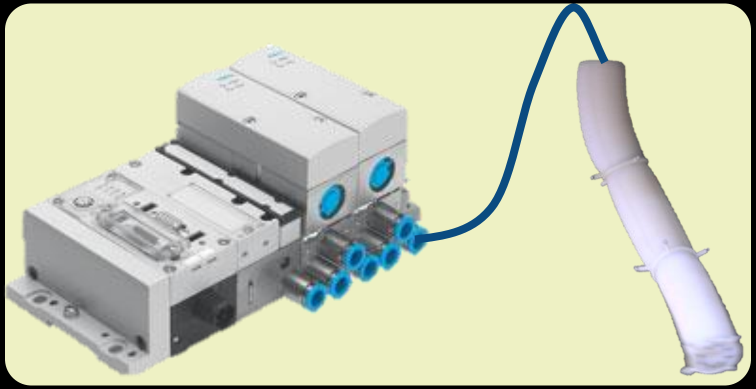
Katzschmann et al., ISER (2014)
Katzschmann et al., IROS (2016)

Pneumatic cylinder



Marchese, Katzschmann, Rus, IROS (2015)

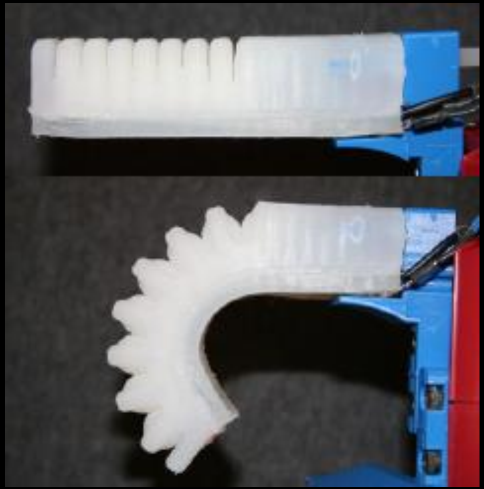
Valve Array



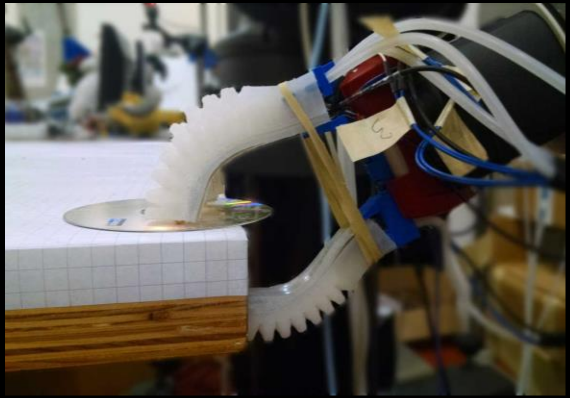
Katzschmann, Della Santina*, Toshimitsu, Bicchi, Rus, RoboSoft (2019)*

From making contact to manipulation:
Multi-finger hand with inlaid strain + force sensors

Bending through inflation



Sliding off table



Use of environment

Small envelope

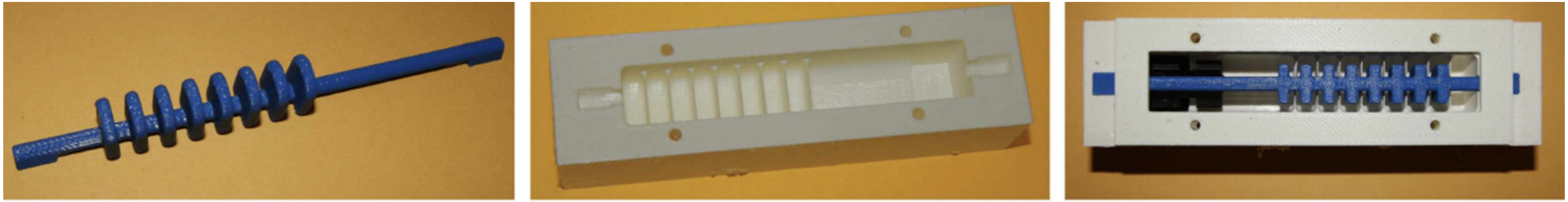
Large envelope

Pinch

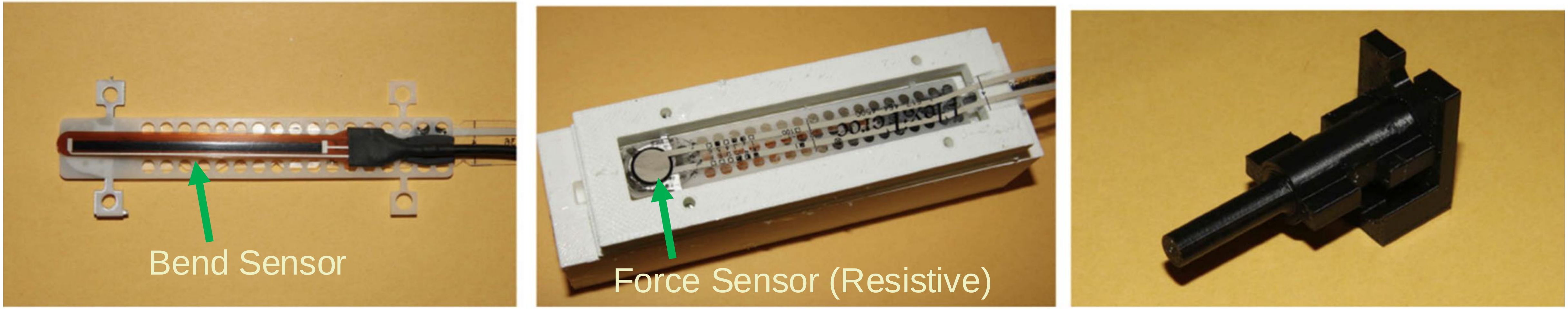
SoftRobotics
Laboratory

Homberg, Katzschmann*, Dogar, Rus, IROS (2015) + Autonomous Robots Journal (2018)*

Bend and force sensor in finger



(a) *Wax core model* **(b)** *Base finger mold* **(c)** *Mold assembly for finger base*

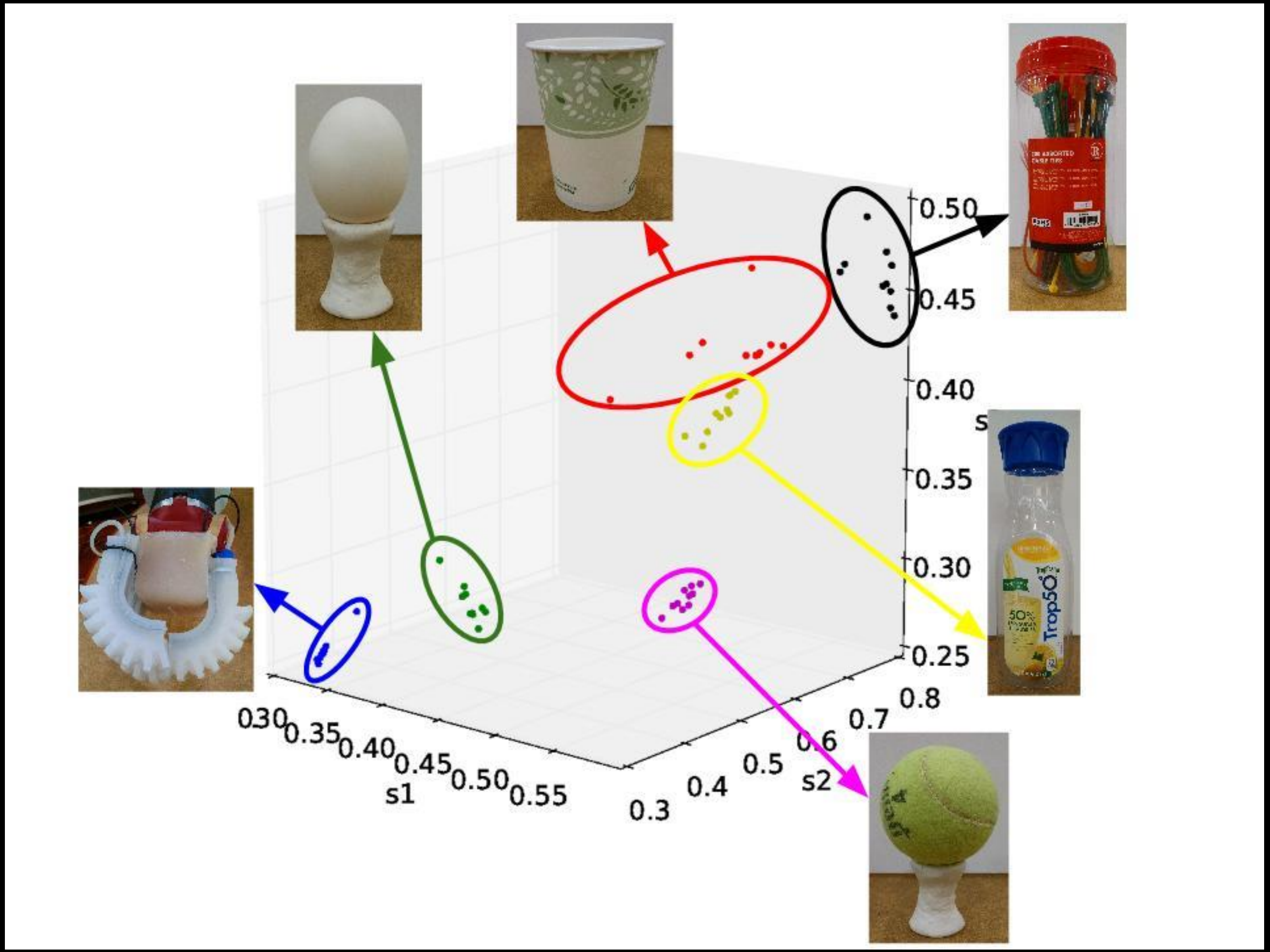


(d) *Constraint layer* **(e)** *Top mold for constraint and sensor* **(f)** *Insert part*

Homberg, Katzschmann*, Dogar, Rus, IROS (2015) + Autonomous Robots Journal (2018)*

Gripper identifies objects in hand through proprioceptive sensors

Clustered Data using K-Means



Objects tested

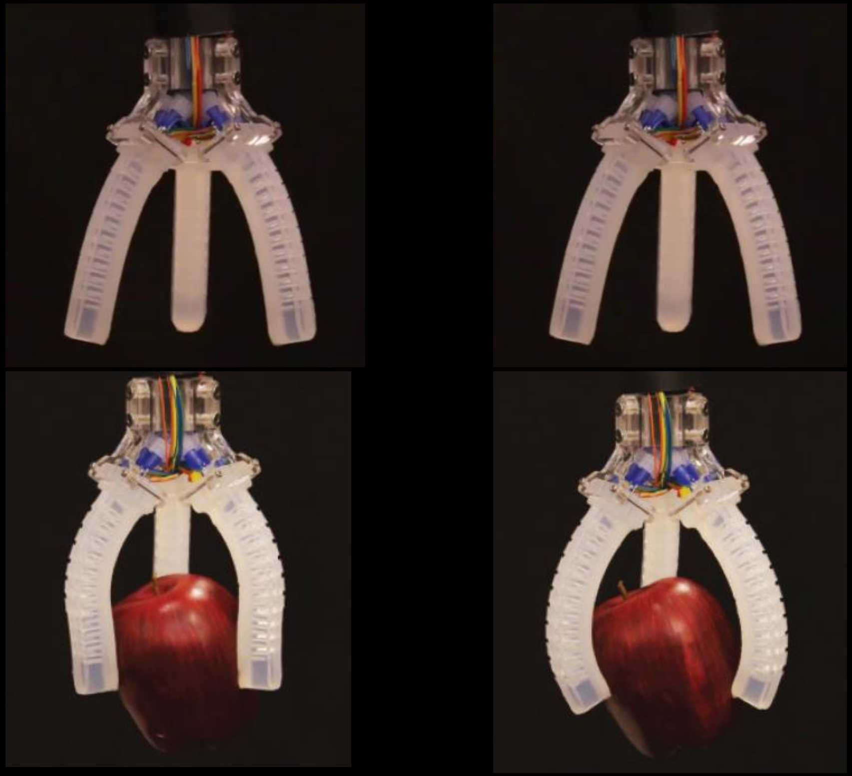
SoftRobotics Laboratory

Homberg, Katzschmann*, Dogar, Rus, IROS (2015)*
Homberg, Katzschmann*, Dogar, Rus, Autonomous Robots Journal (2018)*

Guide the gripper to make contact before lifting

Actuation

Base only | Base + Tip



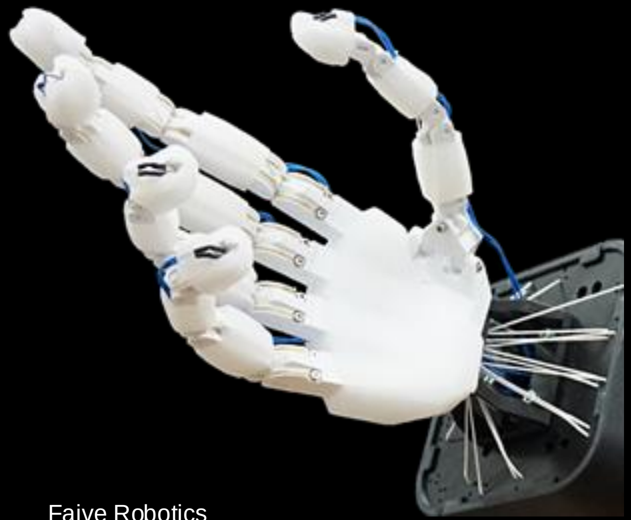
Truby, Katzschmann, Lewis, Rus, RoboSoft (2019)

Summary

Pin (+ Tendon)

Weiner et al. 2018

Rolling Contact (+Tendon)

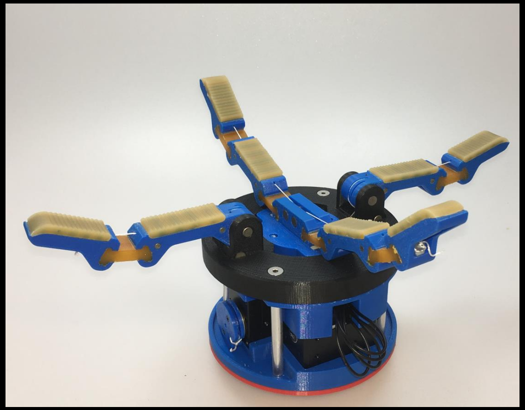


Faive Robotics

Synovial (+Tendon)

Xu et al. 2016

Flexure (+Tendon)



Yale OpenHand Model Q

Motor in Joint

Wonik Robotics Allegro hand

Soft Fluidic

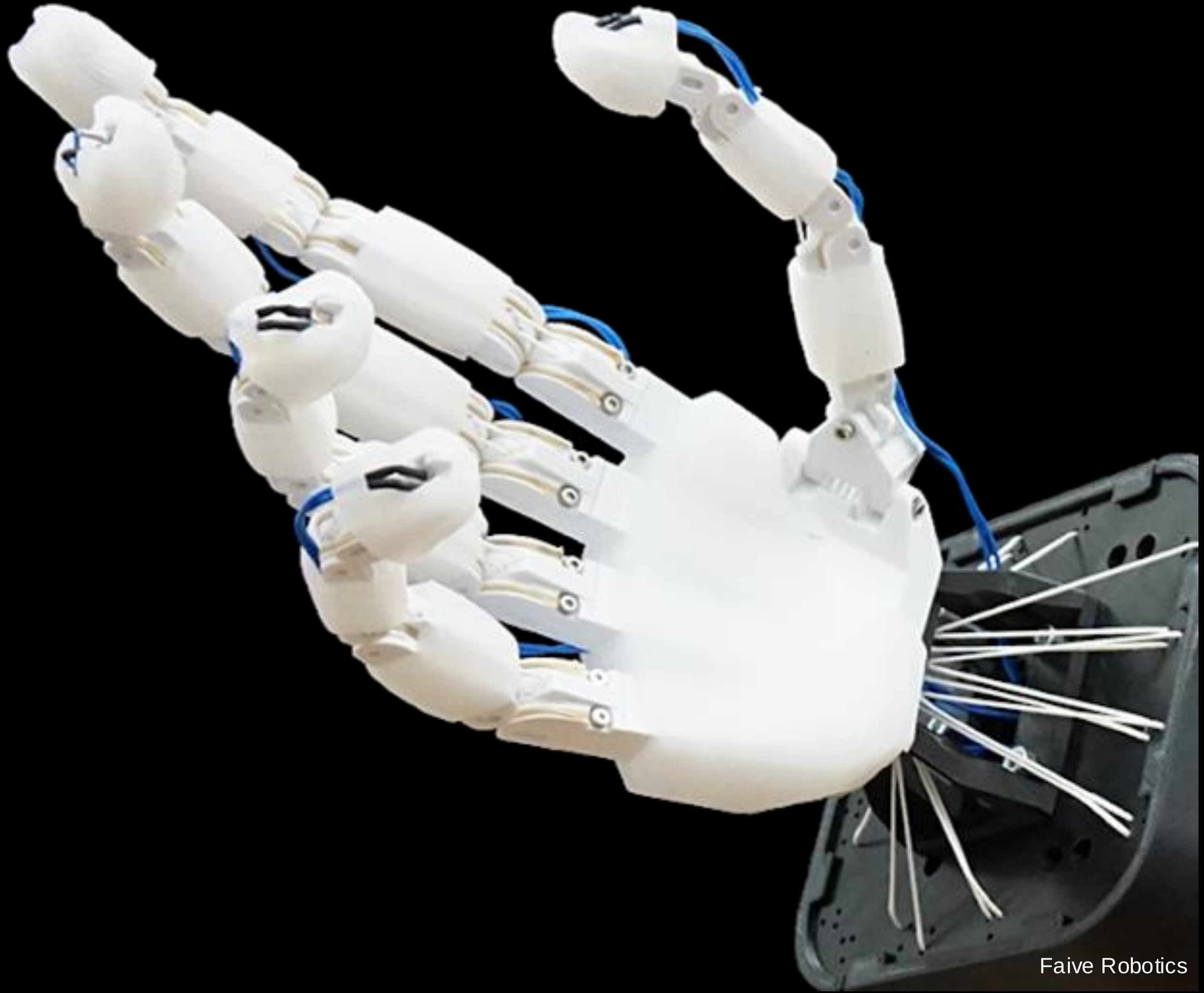
Truby et al. 2019

SoftRobotics
Laboratory

Fabrication Techniques to build an Articulated System with Soft Skin Focus & Q&A

Prof. Dr. Robert Katzschmann
Soft Robotics Lab
ETH Zurich

How to make a hand?

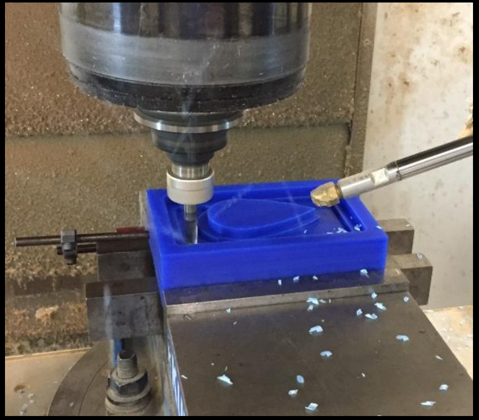


Faive Robotics

Iterate…

Summary of Fabrication Techniques for Robotic Hands

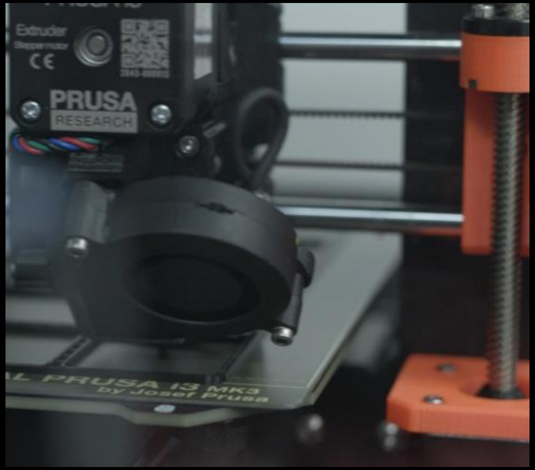
Machining



Joining

Casting / Molding

Additive Manufacturing

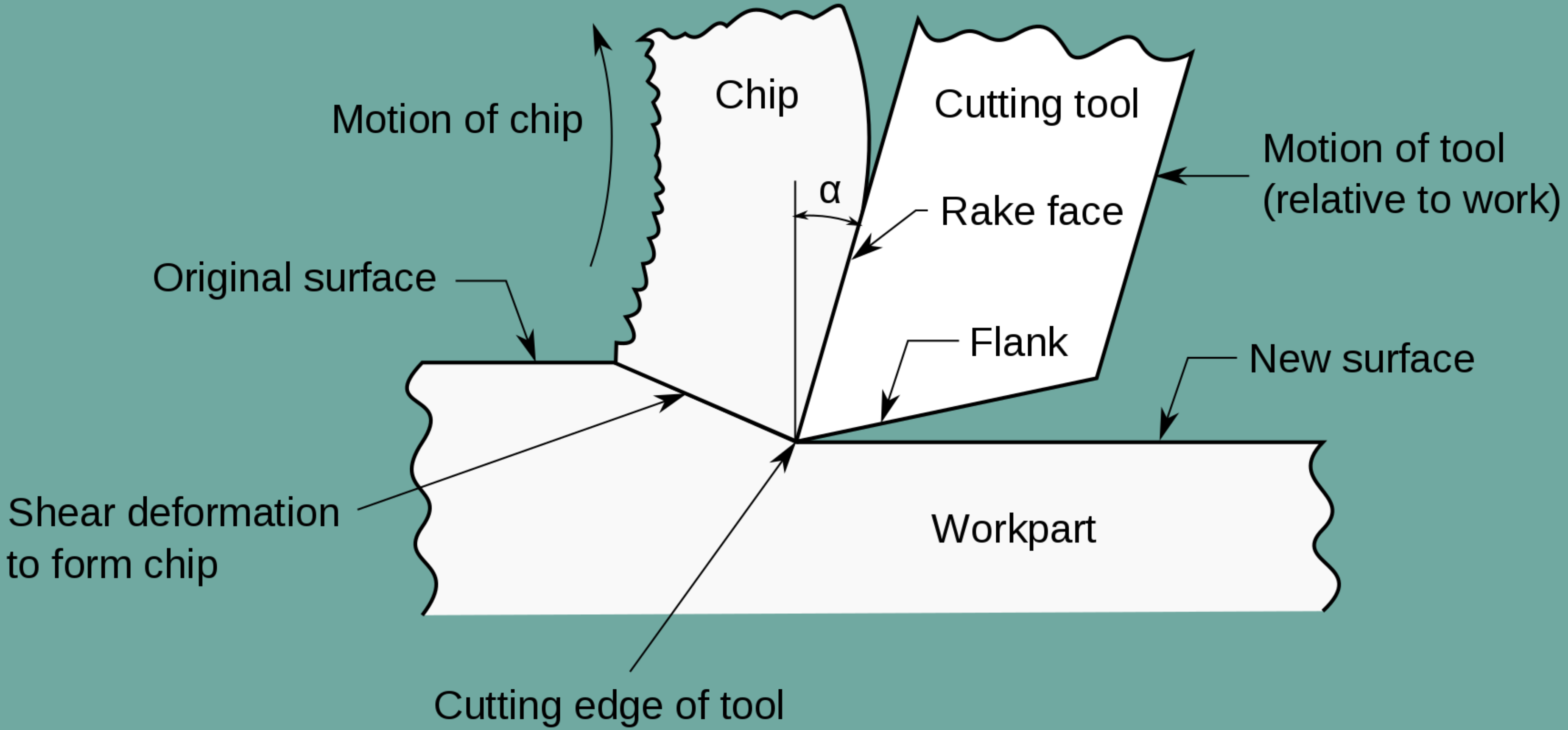


https://en.wikipedia.org/wiki/List_of_manufacturing_processes

Machining

A material is cut to a desired final shape and size by a controlled material-removal process

Machining - Principle



Machining, Wikipedia

SoftRobotics Laboratory

Drilling

SoftRobotics
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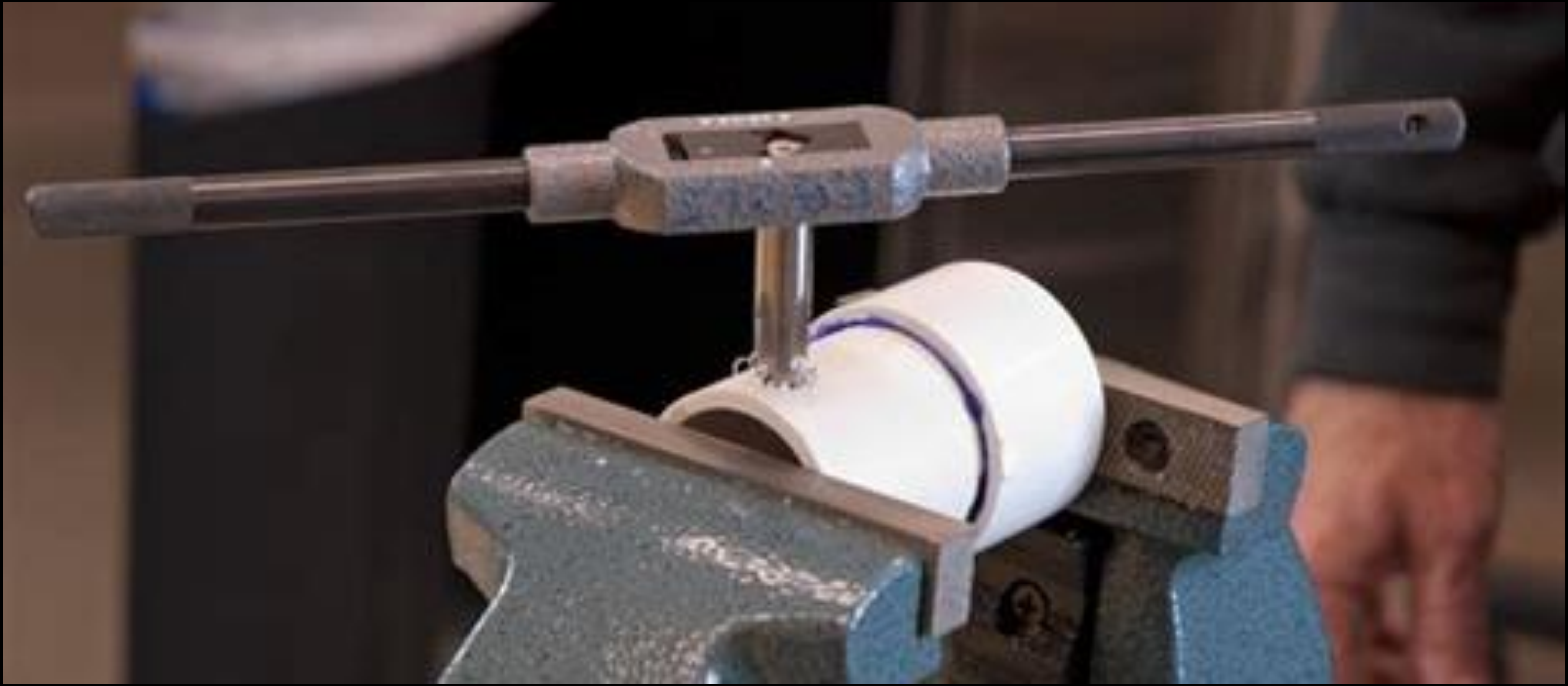
Tapping



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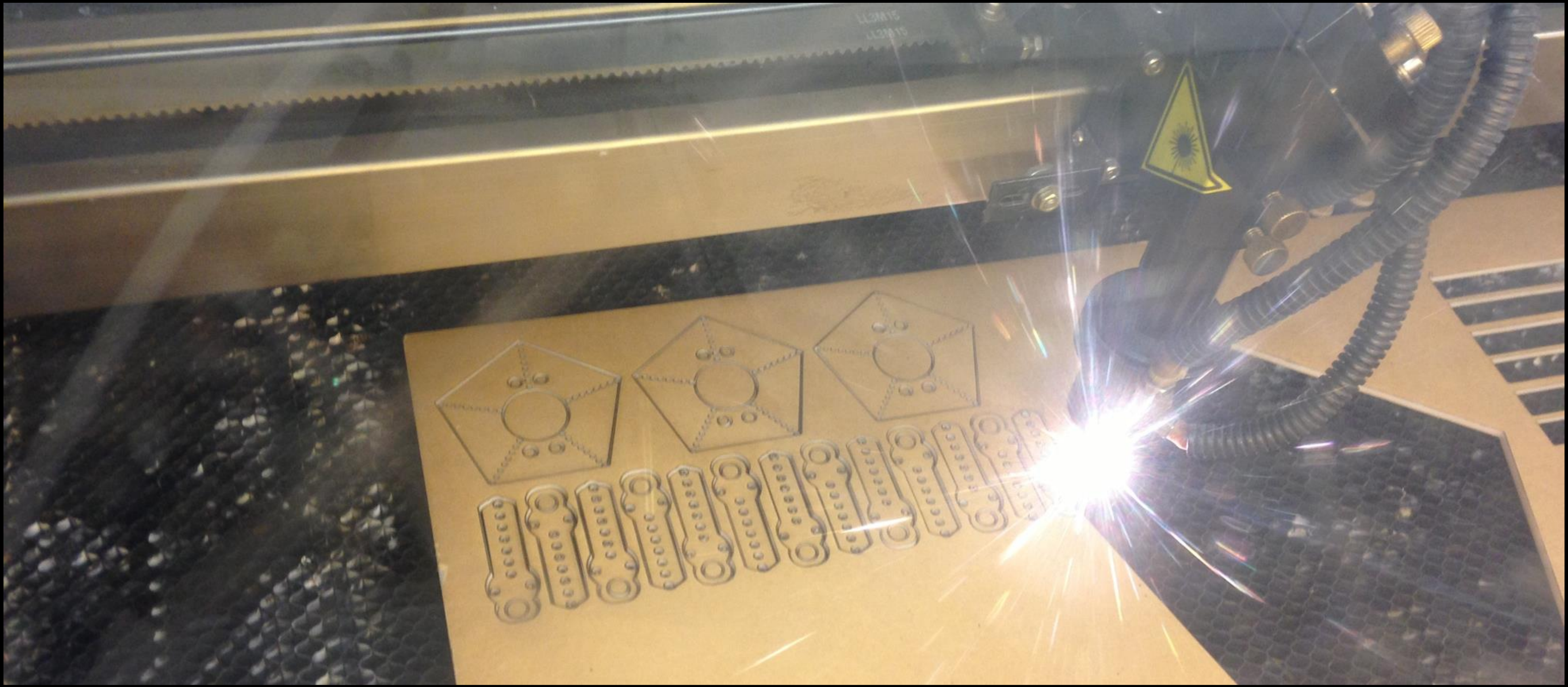
Laser Cutting



Water Jet Cutting

SoftRobotics Laboratory

Milling

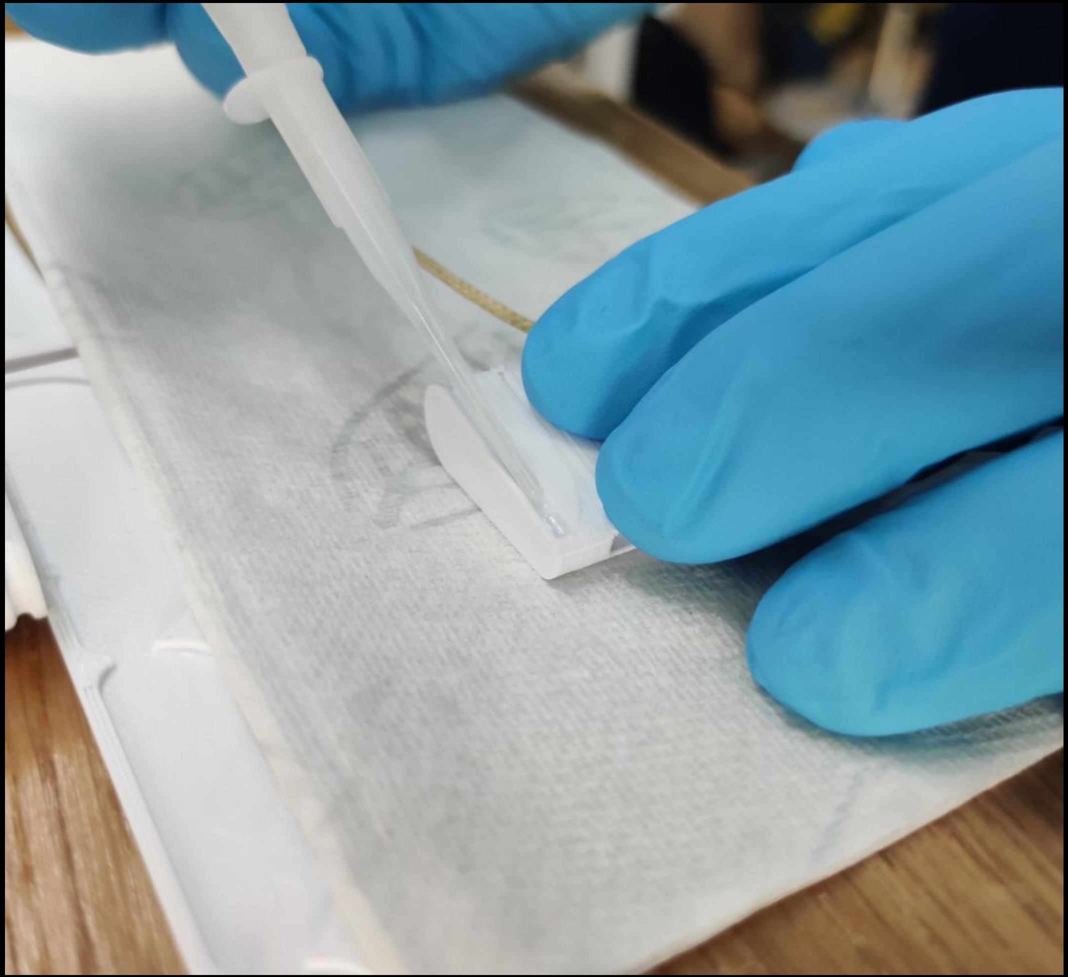
SoftRobotics Laboratory

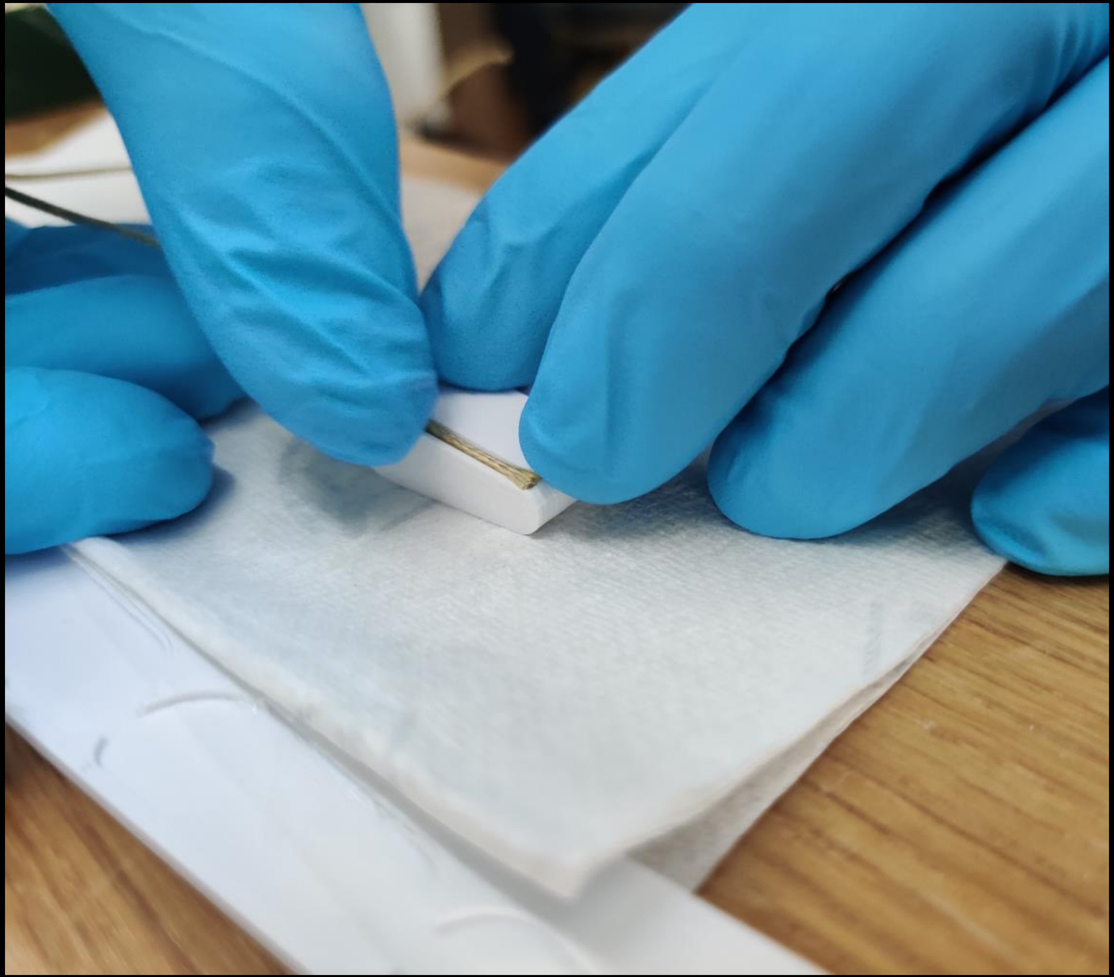
Turning

Joining

Two or more materials can be permanently or temporarily joined or assembled together with or without the application of external element to form a single unit

Adhesive Bonding





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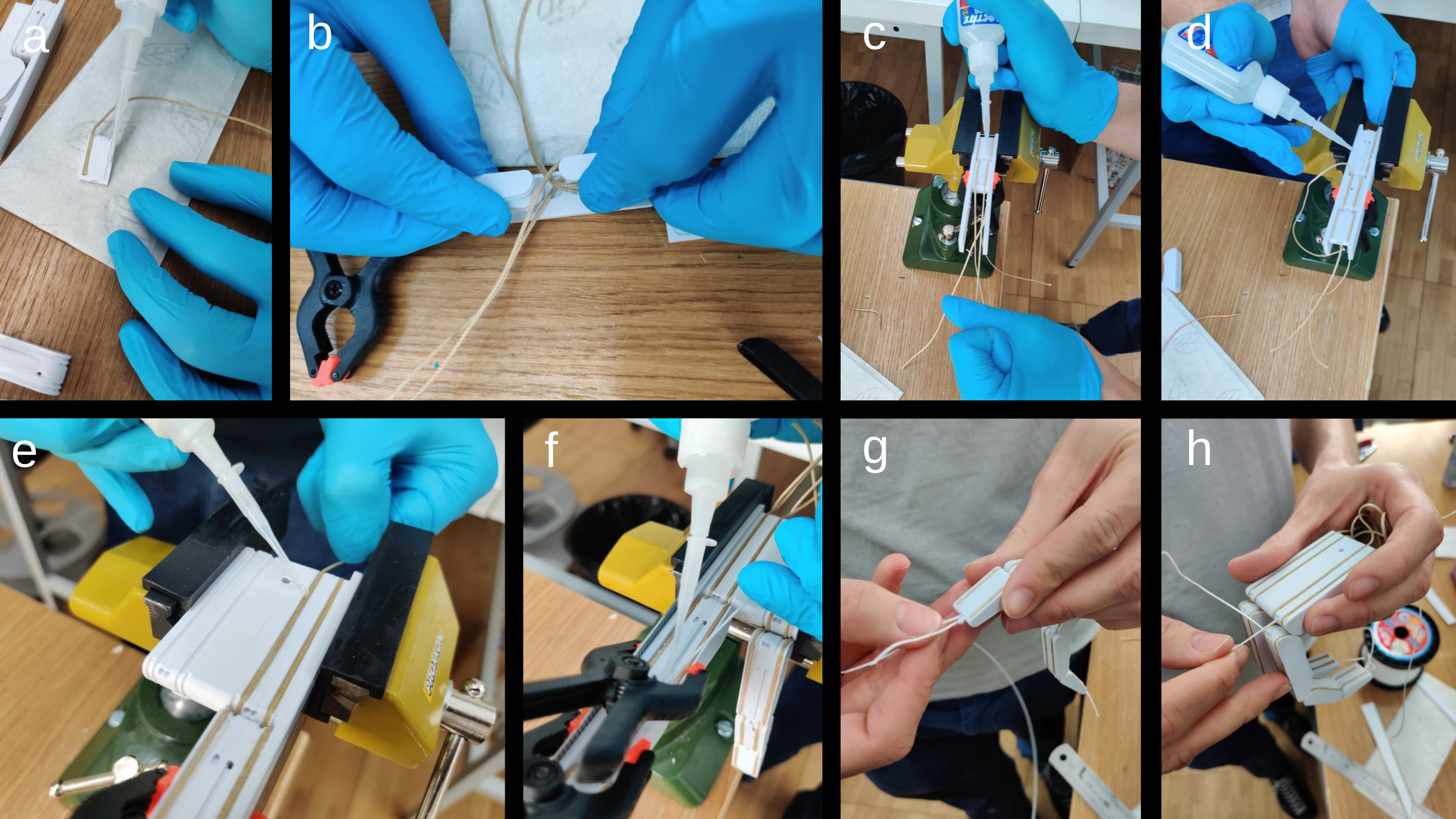
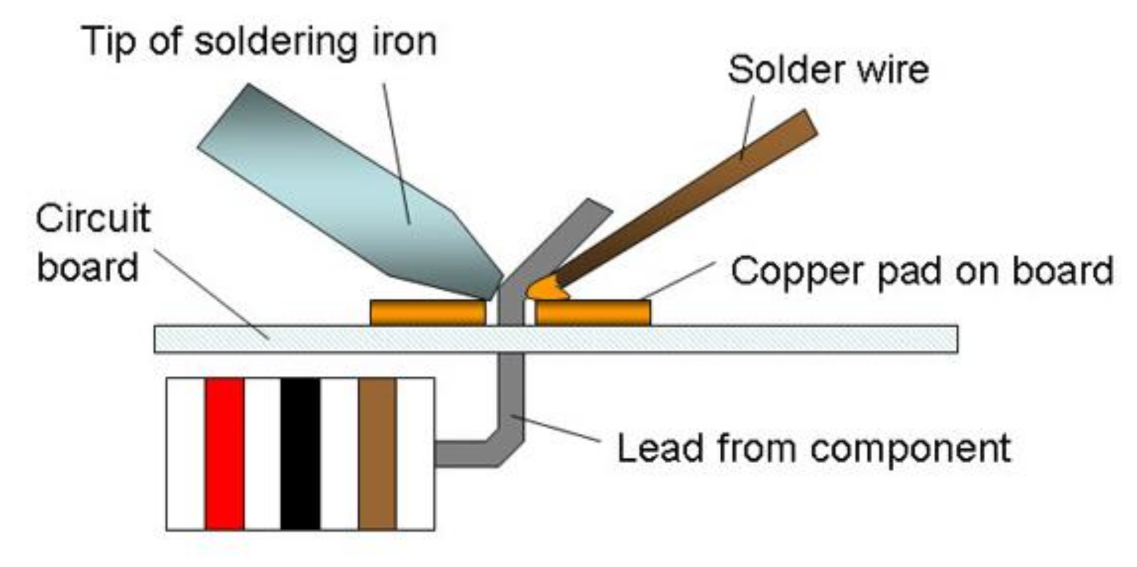

a
b
c
d
e
f
g
h
PROXXON

Fastening

Soldering


Tip of soldering iron
Solder wire
Circuit board
Copper pad on board
Lead from component

ETH zürich

Casting and Molding Techniques

Fabricating or replicating structures using (elastomeric) stamps, molds, and masks

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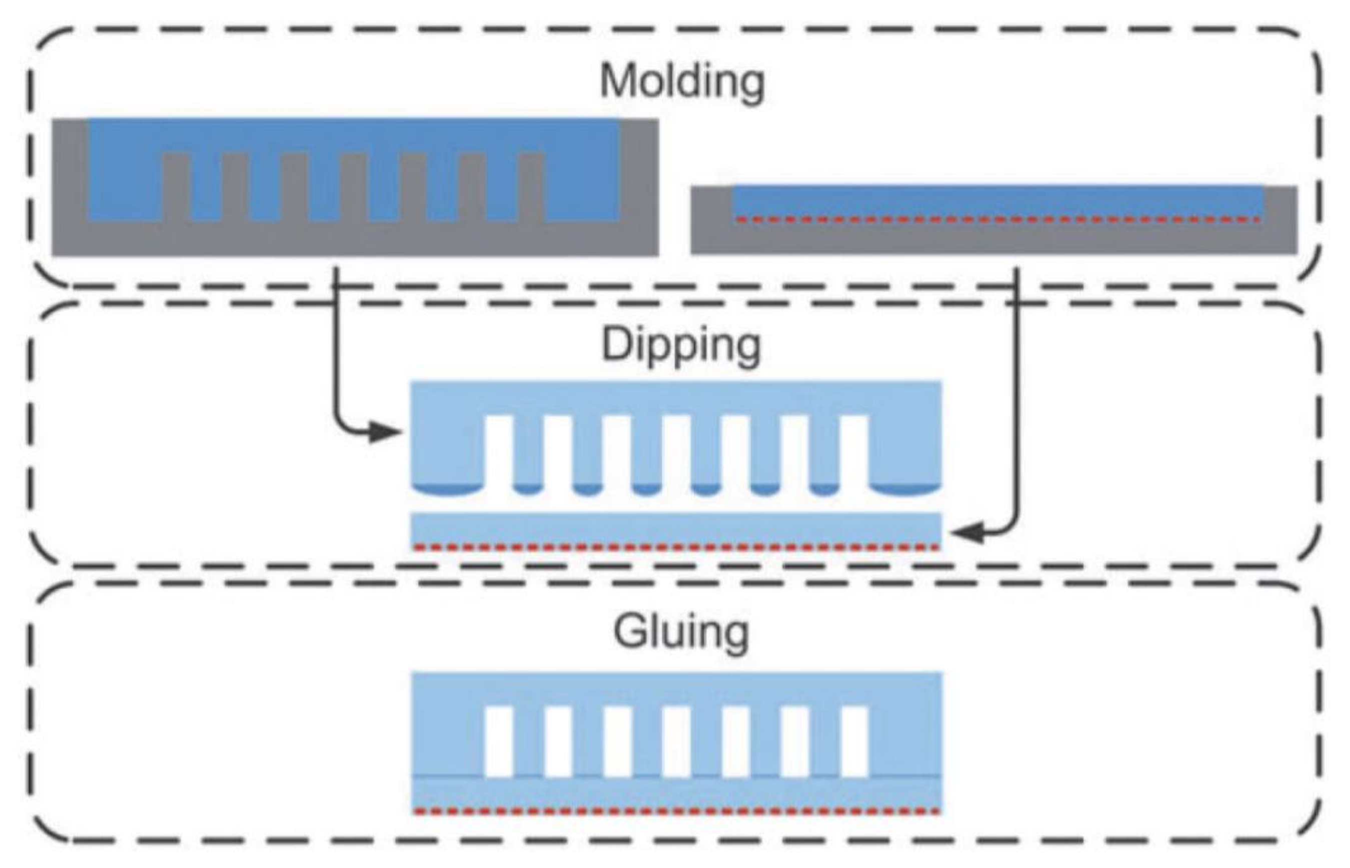
Layer-by-layer Molding of Silicone Elastomer (Soft Lithography)

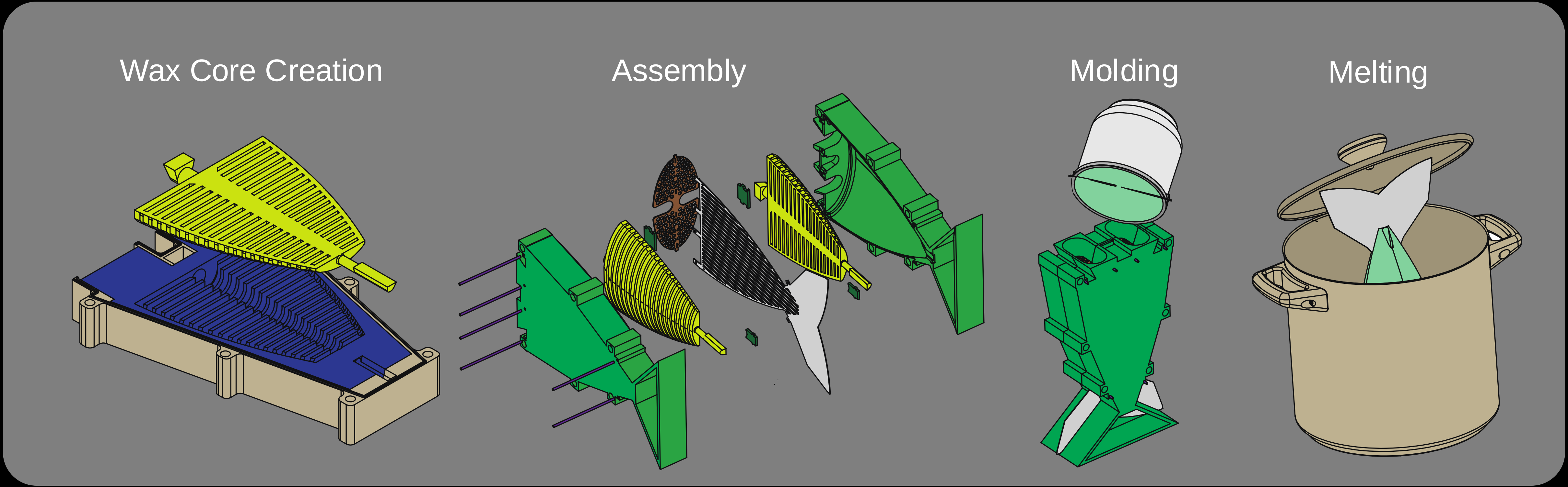


Each layer is casted and cured in separate molds.

Cured layers are removed and joined using a thin layer of uncured elastomer as glue.

https://www.elveflow.com/microfluidic-reviews/general-microfluidics/soft-robot/

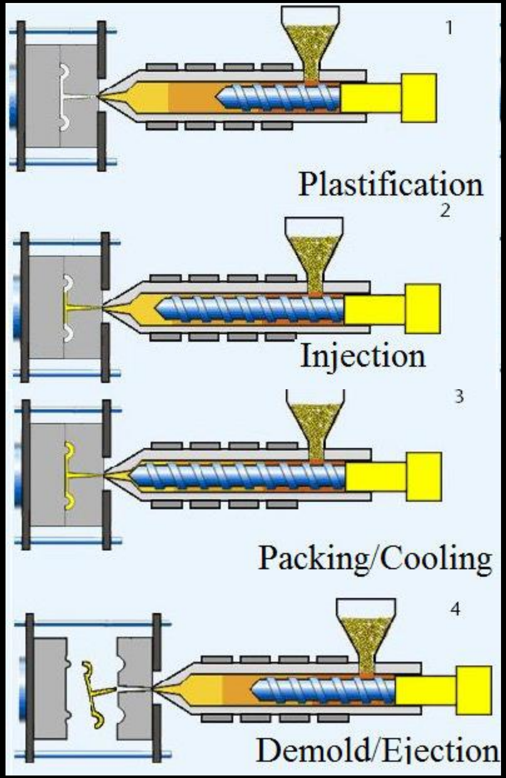
Lost-wax casting to produce interior cavities in molded elastomer materials



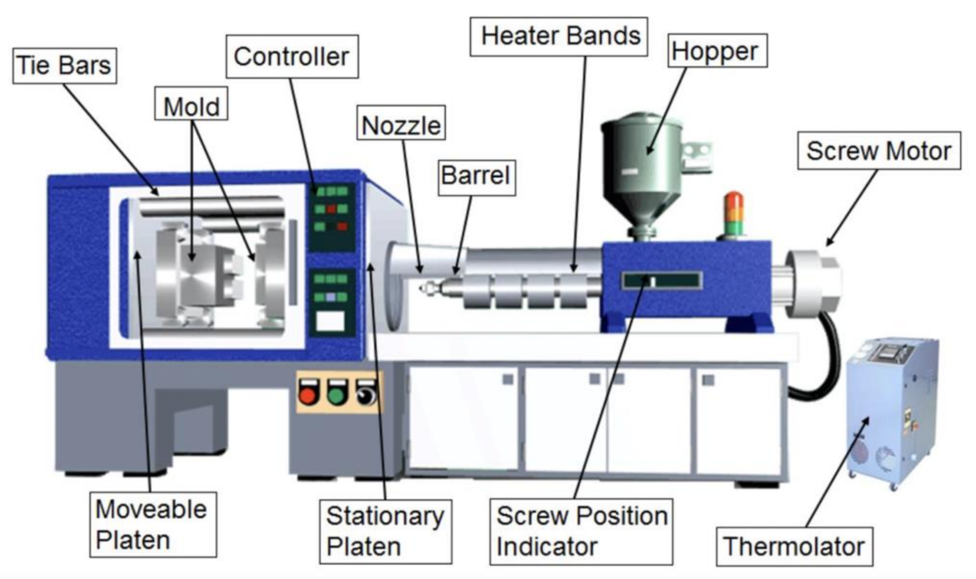
Katzschmann et al., ISER (2014)

Injection molding of molten materials

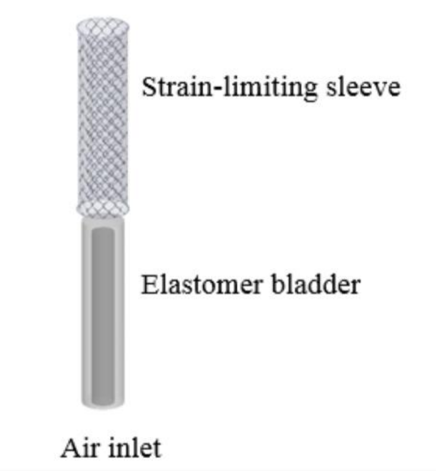
A manufacturing process for producing parts by injecting molten material (thermoplasts) into a mold



Injection molding process



The structure and components of injection molding machine



Example: Pneumatic actuator fabricated using injection molding

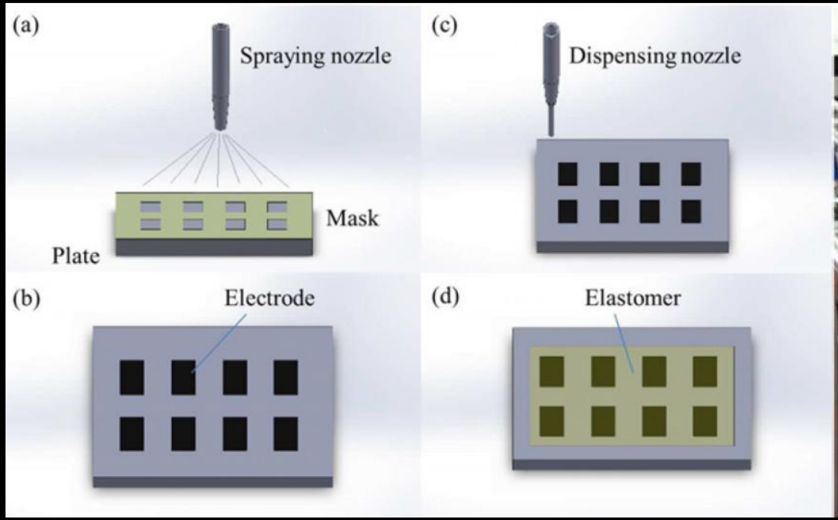
Li, Wanying. "Fabrication of soft robotic actuators by using injection molding technology." (2017).

Cho, Kyu-Jin, et al. "Review of manufacturing processes for soft biomimetic robots." *International Journal of Precision Engineering and Manufacturing* 10.3 (2009): 171-181.

Coating of Electrostatic Actuators

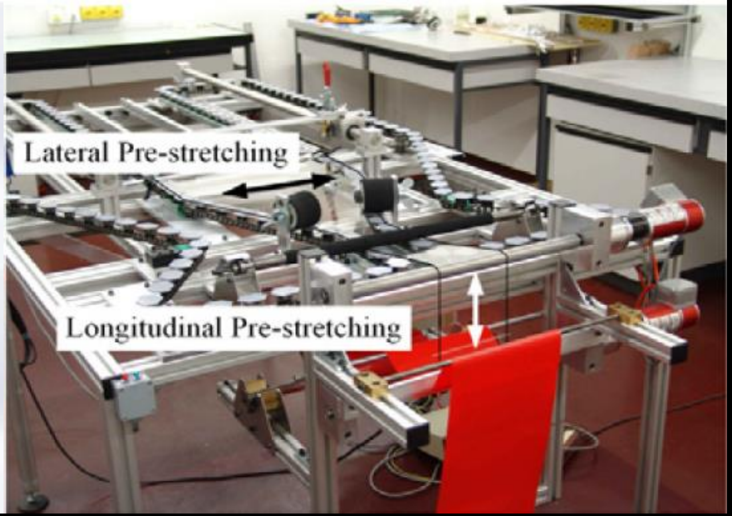
Spraying

Molding



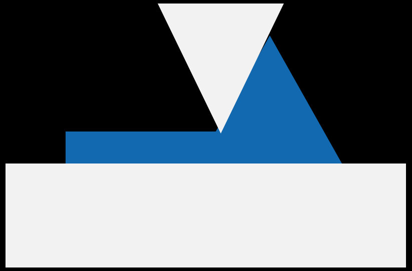
[Nguyen et al. 2014]

Premanufactured tapes

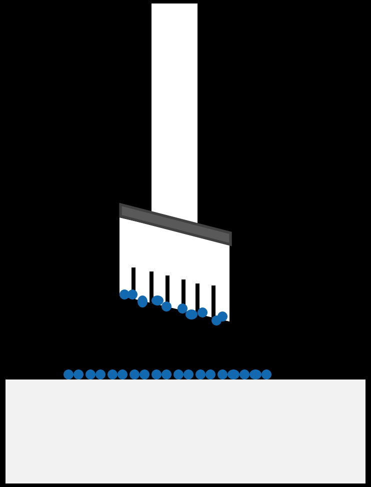


[Kovacs et al. 2007]

Blade Coating



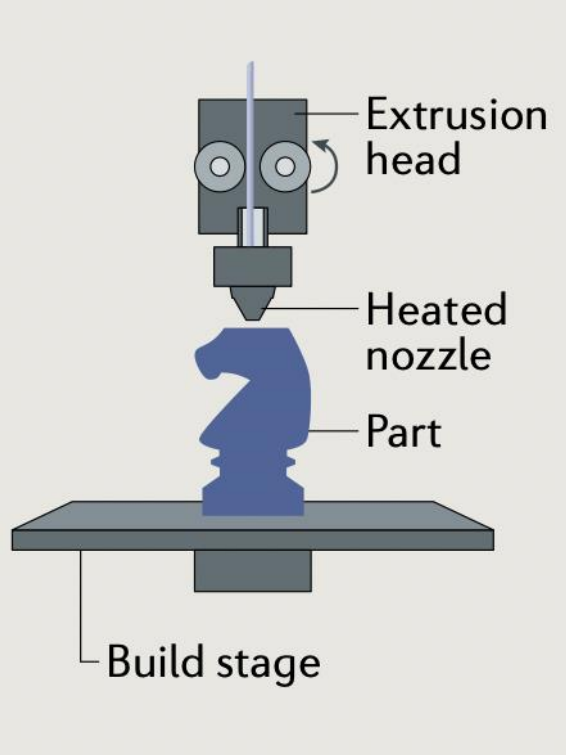
Brushing



3D Printing Technologies

A subset of additive manufacturing that creates 3D objects from design files through the digitally controlled deposition of material layers

Fused Deposition Modeling (FDM)



The working principle: A solid thermoplastic filament is extruded through a heated nozzle to melt, deposit, and fuse the material.

The head moves in 2D to deposit one horizontal plane at a time; the build stage or the print head is then moved vertically by a small amount to begin a new layer.

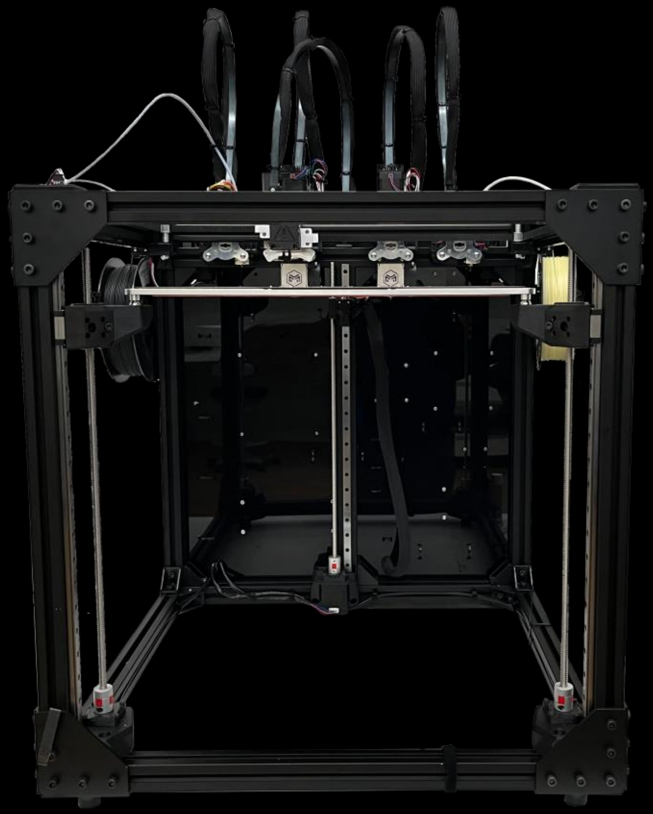
The reliance on melting and cooling processes limits the use of FDM to thermoplastic polymers.

The most successful FDM material for soft robotics is the Ninjaflex family of thermoplastic polyurethanes, which can withstand strains above $\gamma_{ult} > 500\%$ with a Young's modulus $E \approx 10$ MPa.

Approximate deposition rate: 10^5 mm^3 h^{-1}
Approximate resolution: 100 μm

Wallin, T. J., J. Pikul, and R. F. Shepherd. "3D printing of soft robotic systems." *Nature Reviews Materials* 3.6 (2018): 84-100.

FDM Example:
Hydra MK1 – developed at the Soft Robotics Lab

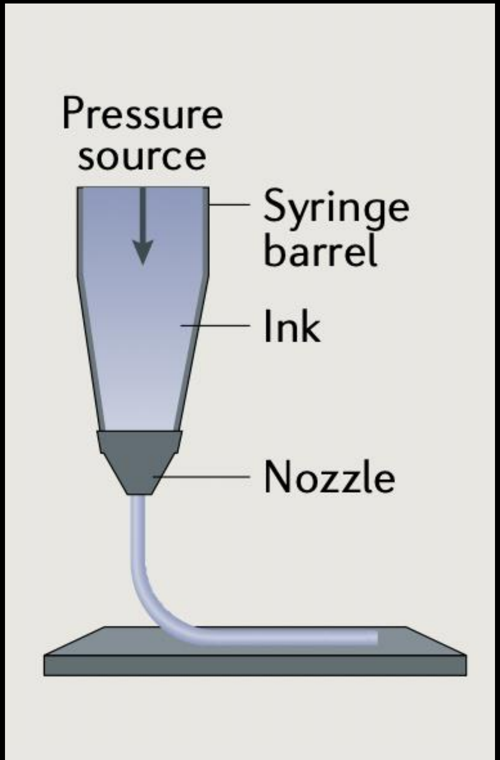


- The Hydra MK1 is an open-source project that aims to bring multi-material printing of exotic materials to research facilities and individuals worldwide.
- It features a tool swapper that can switch between up to four tools. In the standard configuration, it uses two filament printing heads, and two pellet extruders.
- Detailed documentation:

https://hydramk1.readthedocs.io/en/latest/

Rogler et al., 2022

Direct Ink Writing (DIW)



The working principle: A viscoelastic ink flows through a nozzle. Upon deposition, the ink solidifies into a solid object.

A pressure source forces a liquid ink of a polymeric precursor above the yield stress, allowing it to be selectively deposited through a nozzle.

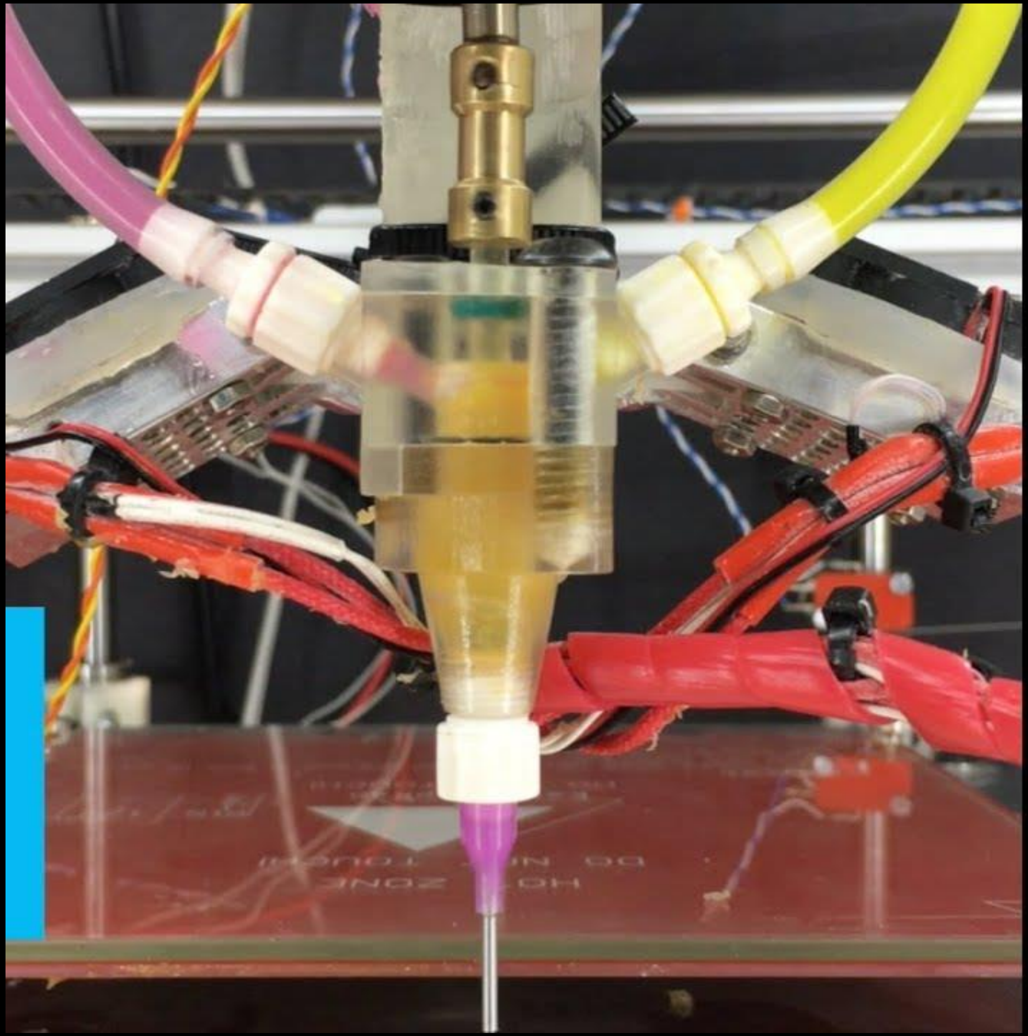
Once extruded, a sudden stress reduction, phase change, solvent evaporation, polymerization (either continuous or initiated in response to external stimuli) or combination thereof restrains the deposited material into a specific shape.

The solidification process competes with the gravitational fluid flow, ‘wetting-out’ and self-levelling tendencies of the ink and must be properly balanced to ensure shape retention and interlayer adherence.

Approximate deposition rate: 10^5 mm^3 h^{-1}
Approximate resolution: 1-100 µm

Wallin, T. J., J. Pikul, and R. F. Shepherd. "3D printing of soft robotic systems." *Nature Reviews Materials* 3.6 (2018): 84-100.

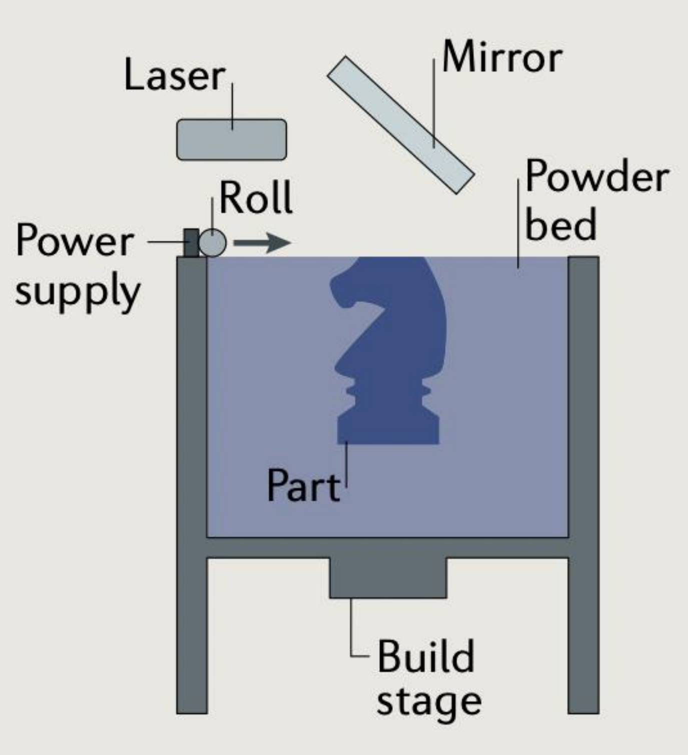
Direct Ink Writing with Two Part Silicone Elastomer



Two soft uncured components are mixed with a drill head and then extruded through a nozzle to deposit the material.

Yirmibesoglu et al. "Direct 3D printing of silicone elastomer soft robots and their performance comparison with molded counterparts." 2018 IEEE International Conference on Soft Robotics (RoboSoft). IEEE, 2018.

Selective Laser Sintering (SLS)



The working principle: A bed of solid, thermoplastic powder is selectively heated by a scanning laser. This irradiation causes localized melting and fusion of the material. Powder is then cast to recoat the bed, and the process is repeated. This technique is also called ‘selective laser melting’ when thermoplastic polymers are printed.

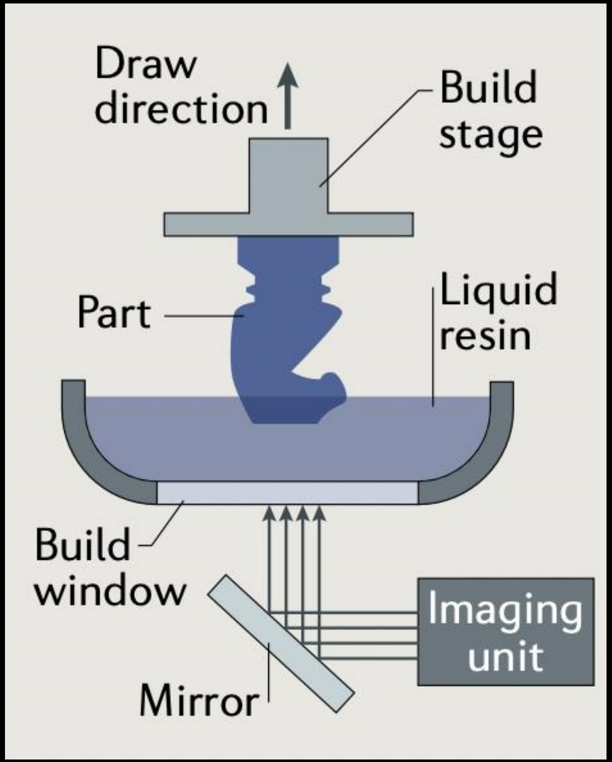
SLS requires a thermoplastic material in the form of a powder with narrow size distribution and homogeneous morphology to promote a uniform, dense powder bed.

Moreover, the temperature fields must maintain an appropriately sized melt pool in order to fully melt and fuse the material without distorting previously printed geometries.

Approximate deposition rate: 10^6 mm^3 h^{-1}
Approximate resolution: 100 μm

Wallin, T. J., J. Pikul, and R. F. Shepherd. "3D printing of soft robotic systems." *Nature Reviews Materials* 3.6 (2018): 84-100.

Stereolithography (SLA)



The working principle: A bath of liquid photopolymer is selectively exposed to light (through either a scanning laser or a projected photo pattern). The liquid resin polymerizes into a solid layer in response to photoirradiation. The object is then translated, liquid recoats the interface and the next layer is similarly exposed.

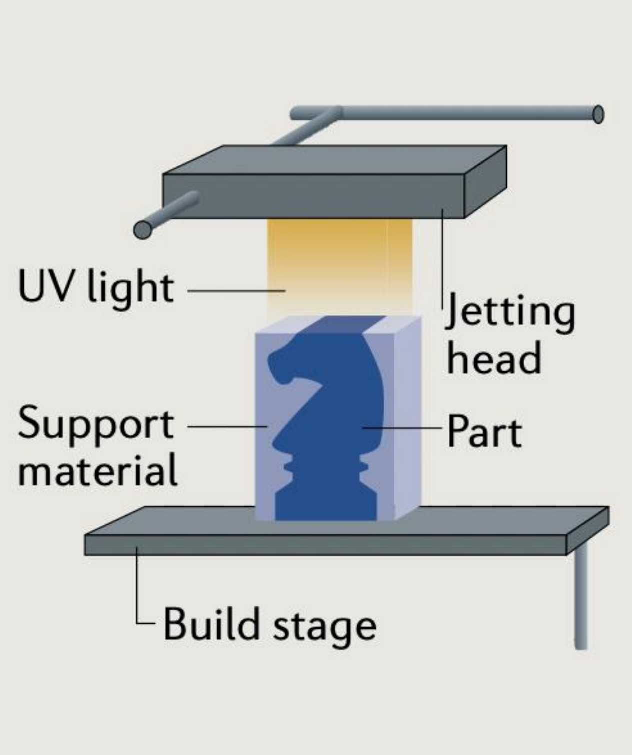
Synthesis in a dense medium provides buoyant forces capable of supporting soft, compliant structures, which is particularly useful for the printing of thin, overhanging structures.

The free-radical polymerization of acrylates and the cationic polymerization of epoxies provide the basis of many SLA resins.

Approximate deposition rate: 10^6 mm^3 h^{-1}
Approximate resolution: 1 µm (microsystem-based), 50 µm (projection-based)

Wallin, T. J., J. Pikul, and R. F. Shepherd. "3D printing of soft robotic systems." *Nature Reviews Materials* 3.6 (2018): 84-100.

Inkjet Printing



The working principle: Small droplets of liquid ink are simultaneously ejected from print heads. These droplets then solidify on the surface, often in response to light or heat. Jetting and solidification are iteratively repeated until the entire object is built.

Multiple nozzle heads can jet millions of droplets of different inks within seconds and at the same time maintain a lateral resolution on the order of 50 μm.

Mainly the flexible urethane-acrylate Tango series of materials ($E \approx 0.7$ MPa and $\gamma_{ult} \approx 270\%$), commercially available from Stratasys, has been used for soft robotic devices.

Limitation: limited viscosity range of ink

Approximate deposition rate: $5x10^5$ mm^3 h^{-1}

Approximate resolution: 50 μm

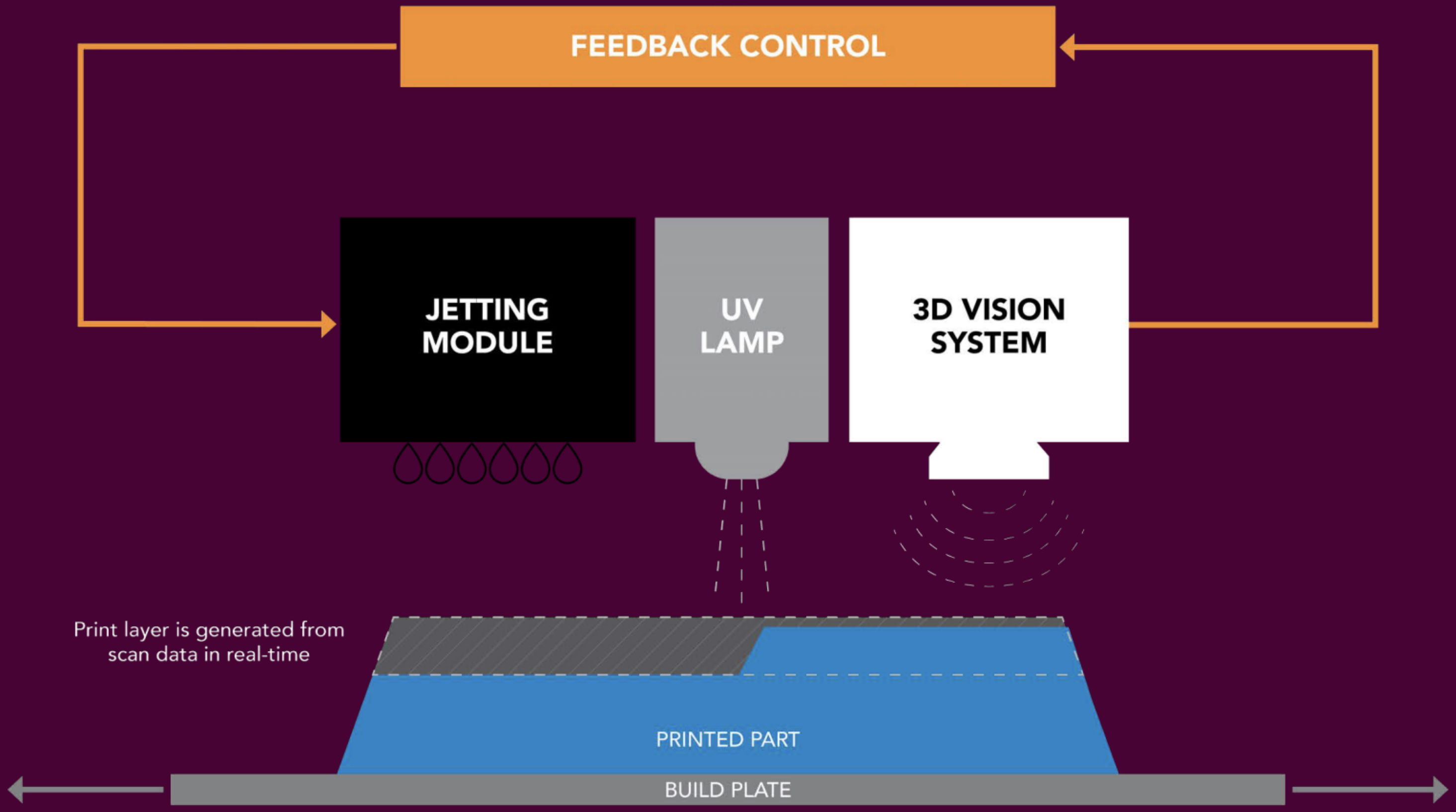
Wallin, T. J., J. Pikul, and R. F. Shepherd. "3D printing of soft robotic systems." *Nature Reviews Materials* 3.6 (2018): 84-100.

Inkjet Printing without Contacting: Vision-Controlled Jetting

Printer

Medical Device Example

Print Principle



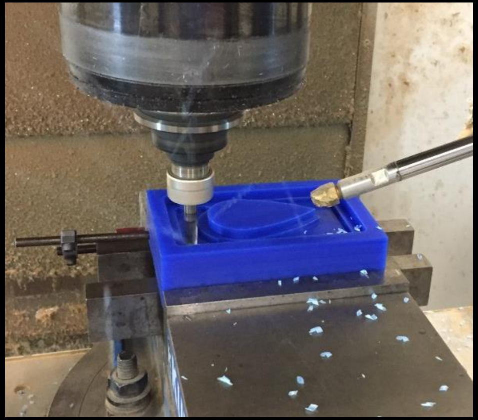
Buchner et al. 2023 / Inkbit

Summary

Machining, Joining, Casting, and 3D Printing

Fabrication Techniques for Robotic Hands

Summary



Machining

1. Drilling
2. Tapping
3. Laser cutting
4. Water jet cutting
5. Milling
6. Turning

…

Joining

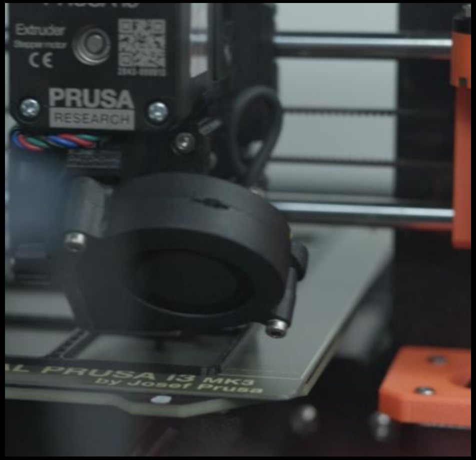
1. Adhesive Bonding
2. Fastening
3. Soldering

…

Casting / Molding

1. Soft Stereolithography
2. Lost Wax Molding
3. Injection Molding

…



3D Printing / Additive Manufacturing

1. Fused deposition modeling (FDM)
   Fused filament fabrication (FFF)
2. Direct Ink Writing (DIW)
3. Selective Laser Sintering (SLS)
4. Stereolithography (SLA)
5. 3D Inkjet printing

…

SoftRobotics Laboratory

Many more manufacturing techniqure: https://en.wikipedia.org/wiki/List_of_manufacturing_processes

Open To Dos

1. Determine responsible for the key to the workshop room
2. Start designing and building your hand
3. Use the submission form for 3D printing
4. Hardware checkup is end of this month

5. Please submit quiz on time
6. Please ask questions on Moodle:
   - on the tutorials
   - in the forum
7. Provide feedback to us about your experience in the course