# Mechanisms and Sensors for Robotic Fingers

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***Abstract*— : Grasping is achieved in robots by suitable finger mechanisms inspired from structures in nature. This paper discusses anthropomorphic fingers, their actuators and sensors, their characteristics and operation of their mechanisms.**

## I. Introduction

The first robotic hand, as it is commonly referred to, was perhaps the end-effector of the Handyman, a robot developed by Ralph Mosher for General Electric in 1960. Around 1969, the first research projects on robotic hands with three fingers including a "thumb" in opposition—hence an anthropomorphic design—began in the United States and in Japan.
The idea of copying the human hand is so old and may be contemporary of the first automata in the 18th century, e.g., La Musicienne of the inventor Jacquet-Droz (Rosheim 1994). This automate was able to play a wide variety of organ partitions with two five-finger hands actuated with steel cables connected to a programming cam shaft.
For a prosthetic hand the focus is much more on aesthetics, weight and broad range of functionality, while the supply of power is limited, so self-locking mechanisms are preferred. Today's prosthetic hands have integrated drive technologies and weigh less than 500 g.
Because of the dexterity of the human hand, most recent humanoid robots research projects addressed in their designs the anthropomorphism of the robotic hand. Many research laboratories around the world have developed prototypes of such hands as early as in the mid 1980's when the foundations of these studies were laid (Mason and Salisbury 1985), by taking the human hand as a model for the robotic manipulation, in terms of performance and versatility. But results thus far are not comparable with the performances of the human hand.
Anthropomorphism is the capability of a robotic end-effector to mimic the human hand.
Dexterity is the ability to autonomously perform highly precise operations with a certain level of complexity (visual/perceptual/tactile feedback). The dexterity domain can be divided in two main areas, grasping (grasped object is fixed with respect to the hand workspace) and internal manipulation (controlled motion of the grasped object inside the hand workspace).
The dexterity of robots has always been clearly more limited than that of a well-trained human being.
In fact we can find anthropomorphic end-effectors with very poor dexterity level, even if they are called hands, they perform very rough grasping procedures. Similarly, we can find smart end-effectors, capable of sophisticated manipulation procedures, but without any level of anthropomorphism.
Anthropomorphism is not necessary for achieving dexterity, and nor sufficient. But still it is desirable goal in the design of robotic end-effectors in operating in an environment where tasks may be executed by a robot or by a man, or in tele-operation of the end-effector by a man, or when it is required that the robot has human-like aspects and behavior.
Considering that the human hand is capable of prehension (grasping objects of different size and shape) and apprehension (understanding through active touch), then it is both an output and input device. It can apply forces and provide information about the state of the interaction with the object. These characteristics are desirable in advanced robot hands.
The average human hand is around 0.58% of total body weight (approximately 400g).
Human hands have a highly articulated thumb. Amputation of the thumb is cited to cause 40% loss of hand function and around 20% disability of the whole person. The main motions of the thumb are flexion, extension, abduction/adduction and opposition. The thumb facilitates the grasping tasks by means of these motions.

## II. Robotic Fingers

Fingers of the hand are organs of manipulation and sensation. They move in the following ways: flexion, extension, abduction and adduction.
The number of joints per finger in anthropomorphic robotic hands is extremely important since it provides the hand with conformance to shapes and acts as a contact surface for gripping and support structure for grasps.
Number of fingers in anthropomorphic robotic hands can differ, but increased number of fingers provide a larger grasping surface and increases conformity to shapes.
The anatomy of fingers in nature shows us the following

design characteristics:

- A serial bone-link structure mainly for rigidity and load capability.
- An actuation muscle system aiming to rotate each bone-link independently but with coordinate movements with other finger links.

## III. Requirements for Artificial Fingers

In general common requirements can be identified mainly in the aspects for:

1) Motion properties in:
   - Grasping configurations
   - Smooth approaching motion
   - Adaptable motion configuration to object shapes
   - Reconfigurable grasping configurations
   - Workspace ranges
   - Limited motion impacts again objects to be grasped
2) Force capability in:
   - Stable grasping configurations
   - Efficient transmission of input power to grasping forces
   - Distribution of grasping forces among several contacts with grasped object
   - Positions of application points of the grasping forces
   - Adjustable grasping forces
3) Mechanical design in:
   - Stiff or compliant structure at grasp
   - Phalanx shape for adaptability to object shape
   - Room for sensors
   - Compact design versus human-like solutions
   - Lightweight solution with smart or traditional materials
   - Low-friction joints
   - Location of power source

A general procedure can be outlined as in Fig.1.

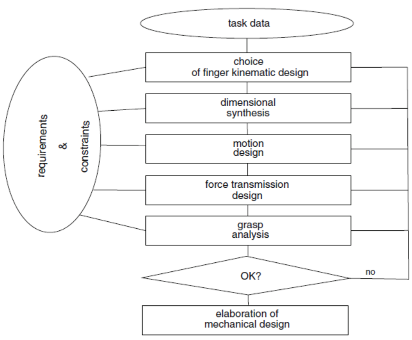


Fig. 1: A flowchart for design procedure of finger mechanisms

## IV. Actuators

Human hands vary greatly in their speed and grip force and are capable of reaching up to 400 N in everyday tasks. This kind of actuation characteristics is not achievable with the current motors available in the market, considering them to be situated in the hand. For that reason remote actuation is used in many cases, for example by placing actuators in the forearm and using tendons to transmit the forces to the finger joints.
For developing anthropomorphic finger mechanisms researches used two different approaches: complex mechanisms for performing manipulation tasks with high dexterity, or mechanisms with a reduced number of degrees of freedoms (DoFs) and actuators.

1) **Level of actuation:** Aside from the number of fingers and number of joints per finger, robotic hands can be distinguished by their level of actuation.

   - fully actuated: every joint is independently controllable DoF = DoC
   - under actuated: some of the joints are coupled mechanically DoF ¿ DoC

   Underactuated hands are preferred by designers because of the reduction of required actuators which affects the size, the weight and the complexity of the hand. This also makes the control of the system simpler.

2) **Type of actuation:** Actuators and transmissions used in robotic hands can be:

   - electric motors
   - pneumatic actuators
   - hydraulic actuators
   - shape memory alloys (SMA)

   Despite the electric motors represent the choice with smallest power density it is the most common solution adopted in the development of robotic hands. This is compensated by the flexibility and simplicity of the control, and the wide availability of the batteries.
   Pneumatic actuators have high power density, but low stiffness, and that makes the control complicated. The energy required has to be stored in a tank (big volumes), the system needs compressor, pressure sensors and regulator. All these components take a quite a bit of valuable space and are quite expensive.
   Hydraulic actuators have very high performance indices but have the same storage difficulties of pneumatic actuators, and they are hard to miniaturize because they need to work with high pressures.
   The shape memory alloys (SMA) are materials that have the ability to contract when heated above a certain temperature allowing muscle-like movements.

They are very compact, totally silent and when contracting exhibit ample forces. Consequently, they can be successfully used for driving dexterous prosthetic hands.
One major disadvantage is their response speed which is relatively slow being limited by the speed with which the SMA can be heated and cooled. Other disadvantages are the power requirements, control difficulties and the limited internal space. This technology seems to be not mature yet.

3) **Type of transmission:** The mechanism for transmitting the motor power to the joints could be categorized as:

   - tendon and pulleys or sheath, like steal wires, synthetic strings, plastic strips
   - link transmission (rigid connection), like gears, articulated mechanism

   Using tendons to transmit the power to the joint shaft allows us to place the actuators remotely. It also allows us to reduce the number of parts required for the linkage.
   The classical geared coupling mechanisms add weight to the device but offer better performance in terms of friction. It is a good solution especially when we are limited with the available space and actuators have to be integrated in the palm of the hand or in the fingers.

## V. Sensors

Sensors play a major role in anthropomorphic robotic hands. They are what robotic systems use to get useful data of its own state or the environment around it. Some of the key types of sensors are:

- **Joint / Position sensors:** They give feedback on the link and joint position in the robot's workspace. In underactuated hands, it also provides feedback on the grasp and its conformity with the shape of the object being handled.

- **Force / Torque sensors:** To get information on the amount of the force being applied by the hand on the environment and the forces and torques that are present within the system itself.

- **Tactile / Touch sensors:** The functional versatility (adaptability to different situations) of the human hand comes from the integration of its exteroception (sensitivity to environmental stimuli) and proprioception (perception of the position and movement) abilities. Information gathered by both of these classes is what is referred to as "haptic perception". Touch is a complex human sense distibuted on the body and gives a whole body experience. It allows us to determine things about the objects we come in contact with, like their hardness, texture, shape, temperature, etc. But also allows us to realize the changing state of our interactions with them.
  Motivated by these aspects of the human touch emerged the study of artificial tactile sensing to enhance the performance of the robotic end-effectors by equipping them with tactile senors that give feedback about the magnitude and direction of forces at contact points with the objects they are interacting with.
  As proposed by [1] the minimum functional requirements for a robotic tactile sensing system mimicking human manipulation is summarized as:

  - Detect the contact and release of an object.
  - Detect lift and replacement of an object.
  - Detect shape and force distribution of a contact region for object recognition.
  - Detect contact force magnitude and direction for maintaining a stable grasp during manipulation.
  - Detect both dynamic and static contact forces.
  - Track variation of contact points during manipulation.
  - Detect difference between predicted and actual grip forces necessary for manipulation.
  - Detect force and magnitude of contact forces due to the motion of the hand during manipulation.
  - Detect tangential forces due to the weight and shape of the object to prevent slip.
  - Detect tangential forces arising from variations in object parameters (e.g. surface friction, elasticity, etc.) to prevent slip.

  Most common tactil sensor configurations are:
  - Resistive sensors
  - Piezoelectric sensors
  - Capacitative sensors
  - Magnetic transduction sensors
  - Photoelectric, or optical, tactile sensors

- **Other sensors:** temperature, olfactory, vision, depth sensing, stress, strain, twist etc.

The skin of human body is covered with a continuous network of tactile sensors offering feedback about the amount of force applied and the region the force is applied to, within a threshold.
The skin temperature can assist in identifying the object while grasping especially when there is no visual feedback (trying to grasp in the dark).
Cameras could be integrated on the palm and fingers of robotic hands, therefore making it possible to have a wide view when far away and high resolution when close up, with the freedom to actively avoid occlusions.

## VI. Worldwide evolution of robotic hands

A comparison chart for robotic hands researched and developed between the years of 1979 to 2016 is presented in the Table I

- **iHY robot hand**
  - **Design:**

    Researches at Harvard, Yale and iRobot designed

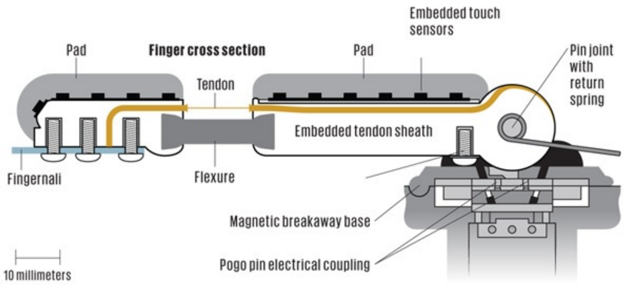


Fig. 2: Cross-section view of the iHY finger design

the iHY hand for the DARPA ARM challenge. The hand is designed to be flexible, strong and versatile. And can grip objects from pair of scissors to 22 Kg kettlebell.

The iHY finger, Fig.2, was constructed using a casting and over molding process. The internal components of the fingers (circuit boards, sensors, wiring, and cable guides) were inserted into the mold cavity. It has a two-link modular design. The links are made of hard plastic and connected by a pliable rubber, they can adapt to almost any shape. Cables that run along the fingers act as tendons, tensing and relaxing to grip and release.

To grip an objects the fingers bend around them mathcing their shapes. Then the cables tense up and form a tight grip around the object.

The proximal finger joint is mounted on a magnetic base, which serves both as an attachment point and as a high-force breakaway coupling, to avoid damages in case of a damaging collision.

Spring-loaded ”pogo pin” electrical coupler makes replacing the finger easier.

The proximal pin joint includes a torsion spring, which provides the proximal joint with some elasticity.

The high elasticity of the fingers is an important feature, especially at the distal flexure. Because the fingers do not have extensor tendons, the joint elasticity alone extends the fingers when the flexor tendons are relaxed. This also serves the purpose of passive adaptation to the shape of the object grasped, which removed the need to detect and react to small variations in surface geometry.

Removable nails are mounted on the fingers, fastened by screws to allow for varying nail lengths. This inexpensive feature on the iHY Hand proved to be useful when grasping small objects or sliding the finger along a surface, which provides a repeatable point of contact and a mean for passively aligning the finger against the surface on which the object is located.

The monolithic structure of the fingers, without seams or fasteners, make the fingers resitant to water, dirt, and impact.

  - **Sensors:**

    The iHY Hand’s sensor system (Fig.3) consists

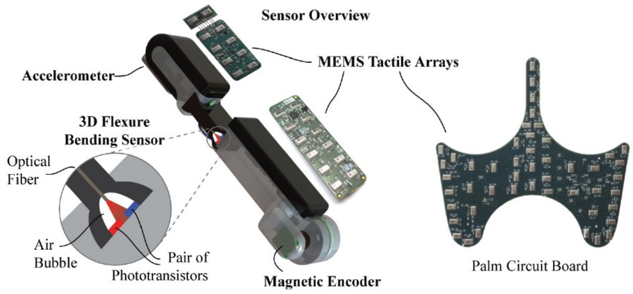


Fig. 3: iHY finger sensors

of tactile arrays that cover the fingers and palm. Flexure deformation sensors in each distal finger joint, magnetic encoders at each proximal finger joint, and acceerometers in the distal finger links.

- Shadow EDC Hand
- The handroid
- DLR hand II
- The PISA/IIT soft hand
- UW’s Hand
- AR10 humanoid hand
- H2 compliant hand
- Robotiq 3 Finger Gripper
- SDM compliant hand
- Modular Soft Robotic Gripper
- RBO Hand 2
- iLimb ultra
- Michelangelo hand
- IH2 Azzurra

TABLE I: Hand comparison chart from 1979 to 2016.

| Name | Sensors | Fingers | Transmission | Research Institute | Year | DOF | DOA | Actuators | Weight [Kg] | Load [Kg] | Load [N] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Okada Hand | Potentiometers | 3 | Tendons | | 1979 | 11 | | DC Motors | | | |
| Stanford/JPL Hand | Tactile Sensors, Tension tendons sensors | 3 | Tendons | Stanford University | 1983 | 9 | 9 | Electrical (DC) | 1.1 | | 110.8 |
| Utah/MIT | Hall effect sensors, Tendon tension sensors, tactile distributed sensors | 4 | Tendons | Utah University | 1985 | 16 | 16 | Pneumatic Cylinders | 9 | 9 | |
| Belgrade/USC Hand | Potentiometers as positions sensors, Force resistors | 5 | | Belgrade University | 1988 | 15 | 4 | Electrical Motors | | 2.26 | |
| BarrettHand | Optical Encoders, Tactile sensors | 3 | Tendons, worm gears | Barret Technology Inc. | 1988 | 8 | 4 | Electrical Brushless motors | 1.2 | 6 | |
| DLR Hand I | 28 Sensors on each finger, hall sensors, optical position sensor, torque sensor, force sensor, tactile sensors and stereo camera | 4 | Tendons | DLR-German Aerospace Center | 1997 | 16 | 12 | Electrical | | | |
| Dist Hand | Rotation sensors in each joint | 5 | Tendons | Genova University | 1998 | 16 | 16 | Electrical | 1 | | 1.96 |
| Robonaut Hand | 42 sensors plus tactile sensors | 5 | Tendons | NASA Johnson Space Center | 1999 | 19 | 14 | Electrical Brushless Motors | | 9 | |
| Gifu Hand | Magnetic encoder in the motors shaft and tactile distributed sensor | 5 | Gears , Links | Gifu University | 1999 | 20 | 16 | DC Micromotors | 1.4 | 1.83 | |
| Robotiq 3 Finger Gripper | current sensor, position sensor, grip sensor | 3 | gears and links | Laval University | 1999 | 10 | 4 | DC Motors | 2.3 | 10 | |
| Blackfingers | Position and force sensors directly on the actuator | 5 | Tendons | Politecnico de Milano | 2000 | 22 | 36 | Mckibben Actuators | | | |
| Tuat/Karlsruhe Hand | | 5 | Tendons | Tokyo and Karlsruhe Universities | 2000 | 24 | 1 | Electrical | 0.49 | | |
| Ultralight Hand | | 5 | NONE | Research Center of Karlsruhe | 2000 | 18 | 13 | Flexible Fluidic actuators | 0.2 | 1.22 | |
| Variable Force Hand | | 5 | Tendons | Hokkaido University | 2000 | 10 | 5 | | | | |
| DLR Hand II | Torque sensors in each joint | 4 | Tendons | DLR-German Aerospace Center | 2001 | 17 | 13 | Electrical | 2.2 | 3.059 | |
| RTR Hand I | Hall effect sensors, strain gages as force sensors | 3 | Screws | Centro INAIL RTR, Scuola Superiore Santa Anna | 2001 | 9 | 3 | DC Micromotors | | | |
| Dexterous Robot | | 4 | Tendons | Maryland University | 2001 | 12 | | | | | |
| Shadow EDC Hand | Hall effect sensors, Tactile sensors | 5 | Tendons | Robot Shadow Company Ltd. | 2002 | 23 | 23 | Pneumatic muscles | 4 | | |
| Thinh Hand | Bend Sensors, Camera for visual control of the thumb pronation angle | 4 | Tendons | Florida University | 2002 | 14 | 6 | Electrical | | | |

*(continued)*

Table I *(Continued)*.

| Name | Sensors | Fingers | Transmission | Research Institute | Year | DOF | DOA | Actuators | Weight [Kg] | Load [Kg] | Load [N] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| High Speed Multifingered Hand | Strain gages, Camera for image processing | 3 | Miniharmonic drive, bevel gears | Tokyo and Hiroshima Universities | 2003 | 10 | 10 | Electrical | 0.8 | 2.85 | |
| SMA Hand | Planed to have Position Sensors, Force Sensors and Touch Sensors | 4 | Shape Memory Alloy Wires | State University of New Jersey | 2004 | 14 | | Electrical | 1.3 | 3.6 | |
| ARMAR Hand | Angle sensors, Force Sensors and Pressure Sensors | 5 | Flexible Fluidic Actuators | University of Karlsruhe | 2005 | 8–18 | 8–16 | Micro Gear Pump | 0.49 | 11.21 | |
| UB Hand III v1 | Strain=gauge based sensors, position sensors, tendon force sensors | 5 | Elastic Hinges with Tendons | University of Bologna | 2005 | 20 | 16 | DC Brushed Motors | | | |
| RL1 Hand | Tendon Tension through mathematical approximation | 3 | Tendons | Universidad Carlos III de Madrid | 2006 | 8 | 1 | DC Motors | 0.25 | 2 | |
| AAA Hand | External optotrank (Infrared optical device) | 3 | Tendons | Scuola Superiore Santa Anna | 2007 | 10 | 4 | DC Motors | 0.25 | 3.56 | |
| FRH-4 Hand | Position Sensors, Tactile Sensors | 5 | Flexible Fluidic Actuators | Research Center Karlsruhe | 2008 | 11 | 12 | Gear Pump | 0.216 | 11.21 | |
| IH2 Azzurra | Tendon Force Sensors, 2 Axis fingertip force sensor | 5 | Tendons | Prensilia | 2008 | 11 | 5 | Electric Motors | 0.6 | 10.2 | |
| UB Hand III v2 | Optical angular sensors, Optical Tensor Sensors, Strain gauge tension sensors | 5 | Tendons | Bologna University | 2009 | 20 | | Mckibben Artificial Muscles | | | |
| TH-3R Hand | | 5 | Gears, Racks | Tsinghua University | 2009 | 15 | 4 | Motors | | | |
| Columbia Hand | Position Sensors, Tactile Sensors | 3 | Tendons | Columbia University | 2011 | 9 | 2 | Motors | | | |
| The Handroid | | 5 | Tendons | ITK Company | 2011 | 16 | 5 | DC Motors | 0.725 | | |
| KYTECH Hand | Position Sensor | 4 | Gears | Korea Institute of Industrial Technology | 2012 | 16 | 16 | DC Motors | 0.9 | 1.5 | |
| The PISA/IIT Soft Hand | | 5 | Tendons, Rolling cylinders | University of Pisa | 2012 | 18 | 1 | Electric Motor | | | |
| TDM Hand | No sensors, force approximation using Ozawa and Moriya technique | 3 | Tendons | Ritsumeikan University | 2013 | 12 | 12 | DC Motors | | 5.1 | |
| iHY Robot Hand | Pressure sensors, Optic sensors | 3 | Tendons | Yale and Harvard University | 2014 | 9 | 5 | DC Motors | | 22 | |
| Soft Robotic Hand | Resistive Bend sensors | 3 | Pneumatic tubing | Massachusetts Institute of Technology | 2015 | | | Pneumatic piston | | | |
| HALS | | 5 | Tendon | Yokohama National U | 2016 | 9 | 5 | DC Motor | 1.2 | 3.059 | |
| RBO Hand 2 | | 5 | Pneuflex | Berlin University of Technology | 2016 | 5 | 7 | Pneumatic | 0.178 | 0.5 | |
| UW's Hand | Joint and Tactile Sensors | 5 | Tendons | University of Washington | 2016 | | 10 | Servo Motors | 0.942 | | |

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