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

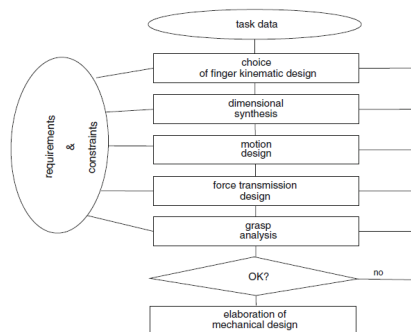A general procedure can be outlined as in Fig.1.

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:** As proposed by Yousef, H. et al. [9] 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.

- **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.

TABLE I: Hand comparison chart from 1983 to 2016.

Name	Sensors	Fingers	Transmission	Research Institute	Year	DOF	DOA	Actuators	Weight [Kg]	Load [Kg]	Load [N]
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			

TABLE II: (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 Pump 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		

LIST OF FIGURES

REFERENCES

[1] M. Ceccarelli, "Notes for a history of grasping devices," in *Grasping in Robotics*.   Springer, 2013, pp. 3–16.

[2] G. Carbone, "Stiffness analysis for grasping tasks," in *Grasping in Robotics*.   Springer, 2013, pp. 17–55.

[3] L. Birglen, T. Laliberté, and C. M. Gosselin, *Underactuated robotic hands*.   Springer, 2007, vol. 40.

[4] M. T. Mason, *Mechanics of robotic manipulation*.   MIT press, 2001.

[5] T. Iberall and C. L. MacKenzie, "Opposition space and human prehension," in *Dextrous robot hands*.   Springer, 1990, pp. 32–54.

[6] L. Biagiotti, F. Lotti, C. Melchiorri, and G. Vassura, "How far is the human hand," *A review on anthropomorphic robotic end-effectors*, 2004.

[7] A. V. Sureshbabu, G. Metta, and A. Parmiggiani, "A systematic approach to evaluating and benchmarking robotic hands-the ffp index," 2018.

[8] H. Yousef, M. Boukallel, and K. Althoefer, "Tactile sensing for dexterous in-hand manipulation in robotics—a review," *Sensors and Actuators A: physical*, vol. 167, no. 2, pp. 171–187, 2011.

[9] J. Huber, N. Fleck, and M. Ashby, "The selection of mechanical actuators based on performance indices," in *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, vol. 453, no. 1965.   The Royal Society, 1997, pp. 2185–2205.

[10] K. Andrianesis and A. Tzes, "Design of an anthropomorphic prosthetic hand driven by shape memory alloy actuators," in *Biomedical Robotics and Biomechatronics, 2008. BioRob 2008. 2nd IEEE RAS & EMBS International Conference on*.   IEEE, 2008, pp. 517–522.

[11] C. S. Loh, H. Yokoi, and T. Arai, "New shape memory alloy actuator: design and application in the prosthetic hand," in *Engineering in Medicine and Biology Society, 2005. IEEE-EMBS 2005. 27th Annual International Conference of the*.   IEEE, 2006, pp. 6900–6903.

[12] M. Ceccarelli, "Finger mechanisms for robotic hands," in *Recent Advances in Mechanism Design for Robotics*.   Springer, 2015, pp. 3–13.

[13] W. T. Townsend, "Barretthand grasper: Programmably flexible part handling and assembly," *Humanoid Robotics: A Reference*, pp. 1–17, 2018.