Introduction

In the coming decades, robotics is expected to impact society on a massive scale economically and socially in the manufacturing, healthcare, medical, and defense sectors. While great achievements have been made in the areas of computer vision and autonomous navigation one of the biggest drawbacks with robots so far is that they cannot accomplish physical interaction tasks in everyday settings. Specifically, robots cannot grasp and manipulate objects in unstructured environments, or environments for which they have not been designed.

A key goal of the robotics community is to build robotic hands that can accomplish human grasping and manipulation tasks in human environments by physically interacting with humans and objects.

The human hand is capable of performing complex and useful tasks using an effective integration of mechanisms, sensors, actuators and control functions, and at the same time is also a cognitive instrument, allowing humans to develop a superior intellectual capacity by interacting with the surrounding environment.

The human hand has been an inspiration for robotic hand designers for decades. There are several reasons for that. First, the human hand exhibits tremendous dexterity and flexibility. Second, everyday tools, objects, and environments are designed for use by a human hand, thus it is advantageous to mimic the human hand when designing robot hands to operate those same tools and objects in human environments. Third, the anthropomorphic form factor is highly relevant to prosthetic applications. Thus most robot hand designs mimic the human hand.

However, the human hand is difficult to mimic since it is a complex system. In terms of “hardware,” the human hand contains 22 joints driven by nearly 38 muscles through a complex web of tendons. In addition, it has thousands of embedded sensors that provide information about posture, muscle and tendon forces, contact, interaction forces, vibration, and temperature. In terms of “software,” there are millions of neurons in the brain and the spinal cord that integrate information from the raw sensory signals before providing control signals through synergistic control inputs and reflex loops. Together, these different features enable the hand to perform a variety of dexterous tasks, but the role that each component plays in different tasks is not entirely clear.

Replicating the human hand is still one of the main challenges of robotics, requiring large efforts, based on multidisciplinary knowledge ranging from engineering to neuroscience.

Note that some researchers are moving away from using the human hand as the template for robotic hands because of the difficulty in mimicking its compactness, form, and control. Specifically, they are designing “underactuated robotic hands” with many degrees of freedom but reduced number of actuators. These designs utilize tendon-driven systems or linkage mechanisms for creating movement and achieving human-like grasping capability. Such hands can surely address design criteria such as robustness and simplicity of sensing and control for static grasping. However, much work is still required to achieve human-like dexterity for manipulation.

The six most important features that should be considered during the design and development phase are:

1- Design

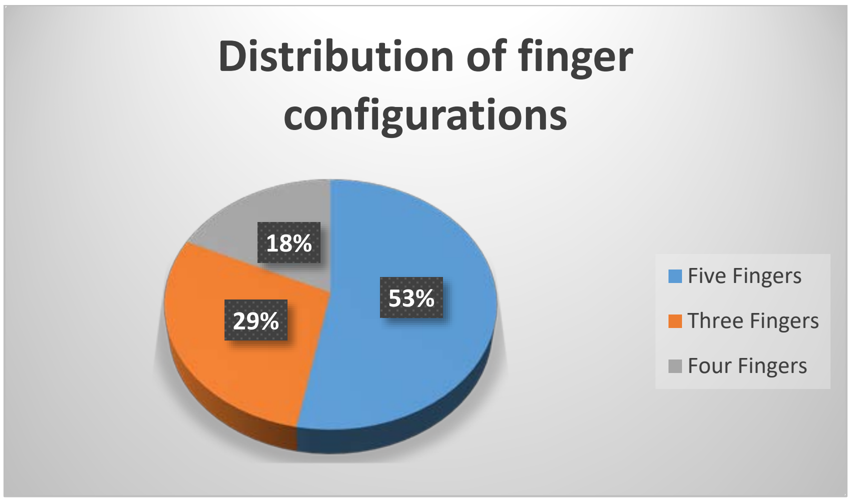
2- Transmission

3- Sensors

4- Materials and manufacturing

1- Design:

Due to the fact that the robots are moving to more dynamic and human populated scenarios where the need to grasp objects under the presence of uncertainty and new objects might arise, five finger configuration of robotic hands is being superior to the three or four finger configurations.



The five-finger hands can provide more flexibility and grasping postures compared to a traditional gripper due to their more available postures. The correct hand configuration is task and environment dependent.

However, problems arise when attempting to produce fully actuated anthropomorphic hands, because obviously, the ability to control becomes more difficult and the weight increases as the number of actuators rises. This is why most of the hands have an underactuated nature (with more degrees of freedom than actuators). The underactuated hands probed that they can grasp diverse objects with ease just as fully actuated hands, but need less energy, their weight and cost are less and the control is simpler. This lead to the research in tendon-based actuation, unconventional actuator systems (the twisted string actuation), sensors and new material to provide reliable tendon networks.

2- Transmission:

Mechanical design should be as simple and reliable as possible. A high number of DoF is desirable in order to obtain a greater dexterity, but it should be obtained without increasing the complexity.

In designing artificial hands a wide range of transmission systems such as tendons, linkages, gear trains, belts or flexible shafts can be employed. Important design goals are to minimize friction, backlash and inertia while trying to maintain small overall size and weight.

Mechanisms reported in literature are:

Multiple Transmission mechanism (MT), which consists on cables driving through pulleys, all at the same time, or independently, allowing movement of each link in the robotic finger (RTR2 hand). MT includes an engine coupled to a gear, a shaft-coupling system and a pulley block system (SARAH Hand).

Differential Mechanisms, which is an important class of mechanism used in underactuation. It provides two outputs for one input. Hence, it is necessary to connect them in order to achieve n DoF.

The slider crank mechanism, which comprises a mechanism driven by a linear actuator, and its movement is used to directly drive the robotic finger joints with multiple phalanges.

Linkages or trains of gears driven Mechanism (underactuation): It is the most common mechanism. The linkage mechanism allows all fingers phalanges manipulation using springs and mechanical limits (Belgrade/USC Hand). Gear train transmission can be found in the DLR/HIT Hand and in the Gifu Hand.

Advantage: they give the best stiffness proprieties to the transmission, low maintenance is required, and they allow bidirectional control of the joint.

Disadvantage: Their employment substantially increases the weight, complexity and sometimes dimensions of the hand.

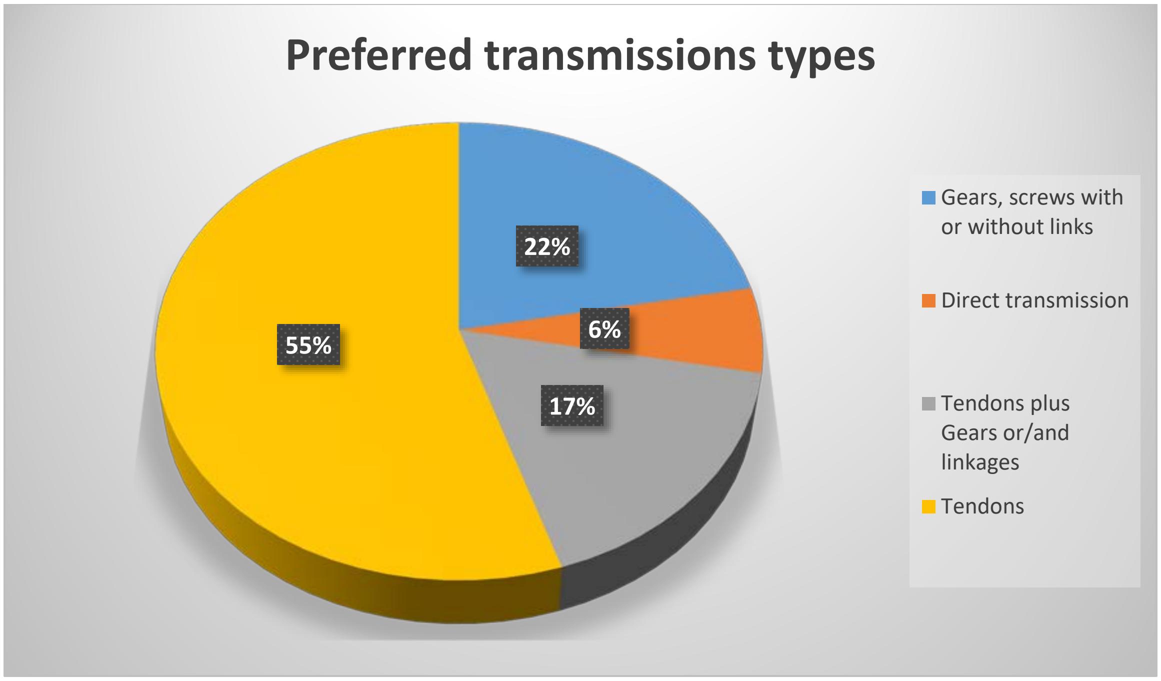
Cable-driven mechanism (underactuation): Also called tendon-pulley mechanism, it is maybe the first modern type of mechanism for underactuated finger. This mechanism can be very effective for small forces, and with appropriate control, can compensate elasticity and friction. It is useful for example, for lightweight prosthesis devices.

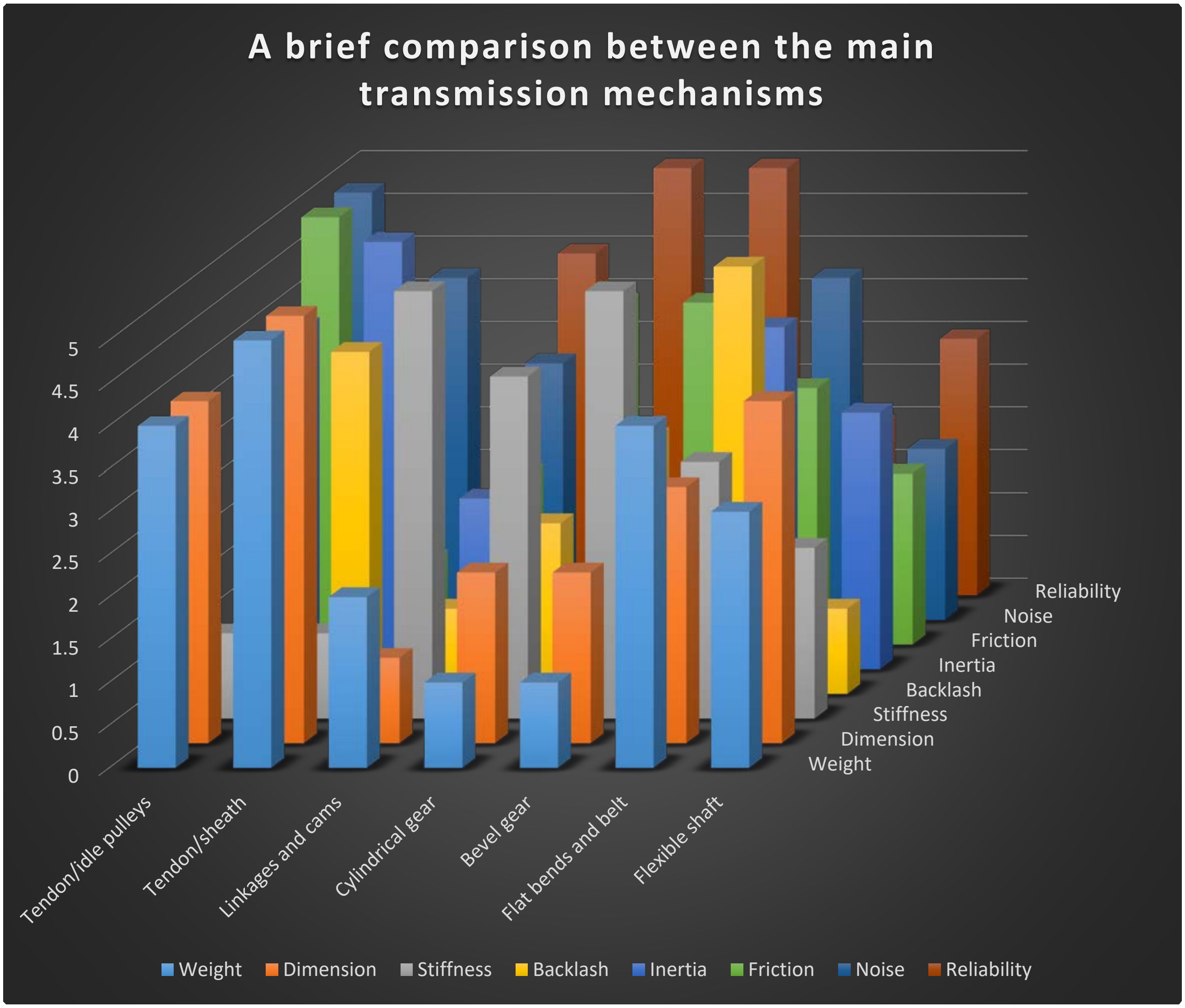
Advantage: It allows actuators to be located remotely from joints, reducing the dimensions and weight of the fingers.

Effects of friction can be drastically reduced by replacing sheaths with idle pulleys at the expense of system and control complexity or by flat bends instead of tendons in order to increase the strength and stiffness of the transmission system, as in the Utah/MIT Hand.

Disadvantage: friction between tendon and sheath that occurs in curves introduces non-linear effects and reduces efficiency.

The preferred transmission type is tendons; tendons simplify the design and allow taking the actuators off from the hand; however, they have the problem of causing errors. The gears with zero backslash have more accuracy, but they have more friction too. The direct transmission could be the best, but its design difficulty makes it less used.


Preferred transmissions types
22%
6%
17%
55%
Gears, screws with or without links
Direct transmission
Tendons plus Gears or/and linkages
Tendons



<u>3- Sensors:</u>

A dexterous robotic hand must be dotted by sensors that can measure internal parameters like position and velocity in the joints, and external parameters like temperature, humidity and surface roughness. Sensors that are adopted in a robot are related to the specific applications of the hand, and also depend on the environment conditions in where the robotic hand is going to operate.

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”.

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 sensors that give feedback about the magnitude and direction of forces at contact points with the objects they are interacting with.

Most common tactile sensor configurations are:

– Resistive sensors

– Piezoelectric sensors

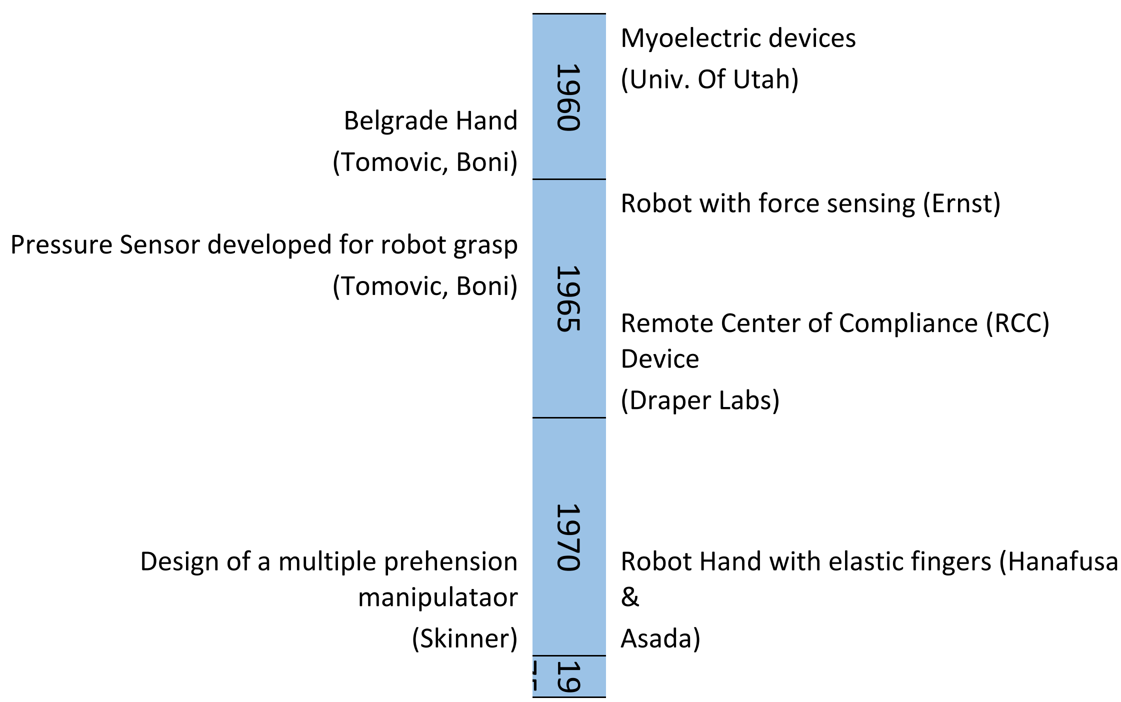
– Capacitative sensors

– Magnetic transduction sensors

– Photoelectric, or optical, tactile sensors

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.

A time line on development of dexterous robotic manipulation:



Computer control of multi-joint finger system for precise object handling (Okada)	1980	Work on fine manipulation begins
Formalizing the Grasp Problem, introduction of the Grasp Jacobian (Mason&Salisbury)		Direct drive robot developed (Asada)
		Salisbury/Stanford/JPL Hand
Grasp Choice Algorithms (Laugier & Pertin, Jameson)		Utah/MIT Hand
Grasp Taxonomies, Grasp/Contact Kinematics (Cutkosky)	1985	Stiffness/Impedence control (Hogan)
		Hybrid position/force control strategies
Operational Space Formulation (Khatib)		Styx Hand (UC Berkeley)
NYU Planar Hand Grasp/Contact Kinematics (Kerr & Roth)		Contact Equations (Montana)
Touch Sensors (Allen, Howe, Mackawa)	1990	Grasp Quality Measures (Li & Sastry)
Grasp Gaiting (Leveroni)	1995	Phase Based Manipulation (Hyde)
Manipulation/Exploration of Unknown Objects (Allen, Bicchi, Okamura, Pai)		Grasp force Optimizations (Buss)
	2000	Hands with very realistic look-and-feel development
		ARMAR hand (SFB588 Research Center)
UB Hand III (University of Bologna)	2005	Proto II Limb (APL, John Hopkins University)

Cyberhand (ARTS, Scuola Superiore Sant'Anna)

2010

4- Materials and Manufacturing:

The design and fabrication of a prototype using traditional machinery techniques is a rather long and expensive process, and often the employment of rapid prototyping techniques provides several advantages towards the development of a functional prototype. One of the main advantages is repreented by the chance to develop parts with complex geometry that could not be manufactures using traditional techniques.

Won et al. developed a five-finger anthropomorphic hand by using a Selective Laser Sintering technique (SLS), which allows joints to be manufactured in one-step without requiring assembly. The main drawback of SLS is the lack of mechanical proprieties (such as stiffness and strength), moreover it fails when dimension tolerances are narrowed.

Dalley et al. developed a transradial anthropomorphic hand, in which the parts were physically realized in high-strength, nickel-coated thermoplastic using an additive directly incorporated during the manufacturing process; this method combines the flexibility of the rapid technique with the strength/stiffness of the metallic material. The main drawbacks of this method are the low fatigue resistance, and poor surface finish and geometrical tolerance that often requires re-machining by traditional methods.

Dollar and Howe showed how a further integration of sensors, electronics and actuation could be obtained using polymer-based Shape Deposition Manufacturing (SDM). Another advantage of the SDM technique is the possibility of simultaneously creating rigid links and compliant joints of the fingers, providing the hand with passive mechanical compliance useful for grasping in unstructured environments.

The use of compliant materials in manufacturing of joints allows a number of components to be avoided (such as pulleys, axis, torsion springs, and so on) and the ability to embed the extension system, disguised as releasing springs, in the structure thus resulting in a reduction in joint size. Examples of artificial hands exploiting compliant joints based on these principles were developed at the University of Bologna, Stanford, Genoa, Scuola Superiore Sant'Anna, and University of Iowa.

In the last few decades researchers have investigated new materials with proprieties close to the human skin. The necessity of compliant materials for fingers is better understood by considering the physiology of the human finger, which can be summarized as a multi-layer structure where the layers have different mechanical properties.

- The skin: the sense of touch and in the mechanics of contact.

- The soft tissue: responsible for strain dissipation during force interaction so to reduce wear and possible damage.

- The bone: the stiff core of the finger.

- The nail: suppresses excessive deformation of soft tissue and enlarges the range of the possible friction coefficient.

Examples of bio-inspired fingertips for robotic hands were developed by the University of Leeds and Bologna.

Future Trends

- Use of lightweight, low cost, compact and high precision actuator arrays.

- Security and comfort are important issues to consider.

- Soft and compliant materials will often prevail when the hand is used to interact with humans

- Development of artificial skins with denser spatial resolution and a multitude of sensor modalities.

- Sensors employed in smartphones will be employed by the artificial hands driving costs down and increasing reliability.