1

A Mechatronic Perspective on Robotic Arms and End-Effectors

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1. Introduction

The robotic industry has constantly strived towards developing robots that harmoniously coexist with humans. Social robots, as they are often dubbed, differ from their industrial counterparts operating in assembly lines by almost all aspects except the adjective "robotic". Social robots are often classified as robots that interact with humans, suggesting that they must possess a human-like morphology in order to fit this designation. A broader definition of the term social robots, however, encompasses any robotic structure coexisting in a society, capable of bringing comfort or assistance to humans. These robots can range from housekeeping wheeled rovers to bipedal robots, prosthetic limbs and bionic devices.

The distinction between industrial robots and social robots stems from the different environments in which they operate. The nature of the interaction with humans and the surroundings in an urban environment imposes a new stream of requirements on social robots, such as mobility, silent actuation, dexterous manipulation and even emotions. Unlike industrial robots where these constraints are alleviated in favor of strength and speed, the development of social robots for an urban environment is associated with more extreme specifications that often relate to engineering challenges and social considerations, including public perception and appeal. The robot will either be accepted by society or rejected due to unattractive or unfamiliar features. Many of these considerations are sometimes ignored by researchers although they are critical to the integration of these robots in the society as an adjunct to human faculty.

In the context of robotic manipulation related to social robots operating in an urban environment, which constitutes the scope of this chapter, the progress achieved in this field in terms of hardware implementation is remarkable. Recent developments feature manipulator arms with seven degrees of freedom and robotic hands with twenty four joints that replicate the dexterity of a human hand. This level of dexterity is appealing to the end-user because it brings familiarity to the general conception of robotic limbs, thus making the technology more acceptable from a social standpoint especially when it comes to bionic integration and prosthetic rehabilitation.

However, the cost of this technology is high due to hardware complexity and size. Other urban applications, such as search-and-rescue or police operations, favor higher payload capabilities of the arm and end-effector over a higher level of manipulation and dexterity.

Choosing between payload capabilities and dexterity is a decision a user has to make when selecting a robotic system. With the current actuators technology, these two parameters seem to be inversely proportional, with systems providing one or the other, but seldom both.
The social perception of a robotic arm or hand is also affected by the level of autonomy it can provide. In general, the complexity of the kinematics associated with these systems makes their real-time control complicated when operated in closed loop with sensor feedback. A sensor network including tactile sensors, slip sensors, proximity sensors, and encoders is often incorporated into the arm and hand structure in order to execute a desired control scheme. Conversely, bionic devices such as prosthetic hands take advantage of electromyographic (EMG) signals generated by the operator's neural system to control the motion of the prosthetic limb. A complete sensor network in this case is often not required as the operator relies on his senses – including vision – to achieve the desired manipulation. The challenge however resides in the development of a robust pattern-recognition method capable of decoding the original signal in order to control the limb functions.
In this chapter, the major contributions made in the field of robotic arms and end-effectors are evaluated and venues for prospective research outlook are identified. Due to the multi-disciplinary nature of this field and the broad range of possible applications, a comprehensive introduction of the topic requires the coverage of all aspects of the technology including sensors, actuators and automation schemes. Thus, by evaluating the state of the technology from a mechatronic perspective, we can synthesize the multi-disciplinary nature of this field in a chapter that brings together an understanding of the current challenges and advocates for subsequent developmental opportunities.

2. Sensing technology

Sensors play a critical role in the development of robotic arms and end-effectors. In the human anatomy, the skin provides sensorial information to the brain via a variety of nerve endings that react to physical stimulations such as changes in temperature and pressure. This sensorial information can be broadly classified into three major categories: proprioception, haptic perception and exteroception. Proprioception provides feedback on the position of body parts, such as the angular position of the arm's elbow and wrist. Haptic perception enables the recognition of objects via the sense of touch, while exteroception allows the perception of changes in physical variables in reaction to external stimuli. In robotic applications, there exists no single sensor with sensing capabilities comparable to the human skin. In most applications, a dedicated sensor must be integrated in the system in order to measure each and every desired variable.

2.1 Proprioception

Proprioception, such as joints position measurements, is often achieved using encoders technology for robot arms and end-effectors. These can be either absolute or incremental and can measure linear position, as well as angular position of the joints. Linear and angular velocity can be extracted from encoders' data by differentiating the position measurements with respect to time. Resistive, capacitive, optical and magnetic encoders have been studied for this purpose with each principle possessing distinctive properties (Tobita et al., 2005). For end-effector applications however, a unique challenge arises with respect to the integration of encoders on the joints. This is due to the tightness of the available space, especially in the fingers. Thus in this case, miniature encoders fabricated using MEMS-CMOS technology are desirable with sensor footprint of less than 5 x 5 mm^2 (Nakano et al., 2005).

2.2 Haptic perception

Haptic perception is achieved using tactile and force sensors. This perception is essential for handling objects, providing feedback on the amount of force or grip applied on the objects. In the most simplistic form, a tactile sensor measures the pressure exhibited by an object on a membrane which deflects proportionally to the applied pressure or force. Many techniques exist to convert the deflection of the membrane into an electrical signal. These are often implemented using piezoelectric or piezoresistive materials such as Zinc Oxide or Lead Zirconate Titanate (PZT). Membrane deflection also affects the capacitance between the substrate and the membrane. Thus, another method of implementing tactile sensors is through capacitance measurement (Castelli, 2002). These transduction principles of operation are illustrated conceptually in Figure 1.

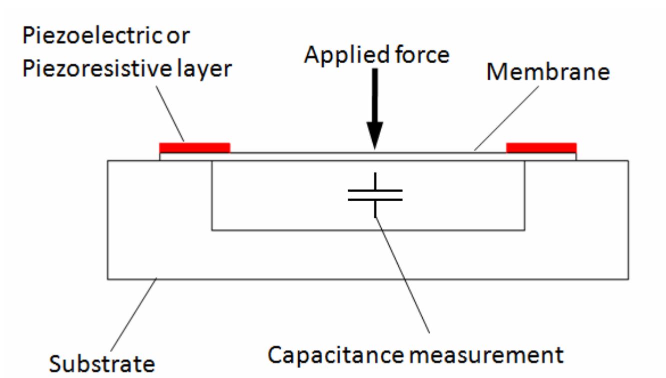

Fig. 1. A conceptual illustration of the operation principle of common tactile sensors

In general, detection of normal loads as well as shear loads is desirable in robotic end-effector applications. Normal load measurements provide information on the griping force exerted on the object, while shear load measurements can detect whether or not the object is slipping during handling maneuvers. Capacitive tactile sensors are most sensitive to normal loads, as their mode of operation requires the deflection of a membrane. Conversely, piezoelectric and piezoresistive materials can be employed to detect normal loads as well as shear loads generated by the surface traction between the object and the sensor face during slippage (Cotton et al., 2007) .

These two components of the applied load can be equally detected using other technologies such as strain gages and optical devices. Load measurements through strain gages integrated in a Wheatstone bridge is a well established procedure, and thus is more cost effective in comparison to piezoelectricity and piezoresistivity (Hwang et al., 2007). Optical measurements on the other hand can provide significant accuracy in the readings (Sato et al., 2010). However this technology requires the implementation of a camera in the structure of the sensor and the incorporation of image processing techniques.

A single tactile sensor is unable to detect the haptic perception of all fingers of a robotic end-effector. In reality, arrays of individual sensors, referred to as tactels, are incorporated together in a distributed structure constituting the tactile sensor. Tactels can be thought of as image pixels, each being sensitive to external loads. Similar to digital imaging, the resolution of a distributed tactile sensor defines the number of tactels on a given surface of the sensor, which consequently dictates the overall sensitivity of the sensor.

2.3 Exteroception

Exteroception on robotic arms and end-effectors is implemented using dedicated sensors. Most commonly, parameters such as temperature and humidity are relevant to robotic applications. These can often be sensed by incorporating appropriate sensors in the structure of the hand, most notably in the fingers. The integration of exteroceptive sensors within the structure of tactile sensors is a common practice gaining more momentum in the field. In some cases, the same physics that govern an exteroceptive parameter also govern a different haptic parameter. For instance, a capacitive sensor with top electrodes in a comb-like structure can detect the proximity of an object to the fingers (exteroceptive), as well as the collision of the object with the fingers (haptic). This is achieved by monitoring the fringe capacitance of two adjacent electrodes as a function of the changes in the dielectric constant influenced by the proximity of the object to the electrodes (Lee et al., 2009). The principle of operation is shown in Figure 2. Other techniques, such as tactile and thermal feedback provided by a single sensor, have also been successfully demonstrated (Yang et al., 2006).

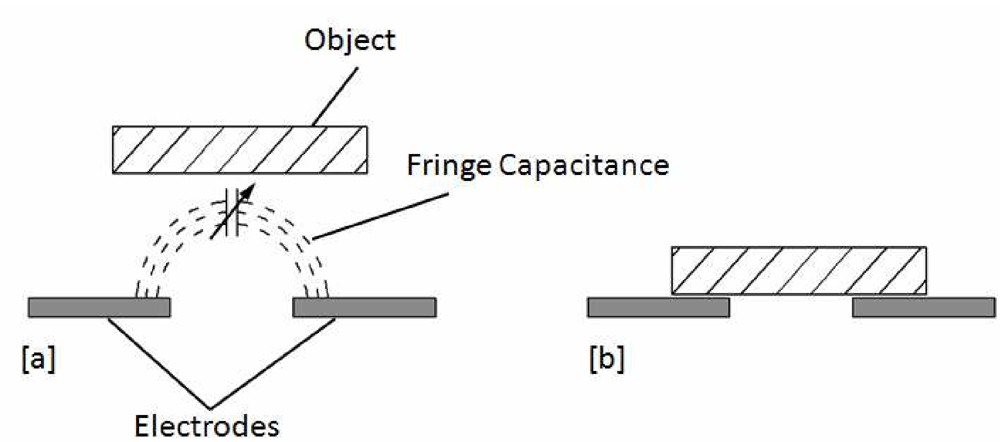

Fig. 2. A dual proximity-tactile sensor for exteroceptive and haptic feedback. [a] Proximity mode. [b] Contact haptic mode

3. Actuation technology

Actuators occupy the largest space in the structure of robotic arms and end-effectors. Although in most cases the same actuation principles that are adopted to actuate a robotic manipulator are also employed to actuate the fingers and joints of an end-effector, the constraints involved in both applications are quite different. Therefore, in order to make the content more meaningful, the two topics are separated and the discussion on the actuation of manipulator arms is carried separately from the discussion on the actuation of end-effectors. For end-effectors, we further distinguish between three categories: highly dexterous end-effectors, self-contained end-effectors and a combination of both. Each of these categories possesses inherent characteristics related to structural complexity and payload capability. Thus, treating their unique aspects separately becomes necessary.

3.1 Actuation of manipulator arms

Electrical motors constitute the most common technology to actuate the joints of manipulator arms. In most cases, the torque generated by the motor is amplified through a gearbox assembly coupled to the motor output shaft. Every motor is capable of actuating one joint at a time. Thus, in manipulator arms with no redundant joints, the number of motors equals to the number of joints. A typical spatial manipulator for a humanoid robot possesses seven independent joints similar to a human arm. These joints provide shoulder, elbow and wrist rotation. In some applications however, the exact replication of the kinematic characteristics of human arms is not desirable. For instance, industrial robotic manipulators often require the incorporation of prismatic joints that allow one link to slide inside the other. On the other hand, mobile robots intended for military applications, such as the one shown in Figure 3, may possess manipulator arms with only two or three actuated joints. A complex manipulator arm on a mobile robot is usually not advantageous due to issues related to ease of use and battery power. Since mobile robots normally operate on limited battery power, reducing the complexity of the arm joints translates into a reduction in power consumption, which ultimately extends the range of operation of the mobile robot (Ben-Tzvi et al., 2008; Ben-Tzvi, 2010; Moubarak et al., 2010).

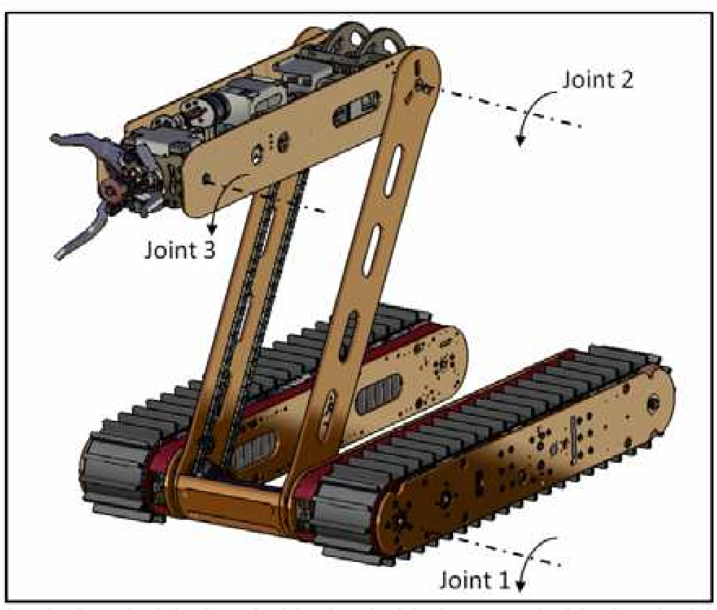

Fig. 3. A mobile military robot with a manipulator arm containing three joints

Hyper-redundant manipulator arms have also been developed using electrical motor technology. A manipulator is dubbed hyper-redundant when it possesses more than the necessary number of actuated degrees of freedom to execute a specific task. These manipulators can provide maneuverability levels analogous to elephant trunks, and are ideal for operations inside tight and narrow environments, such as inside the rubbles of a collapsed building in the aftermath of an earthquake (Chirikjian, 2001). In general, building hyper-redundant manipulator arms using electrical motors results in a discrete non-continuous articulated structure. A more compliant and continuous design shown in Figure 4 can be developed using flexible composite materials such as the Nickel-Titanium alloy (NiTi). NiTi alloys are generally used in the development of shape memory alloys (SMA) and exhibit prehensile characteristics. Thus, by running actuated tendons inside a hollow cylinder of NiTi alloy, it is possible to create a hyper-redundant continuum manipulator with adjustable flexibility dictated by the tension of the tendons (Camarillo et al., 2008).

Fig. 4. A continuum manipulator with tendon actuation

The combination of tendons or cable-drive technology and electrical motor power enables the development of manipulators exhibiting a more natural motion of the joints analogous to the human arm. Normally, cable-driven arms consist of three serially connected links with a 3-DOF shoulder joint, a 1-DOF elbow joint and a 3-DOF wrist joint. All joints are driven by cables actuated by electrical motors. Unlike joint actuation achieved by electrical motors, which requires direct coupling to the joint, cable-drive allows the relocation of the motors to the base of the arm and the transmission of the motor power to the joint via cables and pulleys. The position of the motors at the base of the arm reduces the overall weight of the links, which offers the advantage of increasing the overall payload capabilities of the arm (Mustafa et al., 2008; Ben-Tzvi et al., 2008). A commercial product of this technology known as the WAM™ arm has already been developed.

3.2 Actuation of robotic end-effectors

Table 1 classifies a family of selected robotic end-effectors into three major categories:

a. Highly dexterous end-effectors
b. Self-contained end-effectors
c. Combination of both aspects 1 and 2

The first category relates to end-effectors capable of providing dexterity levels comparable to the human hand without constraining the size and weight of the eventual structure. These hands often include four actuated fingers and a thumb and are capable of providing integrated wrist motion. The second category relates to end-effectors that contain all hardware necessary to operate the joints within the hand's structure. Normally, these end-effectors compromise the dexterity for the self-containment aspect of the structure. The third category combines the benefits of both dexterity and self-containment.

3.2.1 Actuation of highly dexterous end-effectors

Dexterous robotic anthropomorphic hands are mechanical end-effectors that possess a structural compliance comparable to the human hand. The structure of these hands includes four fingers and an opposable thumb mounted on a carpal frame or palm, with each of the

Category	Robot Hand	Structural Features	Actuation Mechanism	Joints/DOF
Highly Dexterous	UB Hand III	4 fingers 1 thumb	Brushed motors with pulling tendons	20/16
	Shadow Hand	4 fingers 1 thumb Wrist motion	Air Muscles with pulling tendons	24/20
	Robonaut Hand	4 fingers 1 thumb Wrist motion	Electrical Brushless motors with flex shafts	22/14
	DIST Hand	3 fingers 1 thumb	Electrical Brushless motors with pulling tendons	16/16
Self-Contained	Barrett Hand	3 fingers Fingers spread motion	Electrical Servo-motors	8/4
	GWU Hand-I	3 fingers Wrist motion	Electrical Brushless motors with worm gears	5/3
Highly Dexterous And Self-Contained	DLR Hand II	3 fingers 1 thumb Curling Palm	Electrical Brushless motors with tooth-belt gear	17/13
	GIFU Hand-II	4 fingers 1 thumb	Electrical Servo-motors	20/16
	Ultralight Hand	4 fingers 1 thumb Wrist motion	Flexible Fluidic Actuators	18/13

Table 1. Comparison of structural characteristics for selected robotic end-effectors

fingers representing a serial linkage mechanism connected by four joints. The advantage of these dexterous hands resides in the ability of the fingers to grasp objects of different shapes and sizes. This enables the restoration of fine motor skills in prosthetic hands, or the accomplishment of delicate tasks requiring a high level of precision, such as remote tele-operated surgery. For this family of anthropomorphic robotic hands, geometrical constraints, such as the overall size of the hand, are often traded for the dexterity level of the fingers. This results in a complicated mechanical structure where the overall weight and size are not taken into account during the design stages.

In most applications however, the top joint of the fingers, which connects the distal phalange to the intermediate phalange, is coupled mechanically to the third joint. This technique moderately simplifies the structural complexity by reducing the number of degrees of freedom for each finger by one. Consequently, the number of joints in the hand will exceed the number of degrees of freedom, making the independent actuation of the coupled joints impossible. The UB-II hand shown in Figure 5 is an anthropomorphic robotic end-effector with a total of 16 degrees of freedom (20 joints), where some of the joints have been mechanically coupled to others in order to reduce the complexity of the overall mechanism. The unique feature of the UB-II hand resides in the tendon-actuation of the joints enabled by servo-motors located in the forearm. The continuum compliance of the fingers in this case is achieved using helical springs mounted inside the shell of each finger. These springs enable the phalanx of the fingers to bend in a continuous fashion, while concurrently restoring the shape of the fingers to the original non-flexed configuration when the tension in the tendons is eliminated (Lotti et al., 2005).

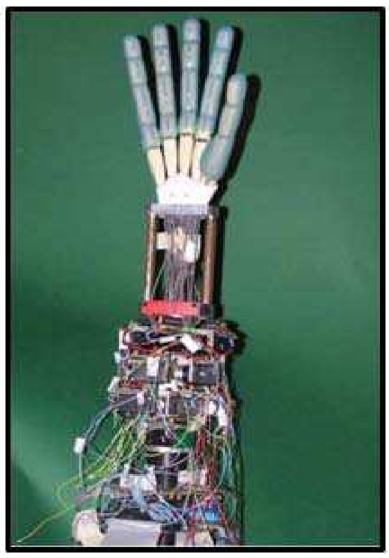

Fig. 5. The UB-II anthropomorphic hand with 16-DOF

Fig. 6. The Shadow hand actuated with air muscles

The wrist joints of the UB hand are not integrated within the structure of the hand; rather, the wrist motion is achieved independently by the manipulator arm carrying the hand on the end-link. Shadow hand kinematics differs from the UB-hand kinematics by the addition of four joints and four degrees of freedom (24 joints and 20 DOF's). One actuated joint is appended to the thumb while the other is added to the little finger, both located inside the metacarpal frame. These two actuated joints allow the palm to curl inwards in a fashion similar to the human carpus. The remaining two joints are appended to the wrist and provide the flexion/extension and adduction/abduction motions of the wrist.

Actuation of the 20 degrees of freedom of the Shadow hand is achieved by pneumatic air muscles mounted on the forearm as shown in Figure 6. Emulating the biological characteristics of a human hand, the actuation of the air muscles is coupled to the joints via tendons routed through the carpus and metacarpus. The volume of every muscle is controlled by the inside air pressure. Each tendon is connected to a pair of antagonistic air muscles, which pull the tendon in one direction or the other in order to achieve clockwise or counter-clockwise rotation of the corresponding joint. The actuation of the 20 degrees of freedom of the Shadow hand therefore requires a total of 40 actuators or air muscles.

3.2.2 Actuation of self-contained end-effectors

The objective of this technology is to develop universal robotic end-effectors that can be mounted on a variety of manipulator arms without significantly modifying the structure of the arm. In the design of highly dexterous anthropomorphic hands, the forearm is used to house most of the hardware, such as servo-motors and pneumatic actuators. Conversely, in the self-contained design, the hardware required to operate the hand is located inside the hand structure itself in an attempt to reduce the overall size of the end-effector. However, the space available inside the palm is relatively small. This leads to a trade-off between the size of the actuators and the number of actuators that can be housed inside the carpal frame. The size of the actuators dictates the payload capability of the end-effector, while the number of actuators determines the level of dexterity the end-effector can exhibit.
For the self-contained end-effectors category, the payload capability is favored over the level of dexterity. This characteristic is desirable for applications that require the manipulation of heavy objects with minimal level of dexterity, such as field robotic and military operations. The Barrett Hand shown in Figure 7 provides a payload capability of 6kg and a total of three fingers, with each finger containing two links connected together by a servo-actuated joint. Fingers F1 and F2 (Figure 7) each contain an extra joint that allows them to rotate peripherally around the wrist to reconfigure the spread angle with respect to the stationary finger F3. With no wrist motion, the Barrett hand contains a total of 8 joints with only 4 degrees of freedom.

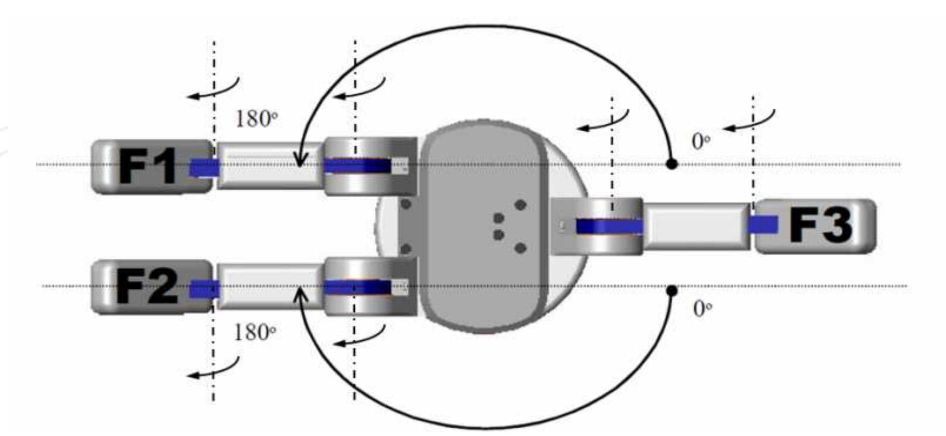

Fig. 7. The Barrett Hand with three fingers showing peripheral spread motion

Another self-contained robotic hand designed at the George Washington University (GWU) provides a payload capacity of 50kg and an integrated 2-DOF wrist motion, allowing flexion/extension, opening/closing of the fingers, and pronation/supination maneuvers as shown in Figure 8. In order to maintain the compact size of the overall structure, the high dexterity level of the fingers is traded for a high payload capability. Thus, each finger contains one joint actuated via a central worm and a brushless motor located inside the wrist. The fingers spread 110° from the closed configuration. The 2-DOF motion of the wrist on the other hand is driven by two separate motors integrated inside the structure. Wireless data communication between the finger sensors and the end-effector processor, as well as between the end-effector processor and the robot processor, allows the accomplishment of endless rotation around the wrist joints. Similar to the Barrett hand, the GWU-Hand-I integrates all hardware inside the end-effector structure including motor drivers, battery power and RF-modules. (Moubarak et al., 2010).

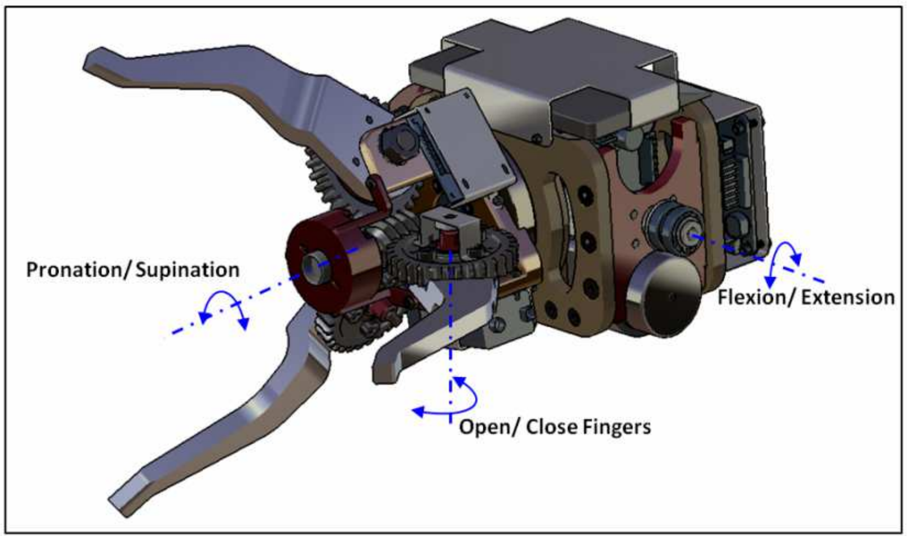

Fig. 8. GWU-Hand-I with integrated 2-DOF wrist motion and payload capability of 50 Kg

3.2.3 Actuation of highly-dexterous and self-contained end-effectors

The discussion introduced in the previous two sections identifies three major structural characteristics attributed to robotic hands: dexterity, size and payload. An ideal robotic hand encompasses all three aspects in a single structure, thereby providing a high level of dexterity within a small and self-contained structure that can handle large payloads. In reality, the size of the actuators employed to develop robotic hands prevents the accomplishment of this maximum performance objective. Few robotic hands however manage to combine the high level of dexterity in a self-contained and small structure, at the expense of lowering the payload capabilities of the fingers.

The DLR hand shown in Figure 9 is an example of a highly dexterous and self-contained robotic hand. The hand is not anthropomorphic as it includes four fingers instead of five. Each finger contains four joints and three degrees of freedom. The thumb is identical to the remaining three fingers and therefore possesses similar kinematics. The unique feature of the DLR hand resides in the palm structure, where the metacarpal frame is divided into two sections connected together by an articulated joint. This improves the compliant curling aspect of the palm and achieves optimal grasping performance of objects of random shapes. The thirteen articulated joints are actuated by brushless motors integrated inside the fingers and the palm frame, and powered using an external battery source. Due to the miniature size of the actuators, the payload capability of the DLR hand is reduced to 3kg with an overall weight of 1.8kg (excluding the weight of the external batteries) (Borst et al., 2003).

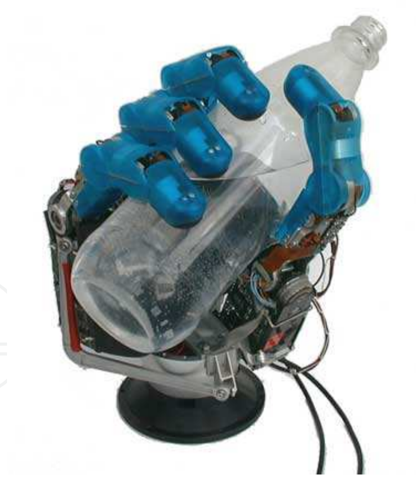

Fig. 9. The DLR hand with four dexterous fingers and a self-contained structure

4. Control methods

The interaction of a robotic arm and end-effector with the surrounding environment requires a high level of autonomy in operation. In general, the complicated kinematic nature of the manipulators and end-effectors makes tele-operation difficult to execute. This is merely due to the high number of articulated joints a robotic arm or hand contains, which makes it difficult to simultaneously actuate the degrees of freedom in order to accomplish a desired task. In most real-time applications, a robotic arm or hand is expected to possess a desirable level of autonomy that minimizes the amount of supervisory intervention from the operator. This, not only facilitates the process of human-machine interaction, but also ensures a consistent and robust operation for optimal performance.

The topic of autonomous manipulation in the broadest sense can be treated from two different perspectives. The first perspective relates to manipulator arms that operate inside a static environment where the tasks executed by the arm, or the dynamics of the assignments themselves are seldom modified. For example, a robotic arm on a static platform, loading microbial samples into a petri dish inside a laboratory environment, would always expect the target object to be located at stationary coordinates with respect to an inertial frame. This kind of operations can be preprogrammed in an exhaustive scheme and executed with extreme confidence provided no perturbations occur in the objective operation. The second perspective relates to robotic arms and end-effectors interacting with a dynamic environment where the trajectory of the arm depends on the target coordinates. In this case, an algorithm rather than a preprogrammed routine generates a control law – based on real-time sensor input – capable of defining an optimal trajectory that produces the desirable outcome.

In either case, the development of the control scheme requires a mathematical representation of the dynamics or the kinematics (or both) of the robotic arm and end-effector. If a dynamic model is available, the objective is to determine a control history that moves the arm along a trajectory from an initial point to a final point. For a kinematic model, the objective is to generate the trajectory that moves the articulated joints from an initial point to a final point in an optimal configuration, while minimizing a cost function subject to constraints. The discussion on robotic control methods can be reasonably lengthy given the significant amount of details in the literature. As such, a broad and abstract discussion on the topic is introduced and summarized under the following three major disciplines:

a. Kinematic Control
b. Dynamic Control
c. Supervisory Control

4.1 Kinematic control

In the kinematic analysis and control of autonomous robotic manipulation tasks, the first objective is to derive a global transformation matrix that maps the local kinematics (such as position or speed) of a point on a specific link into a global inertial frame 0. Every joint i of the manipulator and hand is assigned a local frame $i-1$. Thus, for a robot with n-links, there exist n-frames, where frame n is generally assigned to the end-link or the fingertip in the existence of an end-effector. A global transformation matrix ${}^{0}_{n}T$ that maps the tip coordinates to the global frame 0 can be established using the Denavit-Hartenberg parameters as follows:

$$ {}^{0}_{n}T = \prod_{i=0}^{n-1} {}^{i}_{i+1}T = {}^{0}_{1}T\,{}^{1}_{2}T \ldots \ldots \ldots {}^{n-1}_{n}T \quad (1)$$

where ${}^{i}_{i+1}T \in R^{4*4}$, representing the local transformation matrix between joint $i+1$ and joint i, is defined as

$$ {}^{i}_{i+1}T = \begin{bmatrix} {}^{i}_{i+1}R & {}^{i}_{i+1}d \\ 0 & 1 \end{bmatrix} \quad (2)$$

where ${}^{i}_{i+1}R$ expresses the orientation of frame $i+1$ relative to frame i and ${}^{i}_{i+1}d$ expresses the position of the origin of frame $i+1$ with respect to frame i.

Any kinematic property of any link of the arm and hand expressed in the local coordinates can be mapped into any other local or global frame using a variation of equation (1). For instance, for autonomous manipulation applications, the objective is to define the states x of the hand's fingers (frame n) with respect to the global frame of the manipulator according to

$$ X = {}^{0}_{n}T * x \quad (3)$$

where $X \in R^{n*1}$ defines the states of the fingers with respect to the global frame 0. The resulting kinematic equations for a robotic arm with more than 2 links are highly non-linear, which complicates the closed form analytical solution of the most common inverse kinematics problem. In the case of autonomous manipulation such as the pick-and-place operations, the states of the target object are known. These are either provided by the operator, or synthesized from real-time measurements performed by integrated sensors. The objective therefore is to solve the inverse of the problem stated by equation (3) to generate an optimal joint-configuration of the arm and hand in order to accomplish the desired task.

Optimality in robotic autonomous manipulation can only be derived in the existence of a cost function. Therefore, the purpose of the inverse kinematics problem is to minimize the cost function subject to the kinematics established in equation (3) or the dynamics or both. A variety of numerical algorithms have been investigated in the literature to solve the inverse kinematics problem, some of the most popular are the Newton descent and the Newton-

Raphson algorithms (Agirrebeitia et al., 2002). In most cases however, the solution depends on the dimensions and singularity properties of the Jacobian matrix J, which dictates the existence of J^{-1} and therefore the kinematic properties of the arm and hand. More versatile methods dealing with redundant manipulation are proposed to solve the inverse kinematics problem for robotic structures with more than 6 degrees of freedom (Klein & Huang, 1983; Seraji et al., 1993; Tarokh & Kim, 2007).

4.2 Dynamic control

A general model that represents the forward dynamic behavior of a robotic arm and hand with n-links can be illustrated in a conservative form in terms of the generalized coordinates q(t) as follows :

$$M(q,t)\ddot{q} + F(\dot{q},t)\dot{q} + V(q,\dot{q},t)\dot{q} + G(q,t) = \tau(t) \tag{4}$$

where $q(t)$, $\dot{q}(t)$ and $\ddot{q}(t) \in R^{n*1}$ represent the links position, velocity and acceleration of the arm and hand, respectively. $M(q,t) \in R^{n*n}$ represents the mass or inertia matrix, $F(\dot{q},t) \in R^{n*n}$ represents the dissipative terms such as Coulomb damping or friction, $V(q, \dot{q}, t) \in R^{n*n}$ represents the Coriolis matrix, and $G(q,t) \in R^{n*1}$ represents the non-dissipative components such as gravity. $\tau(t) \in R^{n*1}$ represents the torque input vector.

Mapping between the generalized coordinates q(t) (and their derivatives) and the work-space coordinates x(t) (and their derivatives) can be performed using the Jacobian matrix $J(q) \in R^{n*n}$ where:

$$\dot{x}(t) = J(q)\dot{q} \tag{5}$$

The objective of a dynamic control scheme is therefore to calculate a time history of the control law τ(t) that allows the links of the arm and hand to either follow a desired trajectory, or maintain a desired position (or speed) by overcoming the resistance from the environment. This control scheme includes methods that correlate the input vector to the position of the links, known as position control, or methods that correlate the input vector to the velocity of the links, known as speed control. In both cases, the time-dependant feedback of the work-space variables such as position or velocity needs to be integrated in the control loop in order to ensure the stability of the scheme.

In the case where the time history of the torque generated by the actuators is known, the objective of the control scheme is to derive a solution to the dynamic model (equation (4)) that defines the position $q(t)$ or the speed $\dot{q}(t)$ of the links in the generalized coordinate system in terms of the input vector τ(t). The solution can be mapped back into the work-space coordinates using the Jacobian matrix if an exact model is available or an approximate estimation of the Jacobian if the established model contains uncertainties (Cheah et al., 2003). In most cases however, the desired position history of the links or the desired velocity history is specified. In theory, direct substitution in equation (4) would generate the desired control law τ(t). However, the non-linear aspect of the model and the inherent uncertainties complicate the analytical solution. A method, known as inverse dynamics (Khalil & Guegan, 2004), exists in which the linearization of the model is possible. This involves seeking a control law

$$\tau(t) = f(q, \dot{q}, t) \tag{6}$$

expressed in terms of the generalized coordinates q(t), and substituting back into equation (4) to generate a Newton-Euler linear closed-loop representation of the non-linear and coupled model (Khalil et al., 2007). A critical requirement for the ideal operation of the inverse dynamics approach is an exact model of the arm and the hand. In reality, an uncertainty-free model in practical applications is seldom available.

4.3 Supervisory control

Supervisory control is the process of controlling robotic arms and hands in a closed-loop master-slave scheme where the human operator is the master initiating the orders, and the robot is the slave acting or reacting to these orders. State-of-the-art control methods presented in the previous two sections are generally task-driven or environment-driven in the sense that only very specific and tailored tasks can be performed autonomously – with confidence – by the robotic arm or hand. In reality however, the tasks assigned to robotic manipulators are so complicated that traditional dynamic tools fall short from being able to model their aspects accurately. To cope with this problem, the common practice is to place a human operator in the loop to supervise the process.

Supervisory control schemes are most desirable for applications requiring a high level of autonomy for anthropomorphic arms and hands with complex kinematic structures. Research in this field aims at minimizing the input required from the operator in order to strengthen the human-machine interaction. Most commonly, data gloves such as the one shown in Figure 10, are employed to control the joints of robotic hands. In the same fashion, similar sensors can be placed on the arm of the operator in order to control the joint motion of robotic manipulators.

Fig. 10. A data glove controlling the joints motion of a robotic hand

Data gloves convert the motion of the operator’s fingers into electrical signals. These are decoded and interpreted by a computer interface that allows the robotic hand to mimic the operator’s gestures. Flex sensors (such as strain gages) mounted inside the gloves generate an electrical signal proportional to the bending amount of each phalange. A computer interface incorporated in the loop, converts these signals into angular measurements which are then communicated to the robotic hand to mimic the gestures. Other, more advanced data gloves employ acoustic, resistive or magnetic induction sensors to track the motion of the phalanx (Fahn & Sun, 2005).

Supervisory control is also pertinent to biomechatronic applications such as prosthetic limbs and hands. In this case however, more sophisticated algorithms are required to bridge the communication between the operator's mind and the prosthetic limb. Instead of data gloves, electrodes embedded in the operator's residual muscles are employed to measure the electromyographic (EMG) signals generated by the brain activity. These signals are recognized and interpreted using pattern-matching algorithms, and subsequent commands are initiated to the corresponding actuators in the prosthetic limb to perform the motion and restore the original biological functionality (Carrozza et al., 2002).

5. Challenges and opportunities

Despite the progress accomplished in the field of robotic arms and hands as outlined in the previous discussion, the objective of realizing man-like robotic structures with comparable dexterity, robustness and intelligence is far from being achieved. The problem in itself is significantly complicated owing its difficulty to the following aspects:

- With respect to sensing capabilities; the human skin anatomy possesses a near flat exo-layer that contains an infinite number of nerve endings, each powered individually and each providing more than one sensorial measurement to the brain. In comparison, the sensors employed in the robotic industry are dedicated measurement units that are in most cases sensitive to only one parameter. Moreover, the integration of such sensors in a skin-like morphology results in a discrete amalgamation of units that does not cover the whole surface, rather is restricted to some critical areas of interest on the robotic arm or hand.
- With respect to actuation capabilities; human muscles possess a very high fiber density that enables them to deliver a large amount of instantaneous power within a compact and linear morphology. In comparison, electrical motors possess a low power-to-weight ratio and often require additional inefficient amplification stages to deliver a large torque. Linear pneumatic actuators on the other hand, attempt to replicate the muscle's biological functionality; however, they lack the comparable compactness and require extra space to house the additional hardware.
- With respect to autonomy; the human upper limbs are capable of achieving a large number of highly dexterous tasks with extreme ease and extreme confidence. In comparison, the autonomy implemented on robotic arms and hands is task-driven and non-adaptive, where every specific task is modeled individually, and every task requires a dedicated mathematical representation in order to generate an optimal performance.

These challenges are well-known and understood in the research community, and opportunities to address their aspects are constantly considered. Through the development of novel materials and novel mathematical tools, the identified challenges can be addressed gradually, and new generations of sensors, actuators and control methods can be developed. For instance, novel materials such as nanowires, promise the synthesis of highly sensitive artificial skin that can be adapted to prosthetic arms in order to restore biological senses. (Takahashi et al., 2010). Polymers, flexinol and flexible magnetic actuators (FMA) also represent a future opportunity to advance the technology, and develop compact linear actuators with high power-to-weight ratios (Kim et al., 2010). Equal opportunities present themselves in the use of statistical and machine learning methods to promote adaptive robotic intelligence for robust manipulation. The subsequent integration of these new concepts is a promising scheme to bridge the gap between the limitations of robotic arms and hands, and the skillfulness of the human counterparts.

6. Conclusions

This book chapter introduced a comprehensive mechatronic perspective on the current stance of the technology related to robotic arms and end-effectors. Due to the multi-disciplinary nature of the topic, we presented our findings and the state-of-the-art contribution under three major categories: sensors, actuators and control methods.

In the context of sensor technology, proprioceptive, haptic, and exteroceptive sensors were discussed along with the physics adopted in each case to develop the sensing capabilities.

In the context of actuator technology, we distinguished between the actuation of robotic arms – often accomplished via motor actuation or cable-drive – and the actuation of robotic end-effectors. The latter encompassed three aspects of integration: high dexterity, self-containment and a combination of both. For all three categories, the discussion introduced the different techniques employed to actuate the joints of the wrist and fingers. In most cases, direct motor actuation or tendon-driven motor actuation is employed to articulate the joints. Some other techniques that use linear pneumatic air muscles are equally considered.

In the context of control methods and autonomy, dynamic control, kinematic control and supervisory control methods were introduced. For dynamic and kinematic control, a generic discussion on the topic was presented along with the most relevant numeric schemes employed to address the non-linear aspect of the governing equations, and their subsequent solutions. For the supervisory control, two examples of human-machine interaction were introduced, one accomplished through data gloves and the other through interpretation of EMG signals in prosthetic hands.

Future opportunities in the field lie in the development of novel material technology and novel mathematical tools that address the challenges associated with the current practice. Novel materials enable the development of sensor arrays that match the human skin in the anatomy and the versatility in function. Novel materials equally enable the development of compact actuators with high power-to-weight ratios. Mathematical tools on the other hand allow the integration of machine learning techniques and provide robotic arms and hands with adaptability levels comparable to human limbs.

This being said, the contribution of the technical content in this chapter lies in the synthesis of the multi-disciplinary nature of the field in a document that brings a comprehensive understanding of the current technology, identifies pertinent challenges and advocates for subsequent developmental opportunities.

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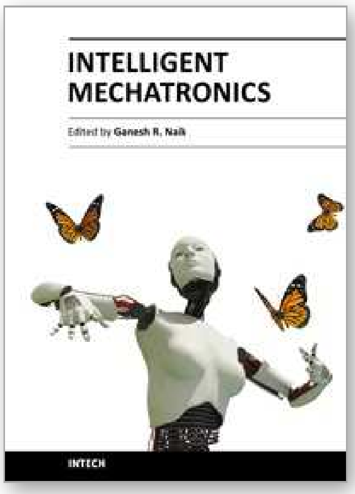

Intelligent Mechatronics
Edited by Prof. Ganesh Naik

ISBN 978-953-307-300-2
Hard cover, 248 pages
Publisher InTech
Published online 28, February, 2011
Published in print edition February, 2011