Chapter 3 - Dexterous manipulation and exploration: from Humans to robots

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Chapter 3

Dexterous manipulation and exploration: from Humans to robots

The human hand is a powerful tool. The dexterous manipulation and haptic exploration movements are some of the most useful strategies to interact with the surrounding environment.

Human manipulation and exploration capabilities result from a combination of a multimodal sensorimotor system [Flanagan et al., 2006] and a powerful effector apparatus. The conjugation and coordination of these two elements is controlled by the human nervous system following an action-perception loop architecture. Successful manipulation strategies require the capability to predict the appropriate motor commands to grasp, in-hand manipulate, transport, and release the object, and to predict and evaluate the sensory events caused by the motor commands.

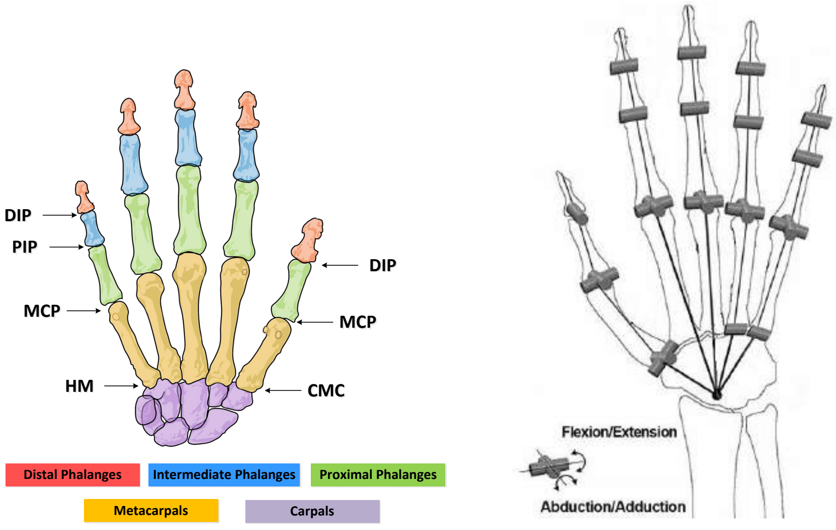
The following sections elaborate on some of the elements involved in the action-perception loop: specifically those related to dexterous manipulation and haptic exploration.

3.1 The human hand

3.1.1 Anatomical structure

The human ability to make and use tools to interact with the environment and other persons is one of the main evolutionary factors that distinguishes humans from other animals. The human hand plays a fundamental role in these capabilities [Jones and Lederman, 2006].

The musculoskeletal system of the human hand consists of bones (skeleton), muscles, tendons, ligaments, and joints. This system is responsible for maintaining the posture and shape of the hands, and providing the ability to move and to produce dexterous movements (interaction with the environment). A schematic representation of the bones



(a) (b)

Figure 3.1: Human hand. a) bones (represented by coloured regions) and joints (specified by arrows) [Wikipedia, 2014]. b) kinematic model of the human hand describing the joints, links, and degrees of freedom [Li et al., 2010].

and joints of the human hand is presented in Figure 3.1a.

Previous work [Lee and Kunii, 1995] proposed that the dexterity of the human hand is supported by a total of 23 internal degrees of freedom of movement. The degrees of freedom are provided by several joints. The elementary movements of the hand can be described by flexion/extension and adduction/ abduction movements. The flexion/extension movements correspond to the rotations toward and away from the palm. The adduction/abduction motions are used to describe the movement of joining and separation of the fingers.

A kinematic model of the human hand was proposed by [Lee and Kunii, 1995], and it is illustrated in Figure 3.1b. The index, middle, ring, and little fingers have four degrees of freedom. The distal interphalangeal (DIP) joint and proximal interphalangeal (PIP) joint have 1 degree of freedom, allowing flexion/extension movements. The metacarpophalangeal (MCP) joint has the remaining two degrees of freedom, allowing flexion/extension movements, as well as adduction/abduction movements. The mechanical structure of the thumb is different from the other four fingers. It has five degrees of freedom that are distributed by two joints: two at the carpometacarpal (CMC) joint (flexion/extension and adduction/abduction), two at the metacarpophalangeal (MCP) joint (flexion/extension and adduction/abduction), and one at the interphalangeal joint (flexion/extension). The curve and fold movement of the palm are accomplished by two internal degrees of freedom located in the transition region between the proximal region of the fingers and the palm.

Figure 3.2: Screenshot of the 3D virtual visualization tool implemented to demonstrate the kinematic model of the human hand. The software tool is available online [Martins, 2009a] (url: `http://www.rmartins.net/phd-docs/st01/`).

Several simplifications of the model may be implemented to reduce the number of free degrees of freedom, considering the objectives of the application for which the model is going to be used. One common simplification considers that the flexion/extension level of the distal interphalangeal joint of the fingers is dependent (by a 2/3 factor) on the proximal interphalangeal joint flexure/extension level [Lee and Kunii, 1995].

The hand is actuated by two distinct groups of muscle [Jones and Lederman, 2006]. The intrinsic muscles are thenar, hypothenar, interossei, and lumbrical muscles. The extrinsic muscles (long flexors and extensors) are located on the forearm.

Kinematic model of the human hand: 3D virtual demonstration tool

Using the the kinematic model of the human hand presented previously, a software tool was developed to demonstrate the kinematic model (various links, types of joints, and degrees of freedom) of a human hand. The software tool was implemented using *Python* programming language and the computer graphics library *Vizard VR Software Toolkit*.

The software tool allows the use of the graphical interface to select a joint and a degree of freedom, which is explored interactively by changing the flexure level by moving a slider. Users also can change the viewing perspective of the 3D avatar. The links are represented by blue lines and the joints by red dots.

The *Python* source code and a compiled version (Windows operating system) of the software tool are available online [Martins, 2009a] (url: `http://www.rmartins.net/phd-docs/st01/`). A screen shot of the graphical interface of the software tool is presented in Figure 3.2. The technical report *Modelling the Human body and hand: kinematic structure, degrees-of-freedom* [Martins, 2008] provides additional details about the kinematic models of the human hand and body. The proposed models were used to build the 3D virtual tool. The technical report also is available online (url: `http://www.rmartins.net/phd-docs/tr01/`).

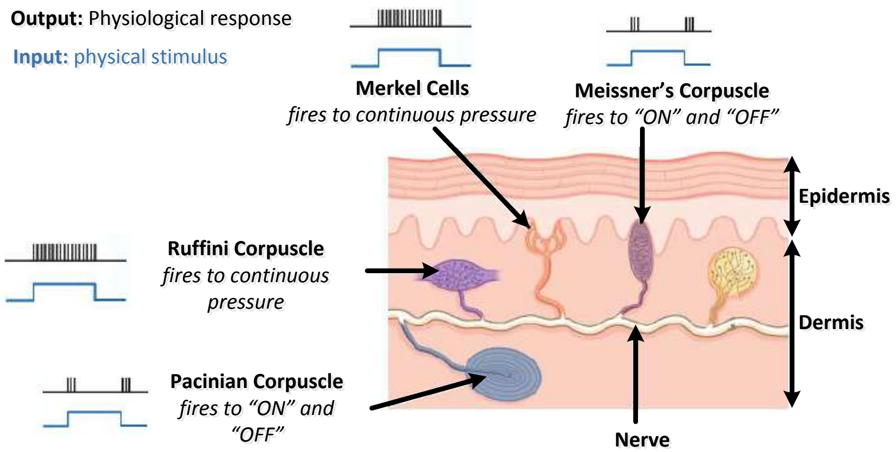


Figure 3.3: Schematic representation of the four classes of mechanoreceptors which can be found on the skin of the human hand. Summary of the different functions [Goldstein, 2002]

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3.1.2 Sensing apparatus

The somatosensory system is a diverse sensory system that contains the cutaneous senses. It is responsible for perceptions such as touch, which are typically caused by the mechanical stimulation of the skin; proprioception, which is the ability to sense the position of the body and limbs; and kinesthesis, which is the ability to sense the movement of the body and limbs.

The human sense of touch is distinct from the other four sensory modalities (vision, olfaction, taste, and hearing) in several ways. Receptors for touch are varied and have different distributions throughout the skin, unlike other sensory modalities (e.g. hearing) which are confined to localized and specialized structures on the human body. The perceptual apparatus (receptors, neural pathways, etc.) mediating touch responds to different types of stimulation.

Touch is involved in the perception of external stimuli through different types of sensory receptors [Goldstein, 2002]. Mechanoreceptors are involved in the discrimination of stimuli related to pressure and vibration. Nociceptors are related to the sensing of pain.

However, nociceptors also respond to intense sensory stimulation of heat and pressure, which are associated with extreme conditions of temperature and mechanical stimulation. Thermoreceptors participate in the sensing of heat transfers.

The research works presented in this thesis are dedicated to the development of artificial perception mechanisms that model the tactile perception of mechanical stimulus during the manipulation and exploration of objects.

The different types of mechanical stimulation (pressure, stretching, and vibration) are detected by different categories of mechanoreceptors, which are represented in Figure 3.3: Ruffini cylinder, Merkel receptor, Meissner corpuscle, and Pacinian corpuscle. The distinction between mechanoreceptors is made by the location on the anatomical structure of the skin. They differ in terms of spatial acuity, dimension of receptive field, and the manner in which the nervous fibers associated with each mechanoreceptor respond to stimuli with different mechanical characteristics. The properties of the response can be associated with a specific function during the execution of dexterous manipulation and haptic exploration tasks. Table 3.1 summarizes the characteristics and functions of the different mechanoreceptors. The work [Romano et al., 2011] proposed a methodology to model and implement the different tactile sensing capabilities of the mechanoreceptors using the PR2 robotic platform equipped with a tactile sensing array on the gripper of the robot.

Table 3.1: Mechanoreceptors: physiological integration, stimulation, and function [Dahiya et al., 2010]

Classification Basis	**Pacinian Corpuscle**	**Ruffini Corpuscle**	**Merkel Cells**	**Meissner's Corpuscle**
Type	FA II	SA II	SA I	FA I
Adaptation Rate	Fast	Slow	Slow	Fast
Spatial Acuity (mm)	10+	7+	0.5	3-4
Vibration (μm)	0.01	40	8	2
Indentation Threshold (μm)	0.08	300	30	6
Stimuli Frequency (Hz)	40-500+	100-500+	0.4-3	3-40
Effective Stimuli	Temporal changes in the skin deformation	Sustained downward pressure. Lateral skin stretch. Skin slip.	Spatial deformation. Sustained pressure. Curvature, edge, corner.	Temporal changes in skin deformation.
Sensory Function	High-frequency vibration detection. Tool use.	Finger position. Stable grasp. Tangential force. Motion direction .	Pattern/form detection; texture perception. Tactile flow perception.	Low-frequency vibration and motion detection. Grip control. Tactile flow detection.

The fibers associated with the sensory receptors, which are integrated on the skin, follow a path to the somatosensory area of the cortex, as illustrated in Figure 3.4. The fibers conducting the electrical signals from the sensory receptors enter the spinal cord through the dorsal root. The signals travel through the spinal cord along two major pathways: the medial lemniscal pathway and the spinothalamic pathway.

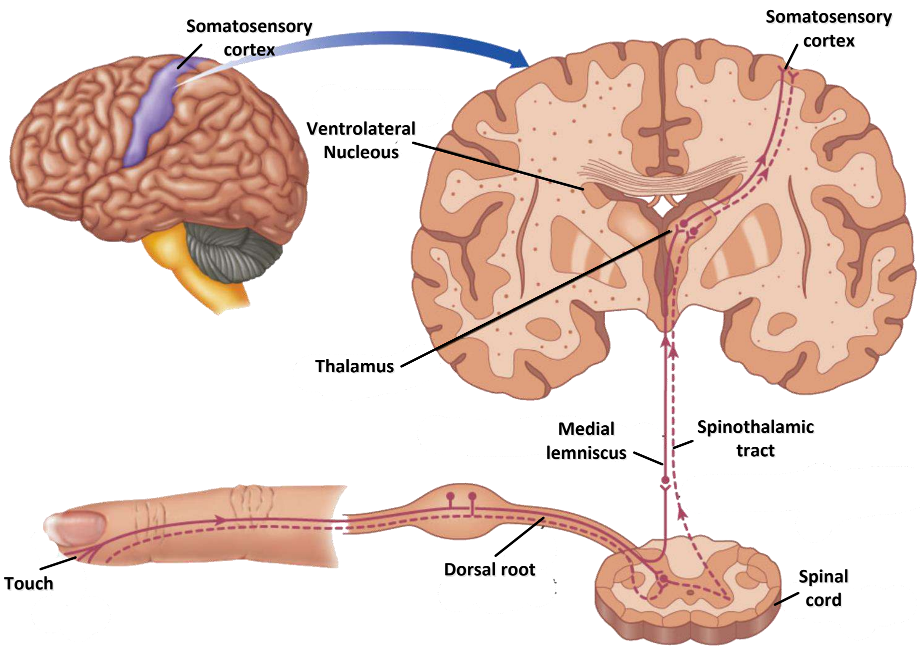

Figure 3.4: Somatosensory pathways: from fingertip to cortex [Goldstein, 2002]

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The lemniscal pathway transports signals related to sensing proprioception and kinesthesis (the ability to sense the position of the body and limbs and the ability to sense the movement of the limbs, respectively) and perceiving touch (mechanical stimulus). The spinothalamic pathway transmits signals related to temperature and pain. Both pathways synapse in the ventrolateral nucleus of the thalamus and then send fibers to the somatosensory cortex in the parietal lobe [Goldstein, 2002].

3.2 Planning and control of dexterous manipulation tasks

When humans intend to perform a manipulation task with an object placed in the surrounding environment, the head and eye gaze are oriented toward the target object. The category of object and the spatial pose are analysed to plan the configuration of hand and arm during the reach-to-grasp or transport movement. During the contact of the hand with the object, the proper amount of force must be applied by the fingers to avoid dropping the object and breaking it [Johansson and Flanagan, 2009].

The mechanisms involved in the visual and somatosensory processes responsible for perception and action during manipulation and haptic exploration tasks are detailed in sections 3.2.1 and 3.2.2.

3.2.1 Reach-to-grasp and transport movements

A model was proposed in [Oztop and Arbib, 2002] that described the neuronal mechanisms and functional relations involved in the planning and control of execution of reach-to-grasp and transport movements.

The online visuo-motor planning and control of the movement integrate visual information provided by two main pathways [Goodale and Milner, 1992]. The ventral pathway (known as *what* stream) is related to recognition, categorization, and assessment functions. The dorsal pathway (known as *where/how* stream) is dedicated to the estimation of the position, orientation, and shape of the target object of the manipulation task.

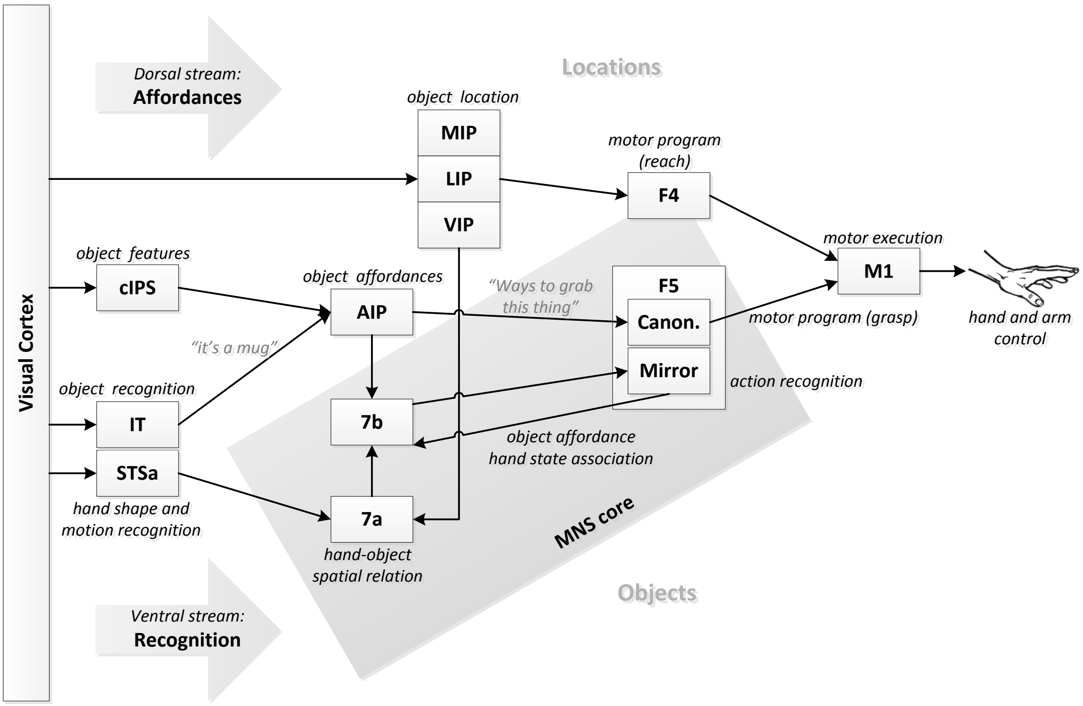

Figure 3.5: Oztop and Arbib model [Oztop and Arbib, 2002] describing the role of the mirror-neuron system in reach-to-grasp manipulation movements guided by vision [Arbib et al., 2008]

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The ventral and dorsal visual information streams work closely together in the planning and control of the dexterous manipulation movement. They also are closely associated with the somatosensory system in both programming and executing this control [Oztop and Arbib, 2002] (e.g. object modelling and recognition, initial hand configuration and grasping forces, and online movement evaluation). These relations are detailed in section 3.2.2.

The model proposed by the work [Oztop and Arbib, 2002] also integrates the representation of a mirror neuron system (MNS). Their work extends the previous FARS model (Fagg - Arbib - Rizzolatti - Sakata) [Fagg and Arbib, 1998]. The mirror neuron system, initially discovered in macaque monkeys, is a fundamental element to understanding the neuronal processes involved in the reaching and grasping movements of human manipulation of objects. The MNS links the visual processes of the superior temporal sulcus (STS) to the parietal regions and premotor regions (F5). Recently, it was demonstrated that the premotor regions (F5) integrate neurons involved with grasping capabilities. The two main classes of neurons on F5 are the mirror neurons and the canonical neurons. The mirror neurons discharge when the monkeys observe other monkeys hand movements which are similar to those whose execution is associated with the firing of the neuron. The canonical neurons fire when the monkey performs a specific action and also when the monkey sees a possible target object of such action. The canonical neurons do not fire when the monkey sees other monkeys or humans performing that action.

Object features extracted by cIPS (caudal intraparietal sulcus), together with the object recognition output provided by IT (inferotemporal cortex), task analysis and work memory, are processed by AIP (anterior interparietal area) to extract grasp affordances. The object affordances are sent to the canonical neurons of F5 that choose a particular prehensile pattern to grasp the object. The location of the object is estimated by MIP (medial intraparietal sulcus), LIP (lateral intraparietal sulcus) and VIP (ventral intraparietal sulcus). These regions provide parameters to the motor programming area of F4 which estimates the characteristics of the reach movement. The motor cortex M1 (F1) integrates the grasp and reach information provided by the canonical neurons of F5 and F4 regions, respectively, and coordinates the execution of the proposed motor program.

The quality of the execution of the defined motor program is controlled. The mirror neurons of F5 recognize the grasping actions being performed to the object, while MIP, LIP, and VIP provide outputs related to the object location, which are combined with hand shape and motion recognition provided by STSa (superior temporal sulcus) in 7a, providing a description of the hand/object spatial relation. The evaluation of the spacial relation between hand/object, action being performed with the object, and selected object affordance is made in 7b, which receives inputs from F5 mirror neurons, 7a, AIP, and STSa. The output of 7b is transmitted to the F5 in order to, if required, readjust the current motor program being executed.

3.2.2 In-hand manipulation and haptic exploration movements

The work [Dijkerman and Haan, 2007] proposes a model, presented in Figure 3.6, to describe the somatosensory processing mechanisms. The model describes a parallel processing approach, which is somewhat analogous to the parallel processing described previously that is happening in the visual system.

Two streams are proposed. A ”what” pathway involved in the processes related to somatosensory perception and a ”how” pathway participating in action mechanisms. As illustrated in Figure 3.6, both pathways start in the thalamus, where the main somatosensory inputs concerning touch and proprioception terminate. The initial somotosensory processing stages occur in SI (primary somatosensory cortex). Simple and complex features are extracted (location and duration). Different theories about the extraction of haptic features have been proposed and are the object of several ongoing studies. The two main approaches describing different mechanisms integrating sensory data are illustrated in Figure 3.7.

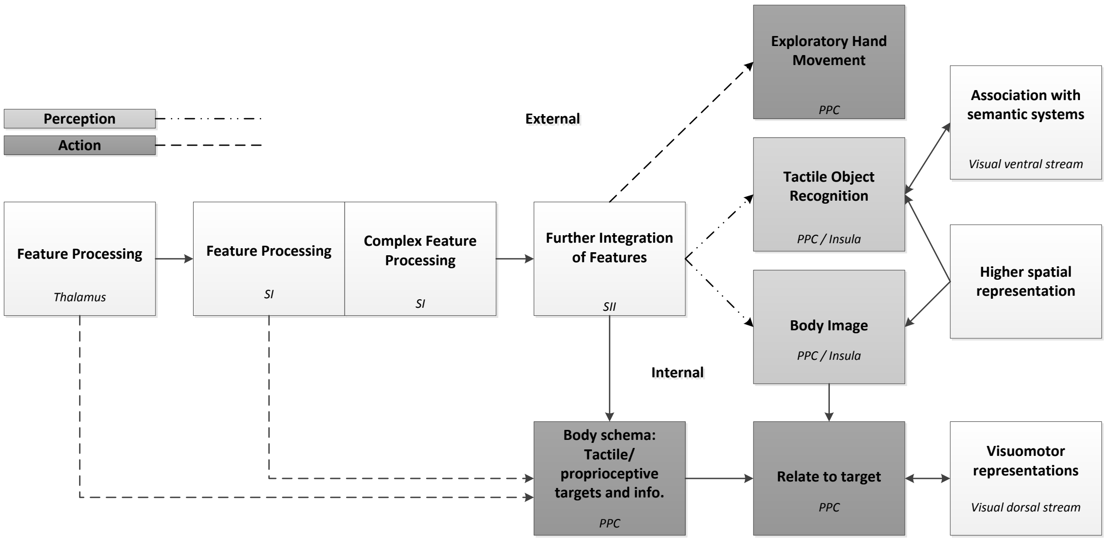


Figure 3.6: Schematic representation of the Dijkerman model [Dijkerman and Haan, 2007], describing the somatosensory processing pipeline occurring in the cortex, supporting action and perception mechanisms.

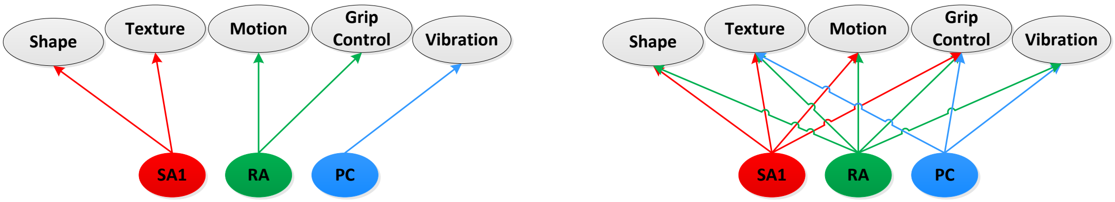
After this common initial stage, the two different somatosensory processing pathways diverge, according to the stimulus characteristics and the purpose of processing.

The ”what” pathway projects from SI via SII (secondary somatosensory cortex) to the insula. PPC (posterior parietal cortex) is involved in the spatial and temporal integration of information (velocity of the stimulus). This pathway provides mechanisms to recognize objects using somatosensory data.

The ”how” pathway projects from SI to SII, terminating in PPC. This pathway is involved in the planning and control of action mechanisms. PPC is subsequently involved in crossmodal integration (interaction with the vision system) and the preparation of movements.

The ”what” (perception) and ”how” (action) pathways are not as independent as they are in the vision system. Haptic perception requires a close cooperation between action and perception, because the sensing apparatus needs to contact directly with the stimulus / object.

The features extracted during the somatosensory processing pipeline can be integrated in high-order association areas to infer complementary properties of objects. All the mechanisms described previously are regarding the perception of external haptic stimulus (environment surrounding the subject).



(a) (b)

Figure 3.7: Integration of somatosensory afferent inputs during the haptic features extraction pipeline. a) submodality segregation. b) submodality convergence [Saal and Bensmaia, 2014]

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At a behavioural level, the tactile recognition of external objects requires close coordination between action-related and perception-related somatosensory processes. This model also demonstrates that the ventral and dorsal streams of the visual system work closely together not only in the programming and control of skilled manipulation movements, but they also have intimate associations with the somatosensory system in both programming and executing this control [Dijkerman and Haan, 2007].

As suggested in [Okamura et al., 2001], the in-hand exploration strategies and grasping movements used by humans are inherently coupled, as shown in Figure 3.8. The execution of the manipulation movements requires an object model to plan the grasping configuration of the hand. By having a more complete and accurate model of the object, the planning of the movements performed with the object can be controlled precisely. If the model of the object is incomplete, typically humans improve the object model by performing in-hand exploration of the object. However, manipulation is required for exploration. To be able to use one or more fingers to explore the surface of the object by moving the fingers over the uncharacterised regions of the object (such as regions not accessible to vision), two or more fingers are required to stabilize the object by grasping it.

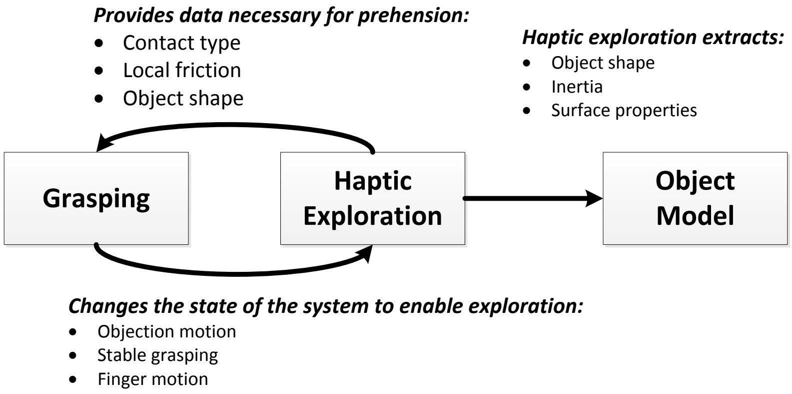

Figure 3.8: Interdependence and complementarity between manipulation and haptic exploration during the representation and progressive update of object model [Okamura et al., 2001]

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3.3 Attention mechanisms in somatosensory system

Humans are integrated and interact with the surrounding environment, which provides multiple sources of noisy sensory data. The sensory overload is not all sensed, perceived, and processed by the human sensory and neural systems [Corbetta and Shulman, 2002] [Petersen and Posner, 2012].

By definition, the attention mechanisms have been identified as the set of processes which allow humans to focus the concious awareness and limited processing resources of the brain on the relevant part of the enormous multi-modal sensory inputs. The attention mechanisms are implemented at different levels of the sensory processing and cortical pipelines. At the physiological level, attention mechanisms are manifested by different processes such as enhanced synchronization, scale of magnitude of response, and variation of thresholds.

The processes involved in the attention mechanisms can be categorized differently, depending on the effect being analysed. Attention mechanisms can be considered top-down (endogenous) or bottom-up (exogenous) [Shipp, 2004]. Top-down attention mechanisms suppress, enhance, or prioritize the representation of sensory information, taking into consideration only the objectives of the task (e.g. haptic exploration of a surface, searching for a cold object, and ignoring the textures of the surface). Bottom-up attention mechanisms prioritize and mobilize resources to analyse unexpected external events and salient sensory signals (e.g. vibration of a cell-phone in the pocket while the subject is resting).

A complementary approach to categorizing the attention mechanisms considers the domain of the sensory inputs being integrated: space-based vs. feature-based attention mechanisms. Space-based attention mechanisms concern processes that enhance or suppress in different ways the sensory information coming from sensing apparatus located in distinct regions. A typical example demonstrating the activation of these mechanisms is the exploration of a surface using the fingertips of the human hand. Stimuli presented to the fingertips are processed faster, with higher priority and detail than stimuli presented in the back of the hand (clothes, watch, bracelet) during the exploration movements. Feature-based attention mechanisms enhance or suppress processes involved in the analysis of specific features of the incoming sensory data (e.g. search and recognition of faces in vision; search for a smooth surface during a haptic exploration task).

The attention mechanisms in vision [Amso and Scerif, 2015] have been studied widely. In the touch / somatosensory system, research is not as advanced. Many research topics are still undergoing active and intense research [Chapman, 2009], [Mller and Giabbiconi, 2008]. This section summarizes the relevant processes involved in the touch attention process and how these mechanisms are integrated in the somatosensory processing pipeline, influencing the perception and action behaviours.

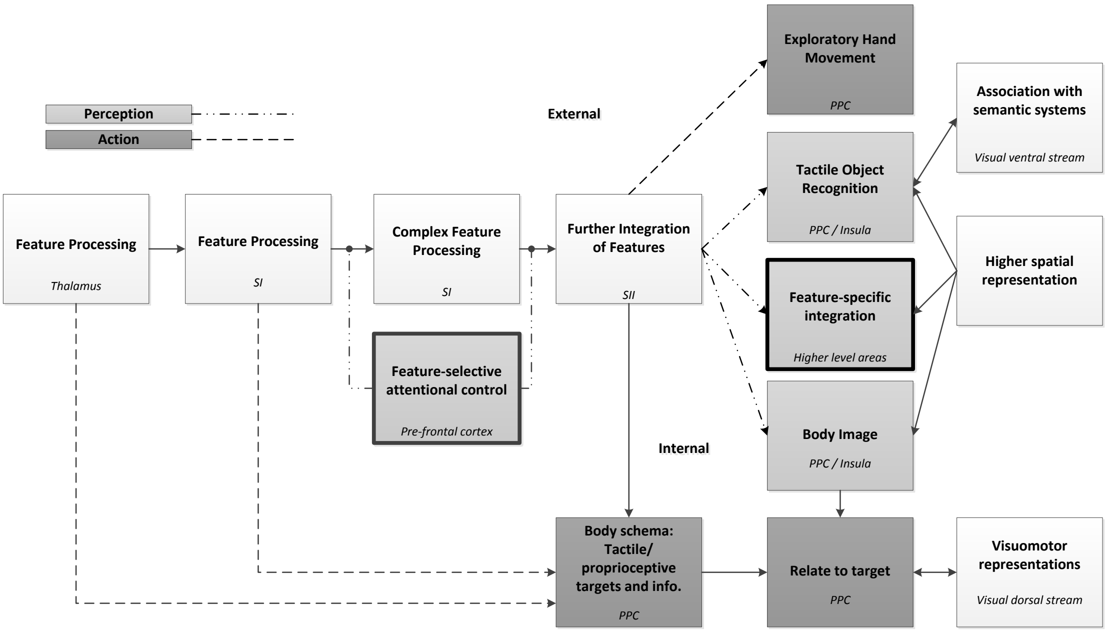

Figure 3.9: Integration of the tactile attention mechanisms (feature-based) proposed by [Wacker, 2011], in the Dijkerman model [Dijkerman and Haan, 2007].

In robotics, as with humans, the artificial sensing elements of touch can be integrated in distinct locations of the robotic system (palm, fingers, torso, arms, feet, legs) and with different extensions and densities [Dahiya et al., 2010]. The selection and hierarchy of the sensory inputs coming from all different sources would be modelled by artificial space-based attention mechanisms. However, in this work, the touch sensing elements are only integrated in the fingertips of the robotic hands. Thus, space-based attention mechanisms are not studied in this thesis. The focus of this section is on the feature-based attention mechanisms.

The feature-based touch-attention mechanisms have been studied using fMRI [Wacker, 2011] . The authors focused the research on the analysis of the role of feature-specific high-order areas for tactile perception and the functional impact of top-down modulation in the processing of haptic features. [Wacker, 2011] extended the model of somatosensory processing for perception and action proposed by [Dijkerman and Haan, 2007] that was presented in section 3.2.2. The extensions are highlighted in bold in Figure 3.9.

In the box highlighted on the left side of Figure 3.9, the top-down modulation of touch attention is represented by signals coming from the pre-frontal cortex. These signals modulate the processing streams between somatosensory areas. Each processing stage of somatosensory features is modulated by feature selective attention, which promotes the extraction and processing of haptic features relevant for the objectives of the haptic exploration or in-hand manipulation tasks. The features considered relevant are extracted and transmitted to feature-specific and/or posterior parietal areas (PPC) to improve the perceptual representation of the object being explored.

The box highlighted in bold on the right side of Figure 3.9 integrates in the model [Dijkerman and Haan, 2007] high-order areas responsible for feature-specific processing. These areas fuse multi-modal haptic attributes in a modality independent representation of the object being perceived (e.g. representation of texture of object, by integrating haptic and visual information).

The inhibition-of-return (IOR) is a behaviour effect that has been described in several works studying perception and action, with seminal work by [Posner and Cohen, 1984]. This effect was identified across different sensory modalities. The work [Klein, 2000] presents an extensive review. The IOR is described as a simple, but powerful, effect. When a salient stimulus is presented at a specific location, the attention mechanisms promote the perception and processing of that stimulus. However, if consecutive stimulation is presented in that region, the enhanced perception of the first stimulus inhibits the processing of the next ones.

The subject of IOR mechanisms in touch is an active research topic. Different theories are proposed to explain the mechanisms underlying IOR effect. The most accepted view describes the IOR as an effect caused by the attention mechanisms which inhibit attention to return to a region attended previously. Alternative or complementary formulations were proposed, presenting mechanisms at the sensory perception or motor control that caused the IOR effect. Studies [Jones and Forster, 2014] [Jones, 2011] present an extensive review of this active research topic: IOR on touch.

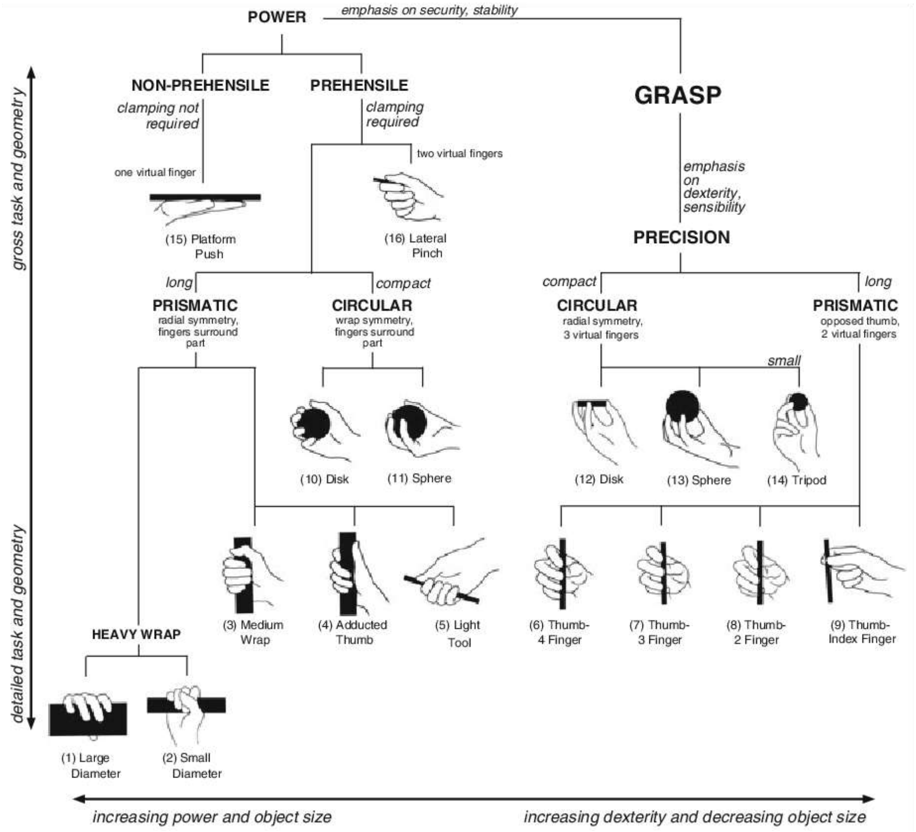

Figure 3.10: Grasp taxonomy proposed by Cutkosky [Cutkosky, 1989].

3.4 Categorization of manipulation movements

3.4.1 Grasping patterns

The dexterity of the human hand provides the capability to perform many different grasp types. This set of possible grasp types has been analysed to model the human strategies used to grasp different objects. These studies have been been applied in multiple contexts: human physical therapy and rehabilitation; and development and evaluation of artificial robotic and prosthetic hands. Several grasping taxonomies have been proposed in the literature. In general, the taxonomies are derived from a statistical study of human hand movements while performing the tasks of a typical day.

[Napier, 1956] characterized the human grasping movements in two general categories: power grasps and precision grasps. In the power grasp, the object is held inside a palm by opposition of the fingers, which exert a pressure on the object. In the precision grasp, the object is grasped by the fingertips. The power grasp is used to stabilize the grasped object. The precision grasp is used in tasks where precision and dexterity are fundamental

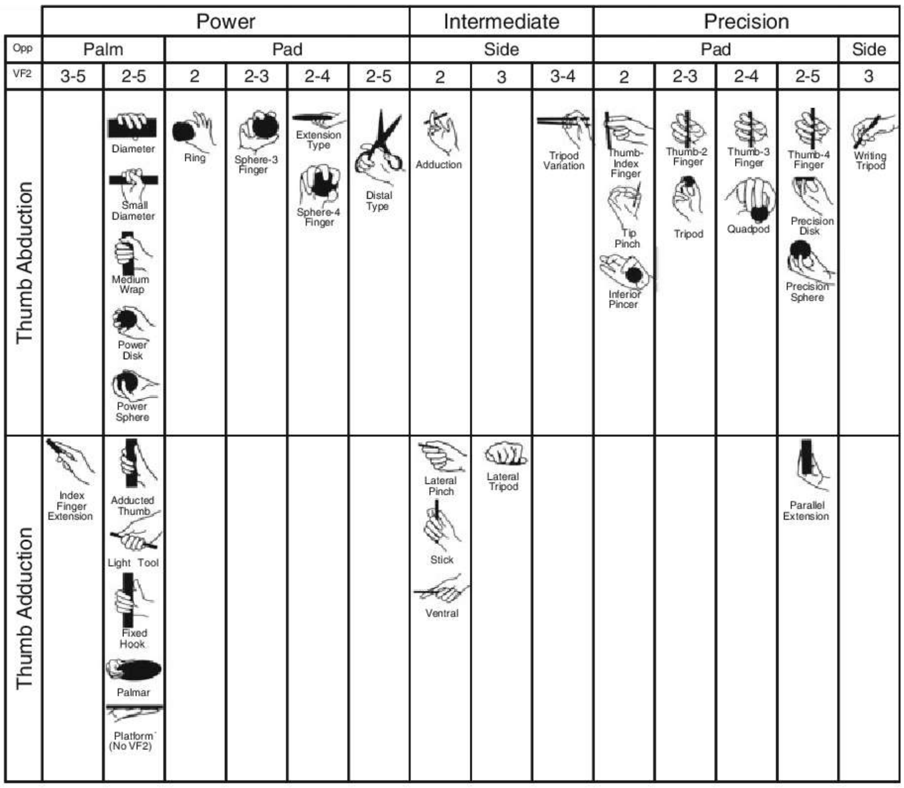

Figure 3.11: Grasp taxonomy proposed by the GRASP project [GRASP, 2008]

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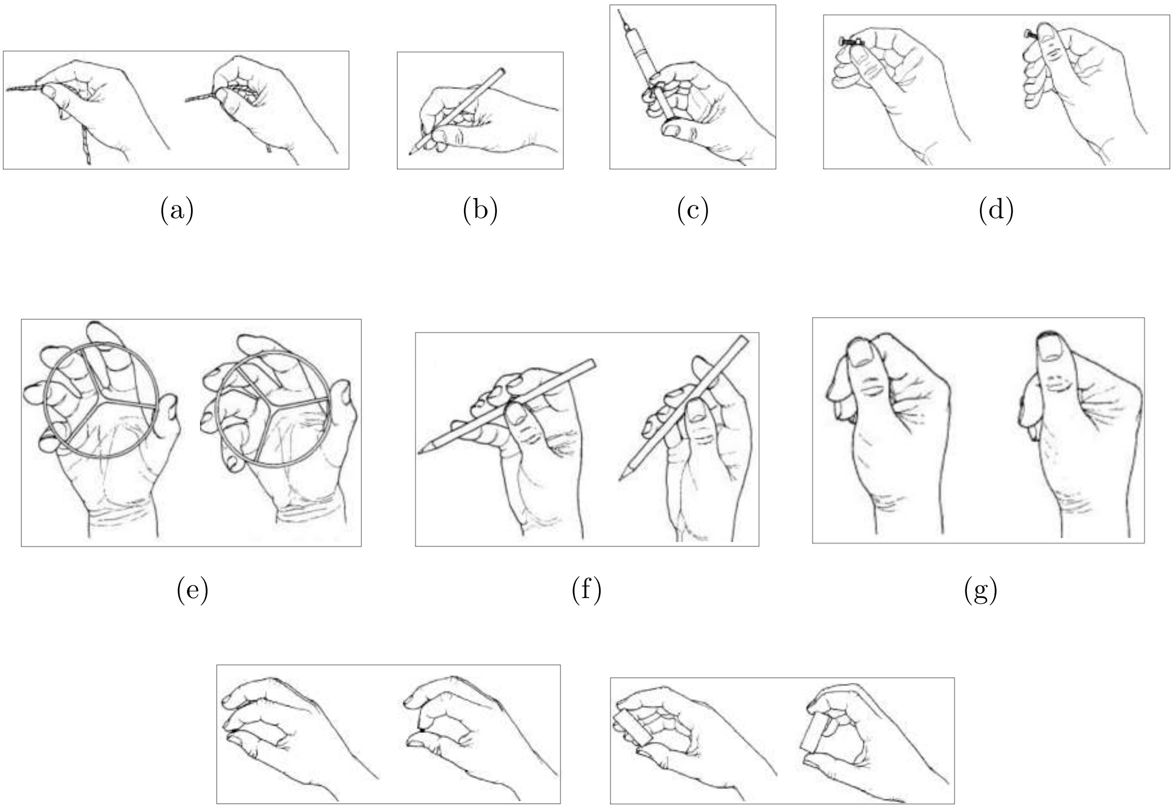
to the success of the task.

[Kamakura et al., 1980] proposed fourteen grasping patterns under four categories. The categorization of the prehensile postures of the hand is made considering the different regions of the hand contacting the object. Each tactile signature is the consequence of the mechanical configuration of the hand and the implicit characteristics of the object being held.

[Cutkosky, 1989] proposed a hierarchical taxonomy suitable to be integrated in grasp planning algorithms for robotic hands (Figure 3.10). The search for the most appropriate grasp type requires information about task requirements and object shape.

The GRASP project [GRASP, 2008] reviewed 14 different works, identifying a total of 33 different grasping patterns. Based on the properties of the grasping pattern, the grasps were rearranged in a new grasping taxonomy, represented in Figure 3.11. Each grasp in that taxonomy is characterized by parameters such as the type of grasp, opposition type, and thumb position.



(a) (b) (c) (d)

(e) (f) (g)

(h) (i)

Figure 3.12: Taxonomy proposed by Elliot and Connolly [Elliott and Connolly, 1984] describing the different types of in-hand manipulation patterns. a) Pinch. b) Dynamic tripod. c) Squeeze. d) Twiddle. e) Rock. f) Radial roll. g) Index roll. h) Full roll. i) Rotary step.

3.4.2 In-hand manipulation patterns

The in-hand manipulation movements are skills performed by humans to manipulate the objects within the hand after an initial grasp. This skill has been studied by different research areas (e.g. human development researchers, occupational therapists, and robotic researchers). Several reference studies have tried to describe, categorize, and test the high diversity of possible in-hand movements performed by the human hand.

[Exner, 1992] developed a taxonomy to classify the in-hand manipulation movements. Exner described five classes of in-hand manipulation movements: finger to palm translation, palm to finger translation, shift, simple rotation, and complex rotation. Pont [Pont et al., 2009] extended Exners classification system with additional categories of movements: finger to palm translation to achieve stabilization, palm to finger translation, simple shift, complex shift, simple rotation, and complex rotation.

Elliot and Connolly [Elliott and Connolly, 1984] extended the previous works and proposed a system to classify the intrinsic hand movements used to manipulate an object within the hand. The study proposed four categories of intrinsic in-hand manipulation movements: simple synergies, reciprocal synergies, sequential patterns, and palmar combinations. For each category of movements, several individual movement patterns are suggested, involving different fingers.

Table 3.2 and Figure 3.12 describe the different classes of in-hand manipulation movements proposed in [Elliott and Connolly, 1984] by Elliot and Connolly .

Table 3.2: Description and demonstration of in-hand manipulation patterns [Elliott and Connolly, 1984]

In-hand manipulation patterns	**Description**	**Demonstration**
Pinch	The object, typically small, is held between the pulp surfaces of the opposed thumb and index finger.	Figure 3.12a
Dynamic tripod	The object is grasped between the radial distal surface of digit and the pulp surfaces of the thumb and index.	Figure 3.12b
Squeeze	With the thumb opposed and all the digits relatively extended, the object is squeezed by synergetic flexion of the digits.	Figure 3.12c
Twiddle	Abduction of the thumb combined with metacarpophalangeal extension and some ulnar deviation of the index.	Figure 3.12d,
Rock	The pattern described in twiddle is executed with the thumb fully opposed and with increasing recruitment of the ulnar digits, moving in synchrony with the index but having a greater excursion.	Figure 3.12e
Radial roll	With the thumb in relatively slight opposition, the object is rolled between the ball of the thumb and the radial surface of the distal phalanx of the index finger.	Figure 3.12f
Index roll	With the thumb in full opposition, the object is rolled between the pulp surfaces of the thumb and index finger.	Figure 3.12g
Full roll	The pattern is similar to Index Roll, but using additional digits, often all five.	Figure 3.12h
Rotary step	The object is stepped around, with brief pauses while the position of the digits is readjusted, using sequential or phased set of movements.	Figure 3.12i

3.4.3 Haptic exploration patterns

The characterization of objects using the hand is not a passive process [Gibson, 1962]. The object is explored actively, promoting the interaction between fingers and palm with the object, building a perceptual representation of the object. The results of psychophysical studies suggest that the movements of the fingers and palm are not performed randomly, but depend on the characteristics of the object being extracted. [Lederman and Klatzky, 1987] observed that when subjects were asked to discriminate a specific characteristic of the object (e.g. texture, hardness, or weight), different types of movements, named haptic exploration patterns, were identified. The stereotypical exploration patterns and the corresponding characteristics are represented in Figure 3.13 and described in Table

3.3. Recently, the invariance of exploration patterns was verified and quantified using motion-tracking, force, and tactile sensing technologies [Jansen et al., 2013].

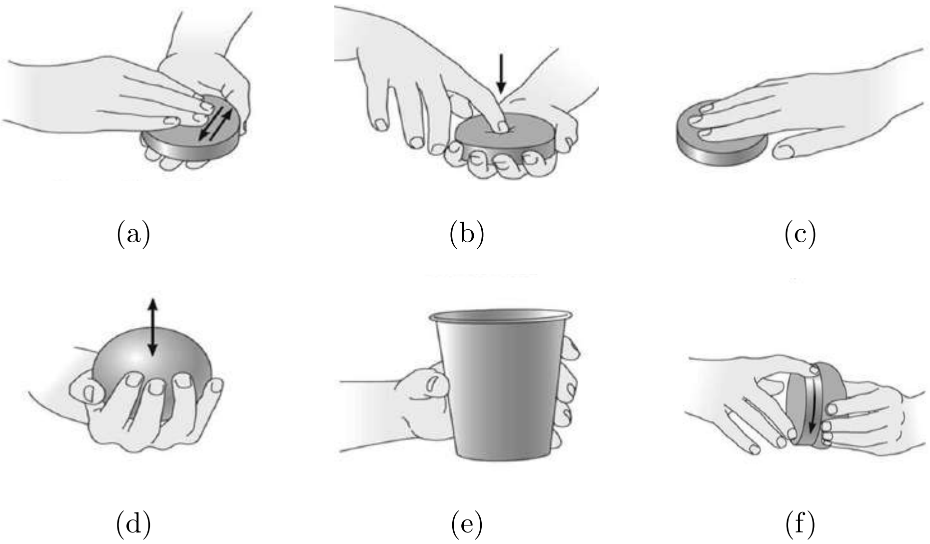

(a) (b) (c)
(d) (e) (f)

Figure 3.13: Taxonomy describing the haptic exploration patterns used to extract object features [Lederman and Klatzky, 1987]. a) lateral motion. b) pressure. c) static contact. d) unsupported holding. e) enclosure. f) contour following.

3.5 Benchmarking robotic manipulation and exploration skills

Different research and industrial sectors (e.g. informatics, manufacturing, and computer vision) have been interested in implementing benchmark methodologies, and in some of those fields, the benchmarks are established, widely recognized, and accepted. Due to an increase in research projects, diversity of robotic platforms, and industrial development, the robotics community is actively discussing and drafting benchmark protocols dedicated to robotic dexterous manipulation [Bonsignorio and del Pobil, 2015].

The definition of the benchmark protocols in robotics is a challenging task. The field of robotic dexterous manipulation integrates multiple research areas (advanced sensors, mechanical design, planning, control, and artificial perception) and can be applied in very different scenarios, executing multiple tasks with specific objects [del Pobil et al., 2014]. Currently, two main approaches are being followed and used in complementary ways to develop the benchmark protocols for robotic dexterous manipulation.

One of the proposed approaches employs robots for the existing clinical protocols to evaluate and score the human dexterous manipulation skills and capabilities.

Table 3.3: Description and demonstration of the haptic exploration patterns [Lederman and Klatzky, 1987]

Exploratory strategy	**Object property**	**Movement**	**Demonstration**
Lateral motion	Surface texture	The skin is passed laterally across a surface, producing shear force.	Figure 3.13a
Pressure	Compliance or hardness	Force is exerted on the object against a resisting force; for example, by pressing into the surface, bending the object, or twisting.	Figure 3.13b
Static contact	Apparent temperature	The skin surface is held in contact with the object surface, without motion; typically a large surface (like the whole hand) is applied. This EP gives rise to heat flow between the skin and the object.	Figure 3.13c
Unsupported holding	Weight	The object is held while the hand is not externally supported; typically this EP involves lifting, hefting, or wielding the object.	Figure 3.13d
Enclosure	Volume; Global shape	The fingers (or other exploring effector) are molded closely to the object surface.	Figure 3.13e
Contour following	Exact shape	Skin contact follows the gradient of the object's surface or is maintained along edges when they are present.	Figure 3.13f

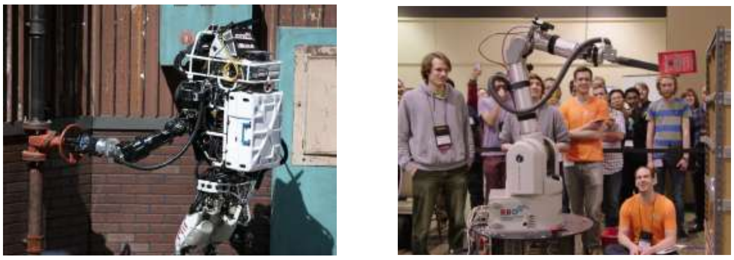
(a) (b)

Figure 3.14: Southampton Hand Assessment Protocol (SHAP) [Adams et al., 2009]: a) complete kit. b) demonstration of assessment of hand function using the kit.

In clinical practice [Pont et al., 2008], different methods have been proposed to evaluate in-hand manipulation skills: the in-hand manipulation test quality [Miles Breslin and Exner, 1999], the test of in-hand manipulation (TIHM) [Case-Smith, 2000], and observation protocol on in-hand manipulation and functional skill development [Humphry et al., 1995]. An extensive review of the dexterity assessment of human hands in clinical practice is presented by [Yancosek and Howell, 2009] .

The Southampton Hand Assessment Procedure [Adams et al., 2009] SHAP is a clinical test originally developed to assess the physical functionality of hand and arm prostheses. However, it has been extended to evaluate the hand skills in humans. The SHAP consists of a kit of general objects and proposes a protocol to evaluate the hand functions during the execution of fourteen daily living activities. The participants are asked to perform the tasks using one of six different grasps. The kit includes software which generates a score to evaluate the impairment level of the hands.

Additionally, the protocols ARAT [Yozbatiran et al., 2008] (a standardized approach to performing the action research arm test) and GRASSP [Kalsi-Ryan et al., 2012] (development of the graded redefined assessment of strength, sensibility, and prehension) are used to access and score the function of upper limbs and the human hand.



(a) (b)

Figure 3.15: a) ATLAS robot [ATLAS, 2013] performing a manipulation task during the DARPA robotic challenge. b) Robotic platform during the Amazon Picking Challenge [Wurman and Romano, 2015].

In addition to the clinical tests, researchers of the robotics community started implementing and discussing benchmark protocols specifically designed for robotic platforms. During scientific forums such as EURON (EUropean RObotics research Network), the robotics community proposed three different scenarios and benchmarking measures involving pick and place tasks, reorientation, and object removal tasks [EURON, 2008].

The DEXMART project (DEXterous and autonomous dual-arm/hand robotic manipulation with sMART sensory-motor skills: A bridge from natural to artificial cognition) presented [DEXMART, 2008], an extensive and detailed guideline to the implementation of benchmarking methodologies [DEXMART, 2009]. The guidelines were designed to evaluate the project outcomes from the data acquisition level to the complete system level. For each of the tasks presented in the document, the objectives and control points of the tasks are defined, as well as the reference outcomes of the task that should be evaluated.

[Matheus and Dollar, 2010] describes a set of tasks compiled from different works in the literature which have been used to evaluate the performance of manipulation robots using objects of daily living. [Calli et al., 2015] also reviews ongoing projects related to the assessment of the dexterous manipulation capability of robotic platforms and proposes a set of objects and tasks to benchmarks the robotic skills. The set of objects is described in detail (3D models with RGB data) to facilitate the replication of the experiments worldwide. [Feix et al., 2013] presents a metric to score the anthropomorphic motion capability of artificial hands and compare them with the human hand.

Recently, several international and large-scale challenges also tried to gather together the robotic community working in (dexterous) manipulation and haptic exploration. Typically, the events elaborate a list of tasks and scoring rules, and promote the competition between different teams (universities, research centres, companies, abd consortia). This allows a good benchmark between the approaches and methods proposed by the different teams. Among others, the main events proposing challenges requiring manipulation tasks are The Amazon Picking Challenge 2015 [Wurman and Romano, 2015], DARPA's robotics challenge [Guizzo and Ackerman, 2015], and RoCKIn 2015: Robot Competitions Kick Innovation in Cognitive Systems and Robotics [Amigoni et al., 2015].

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