Chapter 1 - Introduction

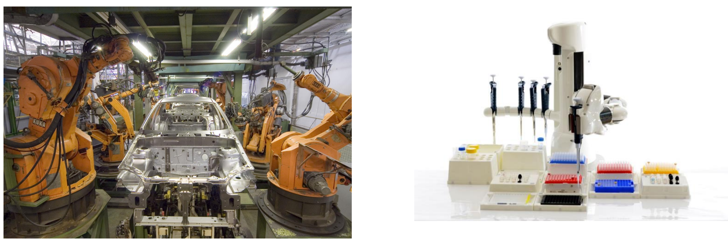
Chapter 1

Introduction

1.1 Motivation

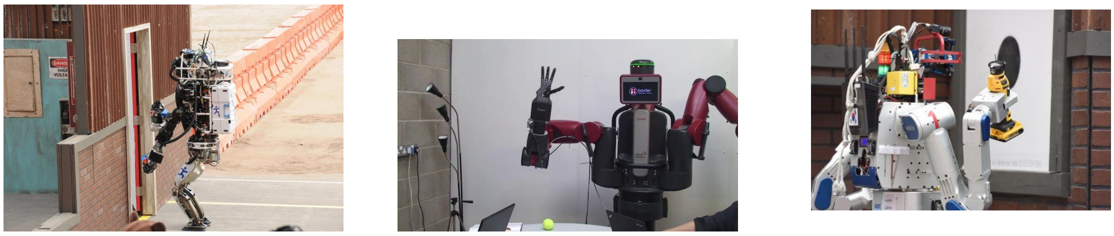
During the past few decades, robotic platforms (e.g. Figure 1.1) have been integrated into industrial and laboratory environments, with the primary task of performing repetitive and monotonous tasks quickly and accurately. Typically, the movements and tasks required to successfully fulfil the job for which the robots were preprogrammed required little or no sensory feedback or interaction with humans during execution time [Nof, 1999]. This type of robotic platform was primarily designed to be integrated in clean environments, rely on complete task information, and, if required, to be reprogrammed for new task execution. This type of platform was not designed to interact directly with humans and to handle the execution of tasks in uncertain environments.

Currently, various types of robotic platforms (e.g. Figure 1.2) have begun being heavily introduced in different environments (including domestic, healthcare, entertainment, and education) in which the robots must manage new challenges, such as the ability to interact with persons and objects in the environment [Zollo et al., 2013]. These new classes of environments are dynamic, unpredictable, and cannot be completely known in



(a) (b)

Figure 1.1: Integration of robotic systems in controlled environments. a) *KUKA IR 160/60* (KUKA Robot Group, Augsburg, Germany) operating at an industrial car factory. b) *Andrew Alliance* (Andrew Alliance S.A., Vernier, Switzerland) anthropomorphic robot handling liquids.



(a) (b) (c)

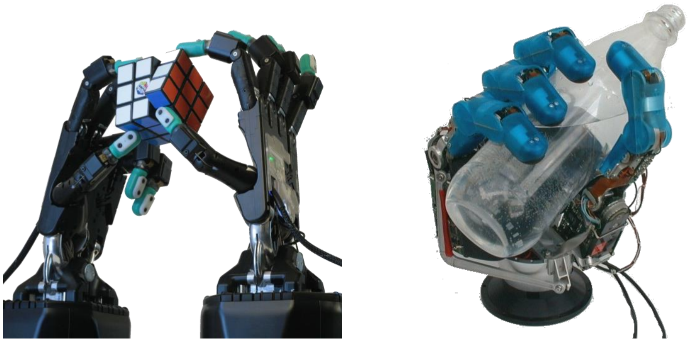
Figure 1.2: Integration of robotic systems on daily-life environments. a) *ATLAS* robot (Boston Dynamics, Waltham, USA) opening a door. b) *Baxter* robot (Rethink Robotics, Boston, USA) grasping objects on table. c) *DRC-HUBO* robot (Rainbow Co., Daejeon, South Korea) operating a power drill.

advance. These factors have led to the development of mobile robotic platforms with multi-modal sensing systems, and complex actuation systems and interaction interfaces such as active vision systems, audition, multi-articulated arms, dexterous robotic hands, touch displays, and microphones. These multi-modal modules, actuators, and interfaces provide a framework to develop artificial perception systems to deal autonomously with the dynamics of the environments and wide variety of objects, and to interact safely with humans.

One of the key elements contributing to the performance of that type of robotic platform is the ability to perform autonomous grasping, manipulation, exploration, and characterization of partially known objects in the environment [Saudabayev and Varol, 2015]. To achieve these objectives, the tendency in the field of robotic research is to move the development of robotic hands from simple grippers toward human-inspired articulated hands (with a mechanical structure, integration on robotic arms, and various degrees of freedom) and introduction on the robotic hand of sensing devices such as tactile, temperature, and force/torque sensors (e.g. Figure 1.3).

The greater relevance of the study and development of robotic hands and issues relating to autonomous manipulation is revealed by the increasing number of projects and funding resources applied to this scientific field. In the past years, several collaborative large-scale research projects (primarily between European institutions) were funded: HANDLE [HANDLE, 2009] (Developmental pathway towards autonomy and dexterity in robot in-hand manipulation), GRASP [GRASP, 2008] (Emergence of Cognitive Grasping through Introspection, Emulation and Surprise), DEXMART [DEXMART, 2008](DEXterous and autonomous dual-arm/hand robotic manipulation with sMART sensory-motor skills: A bridge from natural to artificial cognition), GeRT [GeRT, 2011] (Generalizing Robot Manipulation Tasks), and THE [THE, 2010](The Hand Embodiment).

As presented in Figure 1.4, most of these large-scale research projects in cognitive



(a) (b)

Figure 1.3: Dexterous robotic hands. a) *Shadow* (Shadow Robot Company Ltd, London, UK) robotic hand equipped with *Syntouch Biotac* (SynTouch LLC, Los Angeles, USA) sensory fingertips. b) *DLR* (German Aerospace Center, Cologne, Germany) robotic hand.

robotics follow an approach that develops its engineering solutions to the topic of dexterous robotic manipulation and exploration by integrating principles from the human studies sciences. Neurobiology and neuroscience provide functional models describing the processes involved in the sensing, transduction, and sensory processing pipeline, perception, cognition, and motor capabilities. Neuropsychology and cognitive science systematically describe and categorise the standard human behaviours, which are used as benchmarks to define protocols to evaluate robotic skills [Cheng, 2014].

The objectives of these projects can be grouped in two main classes. One class is related to the development of hardware and sensors, as well as its integration within the structure of the robotic hand or the structure of a main robotic platform. A second class concerns the development of algorithms and techniques dedicated to the modelling and implementation of artificial perception-to-action and action-to-perception systems based on hardware platforms provided by the first class of approaches. This work intends to contribute to the second class of approaches.

The integration of this new generation of robotic hands onto robotic platforms places new challenges concerning the motion (fingers, palm, coordination fingers-fingers and fingers-palm) of the robotic hand, with a certain number of degrees of freedom. However, the introduction of sensing devices opens new possibilities, allowing the replication of human motor strategies and perceptual capabilities concerning the ability to perform dexterous, finer manipulation, and exploration skills. These capabilities are boosted due to the integration of haptic data (flexure level, tactile, force/torque, and temperature) in the control loop of the robotic manipulation [Yousef et al., 2011] .

This new class of skills is related to in-hand manipulation tasks that consist of internal consecutive (re-)grasping and release of the object to perform its reorientation, fine positioning, or more complex interaction such as sequential rotation of the object. Hu-

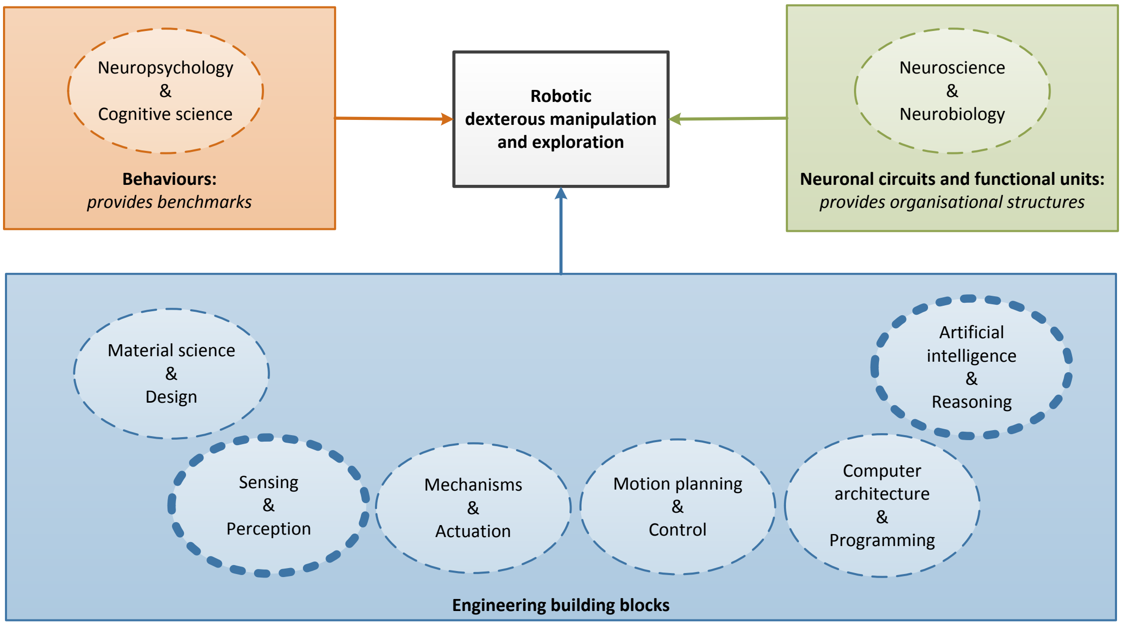


Figure 1.4: Overview of the multidisciplinary approach followed to develop robotic dexterous manipulation and exploration capabilities. The fields of intervention of this thesis are highlighted in bold. Adapted from [Cheng, 2014].

mans also use the in-hand manipulation skills to perform in-hand exploration of objects to complete the construction and definition of the model of the object (e.g. shape, size, superficial texture, superficial friction coefficient, weight, and softness) [Lederman, 1994], when the properties are not completely known in advance or to complete partial information about the object model provided by other sensing modalities (e.g. vision) [Lacey and Sathian, 2014], [Stone and Gonzalez, 2015].

Haptic perception plays a relevant role in this type of skills [Dahiya et al., 2010] by providing sensory cues about the regions of the hand contacting the object, the temporal sequence, and object-hand contact dynamics [Johansson and Flanagan, 2009]. The contributions of this thesis relate to the development of methodologies used to implement artificial haptic perception skills and to establish the interdependence of those skills with actions.

1.2 Thesis outline

This chapter, *Introduction*, describes the context, motivation, and applications of the research works presented throughout this thesis.

Chapter 2, *Fundamentals*, proposes and describes the probability theory, probabilistic grids, and information theory formalisms used by this thesis. The graphical and Bayesian programming notations used to describe the Bayesian models are described as well.

The following chapter, *Recording human manipulation and exploration movements*, reviews the human somatosensory apparatus and processing pipeline involved in the dexterous manipulation and haptic exploration of objects. Special focus is dedicated to the extraction of haptic features, tactile attention mechanisms, and hand motion patterns. Chapter 3 also presents an overview of the current benchmarking guidelines used to evaluate robotic manipulation and exploration tasks.

The experimental area of the AP4ISR laboratory (Artificial Perception for Intelligent Systems and Robotics) used to record multi-modal datasets of human demonstrations of dexterous manipulation and exploration tasks is presented in chapter 4, *Recording human manipulation and exploration movements*. The characteristics of the different data acquisition devices are detailed. The implementation of the global data acquisition architecture is explained. The applications of the datasets recorded during this PhD study are listed. Several software tools developed to promote the acquisition, integration, and demonstration of the datasets are also documented.

Chapter 5, *Recognition of grasping primitives using tactile sensory data*, chapter 6, *Categorization of soft objects during haptic exploration tasks*, and chapter 7, *Active haptic exploration of surfaces using dexterous robotic hands* present different but complementary approaches to endow robotic platforms with dexterous manipulation and exploration capabilities. Artificial haptic perception plays a central role in these three chapters. All three chapters are arranged similarly: introduction; related works discussed using a table to compare this thesis with other works; proposed approach illustrated by two schemes: simplified overview and detailed overview of the flow of data, variables, and algorithms; sections covering methods and algorithms; experimental results; and main conclusions.

Chapter 5, *Recognition of grasping primitives using tactile sensory data*, proposes an approach to recognize different grasp shape primitives during the human demonstration of dexterous manipulation tasks. Chapter 6, *Categorization of soft objects during haptic exploration tasks*, implements an approach to recognize the category of material during the human haptic exploration of objects. Finally, chapter 7, *Active haptic exploration of surfaces using dexterous robotic hands*, demonstrates a system (simulation environment) which performs active haptic exploration of surfaces using dexterous robotic hands. The contribution of tactile attention mechanisms to improve the exploration performance is demonstrated.

1.3 List of deliverables

During the PhD studies conducted in the development of this thesis, several deliverables were produced. The contribution of each deliverable to this thesis is described in the list presented next. All the deliverables are available on line at `http://www.rmartins.net/phd-docs/`.

1.3.1 Peer-reviewed international journals

- `Contributes to chapter 7` ⇒ [Martins et al., 2017] **R. Martins**, J. F. Ferreira, M. Castelo-Branco , J. Dias - ”Integration of touch attention mechanisms to improve the robotic haptic exploration of surfaces” - Neurocomputing, Volume 222, 26 January 2017, Pages 204-216.
  DOI: 10.1016/j.neucom.2016.10.027

- `Contributes to chapter 5` ⇒ [Faria et al., 2012] D. R. Faria, **R. Martins**, J. Lobo, J. Dias - ”Extracting Data from Human Manipulation of Objects Towards Improving Autonomous Robotic Grasping” - Robotics and Autonomous Systems, Special Issue on Autonomous Grasping, Volume 60, Issue 3, Pages 396-410, March 2012.
  DOI: 10.1016/j.robot.2011.07.020

1.3.2 Peer-reviewed proceedings of international conferences

- `Contributes to chapter 7` ⇒ [Martins et al., 2014] **R. Martins**, J. F. Ferreira, J. Dias - ”Touch attention Bayesian models for robotic active haptic exploration of heterogeneous surfaces”. Proceedings of 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2014), pages 1208-1215, Chicago, USA, Sept. 14-18, 2014.
  DOI: 10.1109/IROS.2014.6942711

- `Contributes to chapter 7` ⇒ [Martins et al., 2012b] **R. Martins**, J. F. Ferreira, J. Dias - ”Touch attention Bayesian models for object feature extraction in robotic blind manipulation”. Proceedings of 32nd International Workshop on Bayesian Inference and Maximum Entropy Methods in Science and Engineering (MaxEnt 2012), Munich, July, 2012.

- `Contributes to chapter 7` ⇒ [Martins et al., 2013] **R. Martins**, J. F. Ferreira, J. Dias - ”Touch attention Bayesian models for robotic active haptic exploration”.

Proceedings of 2nd Workshop on Recognition and Action for Scene Understanding (REACTS 2013), pages 45-58, York, UK, 30 August, 2013.
ISBN: 978-84-616-7092-5

- `Contributes to chapter 6` ⇒ [Martins et al., 2012a] **R. Martins**, D. R. Faria, J. Dias - "Representation framework of perceived object softness characteristics for active robotic hand exploration". Proceedings of 7th ACM/IEEE International Conference on Human Robot Interaction (HRI2012) - Workshop on Advances in Tactile Sensing and Touch based Human-Robot Interaction, Boston, USA, March 5-8, 2012.
  DOI: 10.13140/RG.2.1.2739.3445

- `Contributes to chapter 5` ⇒ [Martins et al., 2010] **R. Martins**, D. R. Faria, J. Dias, "Symbolic Level Generalization of In-hand Manipulation Tasks from Human Demonstrations using Tactile Data Information". Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2010): Workshop on Grasping Planning and Task Learning by Imitation, Taipei, Taiwan - October 2010.
  DOI: 10.13140/2.1.3782.2401

1.3.3 Peer-reviewed poster in international conferences

- `Contributes to chapter 6` ⇒ **R. Martins**, J. Dias - "Representation framework of perceived object softness characteristics for active robotic hand exploration". In HANDLE Workshop, Benicassim, Spain, February, 2012.

1.3.4 Research collaborations as co-author

- [Diego Faria, 2012] ⇒ D. R. Faria, **R. Martins**, J. Lobo, J. Dias. "A Probabilistic Framework to Detect Suitable Grasping Regions on Objects". In 10th IFAC Symposium on Robot Control (SYROCO 2012), Dubrovnik, Croatia, September, 2012.
  DOI: 10.3182/20120905-3-HR-2030.00090

- [Faria et al., 2011] ⇒ D. R. Faria, **R. Martins**, J. Lobo, J. Dias. "Manipulative Tasks Identification by Learning and Generalizing Hand Motions". In DoCEIS'11 - 2nd Doctoral Conference on Computing, Electrical and Industrial Systems. Costa da Caparica - Portugal, February, 2011.
  DOI: 10.1007/978-3-642-19170-1-19

- [Faria et al., 2010b] ⇒ D. R. Faria, **R. Martins**, J. Dias - Grasp Exploration for 3D Object Shape Representation using Probailistic Map - In Proceedings of the

DoCEIS'10 - Doctoral Conference on Computing, Electrical and Industrial Systems. Lisbon, February, 2010. Springer
DOI: 10.1007/978-3-642-11628-5-23

- [Faria et al., 2010a] ⇒ D. R. Faria, **R. Martins**, J. Lobo, J. Dias - Probabilistic Representation of 3D Object Shape by In-Hand Exploration - in Proceedings of The 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS'10, pp. 1560-1565 - Taipei, Taiwan - October 2010.
  DOI: 10.1109/IROS.2010.5649286

- [Faria et al., 2009] ⇒ D. R. Faria, **R. Martins**, J. Dias - Human reach-to-grasp generalization strategies: a Bayesian approach - Workshop at Robotics: Science and Systems 2009, Workshop: "Understanding the Human Hand for Advancing Robotic Manipulation" - July 28, 2009 - Dillon Eng Seattle, WA, USA.

- [Faria et al., 2010c] ⇒ D. R. Faria, **R. Martins**, J. Dias - Learning Motion Patterns from Multiple Observations along the Actions Phases of Manipulative Tasks - to appear in IEEE/RSJ IROS'2010: Workshop on Grasping Planning and Task Learning by Imitation, Taipei, Taiwan - October 2010.

1.3.5 Technical report

- `Contributes to chapters 4, 5, 6` ⇒ [Martins, 2010] Distributed synchronization of multi-modal data acquisition devices using NTP (network time protocol).

- `Contributes to chapter 4` ⇒ [Martins, 2013] Installing controller area network (CAN-Bus) drivers and compiling code on Ubuntu.

- `Contributes to chapter 4` ⇒ [Martins, 2012b] Experimental evaluation and calibration protocol of *Tekscan Grip* system.

- `Contributes to chapters 4, 5, 6` ⇒ [HANDLE-UC, 2009] Protocol for the corpus of sensed grasp and handling data: storage of multimodal datasets.

- `Contributes to chapter 3` ⇒ [Martins, 2008] Modelling the Human body and hand: kinematic structure, degrees-of-freedom.

1.3.6 Software tools and documentation

- `Contributes to chapter 3` ⇒ [Martins, 2009a] 3D interactive demonstrator of human body and hand: kinematic structure, degrees-of-freedom.

- `Contributes to chapter 4` ⇒ [Martins, 2012a] 3D visualization tool of instrumented Rubik cube touch data.
- `Contributes to chapters 4, 5, 6` ⇒ [Martins, 2009g] *importDatasetTB*: toolbox for integrating data in MATLAB.
- `Contributes to chapter 4` ⇒ [Martins, 2012c] Annotation tool for multi-modal Human grasping datasets.
- `Contributes to chapters 4, 6` ⇒ [Martins, 2009b] Distributed data acquisition architecture: software client for *CyberGlove* (data glove).
- `Contributes to chapter 4` ⇒ [Martins, 2009c] Distributed data acquisition architecture: software client for instrumented Rubik cube (instrumented object).
- `Contributes to chapter 4` ⇒ [Martins, 2009d] Distributed data acquisition architecture: software client for instrumented sensing can (instrumented object).
- `Contributes to chapter 4` ⇒ [Martins, 2009f] Distributed data acquisition architecture: software client for *Tekscan Grip* system (tactile sensing array).
- `Contributes to chapters 4, 6` ⇒ [Martins, 2009e] Distributed data acquisition architecture: software client for *Polhemus Liberty* system (6D motion tracking).

1.3.7 Datasets

- `Contributes to chapter 4` ⇒ `Human demonstration of dexterous manipulation tasks:`
  - Dexterous manipulation of a laboratory pipette.
  - Thumb movement during manipulation tasks.
  - Screwdriver in-hand rotation.
  - In-hand manipulation of toys.
  - Grasp the Wii remote and press a button.
  - Fill a toy sorting box with objects.
  - Pick up a pen and write.
  - Pick an object and slide.

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