Chapter 1

Introduction

Compared to the most advanced robots, average human manipulation skills are outstanding. Robots that perform manipulation tasks in daily life, are mainly devoted to execute repetitive, preprogrammed tasks. Their lack of adaptability has relegate them to be deployed in factories in a controlled environment, inside a cage. There are a lot of simple tasks in manufacturing that cannot be automated with current robots. Those tasks are performed by humans, that with much greater cognitive abilities are stuck counting cups, packing and unpacking boxes and performing tedious, repetitive and not knowledge based work.

Developing a robot that has close-to-human manipulation abilities would change the way robots are used in the current society. The potential of such machines could transform the life of most of the developed countries inhabitants. Factories could include such robots into their manufacturing lines, move the workers performing repetitive tasks to a higher level duty, and increase their productivity. In addition, robots could start being deployed in real houses to assist elderly or disabled people, boosting their living standards and giving them back some independence. Maybe in the future, service robots will be present in each house and considered another house appliance like the washing machine or the dishwasher.

Unfortunately the current state of the art in robotic manipulation is far away from that purpose. So far, there has been no real interest by the industry to include robots with human-like manipulation skills into their production lines. Nevertheless, with the recent growth of collaborative robotics the interest of the industry may change in the near future.

In this thesis we study and develop a framework that enables robots to perform manipulation tasks in unstructured and changing environments. To do so, we have taken inspiration from neuroscience studies about the human sensorimotor control of manipulation and the visual stimuli processing. In the implemented reactive contact based manipulation system: sensory feedback, adaptive control, contact detection, contact prediction, object detection and object recognition are key.

1.1 Motivation

Social facts

Advances in medicine and lifestyle are increasing the life expectancy of the world's population. Moreover, birth control is reducing the number of young people that in the future will support the elder ones. This fact is inverting the population pyramid[1]. In the near future there will not be enough working force to support a society with too many old individuals. Service robotics is an answer to this problem. It can reduce the cost to take care of an elderly person and increase the life quality of all the population. A service robot that takes care of us and does the housework would definitely increase the life standards without the need for more workforce.

Moreover, robust, flexible and adaptive robots will be also a solution for unpleasant tasks or rescue missions in hazardous environments (e.g nuclear plant, factories) and space missions. However, the threat of a future without enough workforce to maintain an elderly population is not enough to trigger public and private investment into robotics development. Fortunately, the recent rise of collaborative robots has set up the perfect moment to attract the investment into robots that can work shoulder to shoulder with humans.

The rise of collaborative robots

Collaborative robotics is a branch of industrial robotics that unlike classic industrial manipulators, uses compliant robots that work shoulder to shoulder with humans. This robots are more failure tolerant and robust to environment changes. Moreover, they have the ability of dealing with a determined amount of uncertainty.

A clear example of the growing interest of the industry in compliant and adaptive manipulators is the emergence of companies (e.g. Rethink Robotics Inc.[2], Universal Robots[3] A/S) that design cheap and robust robots to fill in that gap in the industry marketplace. Recently, Amazon has also shown its interest in that kind of robotic manipulation tasks. In May 2015, they organized the first Amazon Picking Challenge (APC) where a robot had to grasp some objects from a shelf and place them in a bin. From the scientific point of view, it looked like a solved task. However, it turned out to be an unsolved problem. None of the 30 teams from all around the world were able to grasp all the challenge objects.

Although more investment is being attracted by robotics, the current state of the art is far from being able to provide a robot companion with human-like abilities. One

[1]Source: United Nations, Department of Economic and Social Affairs, Population Division. World Population Prospects: The 2012 Revision.

[2]Rethink Robotics Inc. `http://www.rethinkrobotics.com/`

[3]Universal Robots A/S `http://www.universal-robots.com`

Figure 1.1: Some state of the art full-size humanoid robots. Upper row: ASIMO [Sakagami and Watanabe, 2002], ARMAR-4 [Asfour et al., 2013] and iCub [Metta et al., 2008]. Lower row: Kenshiro [Nakanishi et al., 2012], REEM-C [Tellez et al., 2008] and HRP-4 [Kaneko et al., 2011]

approach to understand and be able to replicate human-like abilities is to perform neuroscience studies and observe how humans solve the challenges.

Taking inspiration from humans

Nature has always been a source of inspiration for the human being. Going back to the renaissance, Leonardo Da Vinci took inspiration from nature for several of his inventions and tried to mimic the bird's anatomy at human scale to build a flying suit.

Biomimicry only replicates the geometry of the observed plants or animals to take advantage of a nature-designed structure. Often it is not enough to replicate the design if the control and behaviour are not replicated too. A good example is Kenshiro (See Fig. 1.1 lower left), a robot from the University of Tokyo [Nakanishi et al., 2012], which mimics mostly all the tendons, bones and muscles of a human but cannot walk, grasp, manipulate or interact with its environment.

The main applications of service and rescue robotics are bounded to human engineered environments (factories, houses, cities, vehicles). As the humanoid robots aim to help humans in their own environment, the human form factor is appropriate for such scenarios. As shown in the DARPA Robotics Challenge (DRC)[4] trials, not always the exact human embodiment is the best for specific scenarios. Even though, the winner team presented a robot with two arms and two legs.

Having robots with the same kinematics as humans, makes learning by demonstration and demonstrating tasks to the robots easier. Moreover, in the future it could also work the other way round, allowing robots to teach humans in a more intuitive way. In addition, the human embodiment allows robots to perform easier non-verbal communication and have better acceptance by humans.

There are already many examples of full size humanoid platforms (see Fig. 1.1), unfortunately none of them has a control software stable enough to let such high Degrees of Freedom (DOFs) robots work standalone alongside humans in real environments. Understanding human sensorimotor control could be a key factor to develop software able to control robots with many DOFs like Kenshiro, REEM-C, ASIMO, HRP-4, ARMAR-4 or iCub (See Fig. 1.1) and transform them into multi-purpose, robust service robots.

Recent advances in measuring technologies, such as eye trackers and fMRI, enable the neuroscientists to study the response of the brain under controlled conditions. Although a lot of useful information has emerged from this field, the brain mechanisms are mostly unknown.

1.2 Aims and scope

Regardless of the hardware constraints, there are many software challenges that need to be tackled before a full size commercial humanoid robot can be available. In this thesis we focus on autonomous manipulation under uncertainty in unstructured scenarios.

The main aim of this thesis is to research how to endow a manipulator robot with sufficient manipulation skills to perform the most common manipulation tasks. The robot has to adapt to unstructured environments and deal with unknown objects. Moreover, a mechanism to define tasks that the robot can execute has to be provided. Finally, the implemented skills should be transferred among different platforms with reasonable effort.

Apart of humanoid robots, the work presented in this thesis can be applied to any industrial or collaborative manipulator with potential manipulation skills. Dexterous

[4] Darpa Robotics Challenge: `http://www.theroboticschallenge.org/`

manipulation and in-hand manipulation are out of the scope of the work presented. However, those skills can be easily added as new components to the framework.

1.3 Methodology

In this thesis, we have taken inspiration from neuroscience theories, derived from experiments on humans, that give some clues on how humans perform manipulation tasks. First, we have identified the components of human manipulation from a wide variety of neuroscience experiments available in the literature. Those components are:

- Action phase controllers: object manipulation tasks typically involve a series of action phases. Each phase accomplishes a specific goal or subgoal of the task.
- Contact events: encode the making and breaking of contact between either the fingertips and the grasped object or the object in hand and another object or surface.
- Sensor fusion: contact events could be detected using many sensory cues, vision, force, touch or even audio.
- Contact event prediction: during object manipulation the brain predicts sensory events that signify goal attainment.
- Corrective actions: a mismatch between the expected sensory event and the perceived sensor signals triggers a learned corrective action.

Second, we have implemented each of the identified components and put them together into the same framework. Each of the components, required its own research effort and were implemented and validated experimentally.

As a result, we have implemented a system capable of performing manipulation tasks in unstructured scenarios and adapt to uncertainties and unexpected events. The manipulation skills are demonstrated along the thesis in the different experiments performed to validate the components of the system. In those experiments, the robot has been able to empty a box full of unknown objects without using visual feedback, only knowing the position and size of the box. Another experiment has shown the ability of the presented framework to grasp a bottle with one hand and unscrew its cap with the other hand.

Beyond the robots used in this thesis, the framework presented can be ported to any manipulator robot through the hardware abstraction mechanism presented. The presented framework has been ported to the Baxter robot and used to participate and solve the APC where the robot has to autonomously grab a set of target objects from a shelf and place them into a container.

1.4 Outline

This thesis is structured as follows:

Chapter 2 - Human-inspired sensorimotor control of manipulation

Chapter 2 summarizes the experiments carried out by R.S. Johansson and J.R. Flanagan, regarding human manipulation of objects, and explains their theories about the sensorimotor control of manipulation in humans.

Inspired by neuroscience, the theoretical models from Johansson and Flanagan are converted into a computational model to define a task as a set of actions connected by contact events. Finally, the elements required for a robotic implementation are identified and bound to the neuroscience model.

Chapter 3 - Manipulation primitives

Manipulation primitives are the basic actions that can be combined in order to perform a task. Chapter 3 presents the manipulation primitive paradigm and shows an example of implementation of a set of primitives. Primitives compose the vocabulary of actions used to describe tasks. Examples of complex task definitions using the paradigm are shown.

While executing a task, there are many situations that can cause the robot to fail. In some of those cases it is possible to detect the failure before it happens, thus instead of failing, a corrective action can be taken that can solve the problem and allow the task to be completed successfully. Chapter 3 describes how reflexes are embedded into manipulation primitives to make them more robust and adaptive.

Chapter 4 - Contact perception

Detecting and localizing contacts with objects and the environment is key for the robot to perform a task. Chapter 4 details the use of vision, tactile, force, proprioception, control and prediction to detect and localize contacts. The mechanisms to generate contact events are also shown. Moreover, this chapter proposes a sensor fusion method to combine different sensory cues and convert sensor readings into contact hypotheses providing a common representation for all the sensors.

Chapter 5 - Contact prediction

In Chapter 5 the mechanisms used for contact prediction are described. Using the perceived state of the environment, a dynamics simulation is executed in parallel to the real action. The simulation provides the on-line prediction of contact events, that will be used with the task description to monitor the task status, detect errors and trigger reactive behaviours. Contacts could also be predicted from previous successful executions of the task, this is also discussed in Chapter 5.

Chapter 6 - Integration architecture

All the components of the system must be organized and orchestrated. Chapter 6 presents the layered architecture used to integrate all the components. Beyond task coordination, there is a system-wide architecture that dictates how modules have to be implemented depending on their role and level of abstraction.

Chapter 7 Embodiment abstraction

In Chapter 7, we show how the manipulation primitives paradigm can be a tool for embodiment abstraction enabling the same task definition to be successfully used on different robots.

Chapter 8 - Object perception

Object detection, localization and recognition mechanisms are not studied by the main neuroscience theories that inspired this thesis. Nevertheless, it is an important part of any robotic system. In Chapter 8 we have taken inspiration from neuroscience experiments that study those abilities and implemented a visual recognition system inspired by primate brain mechanisms.