Appendices

Appendix A

Robotic platforms

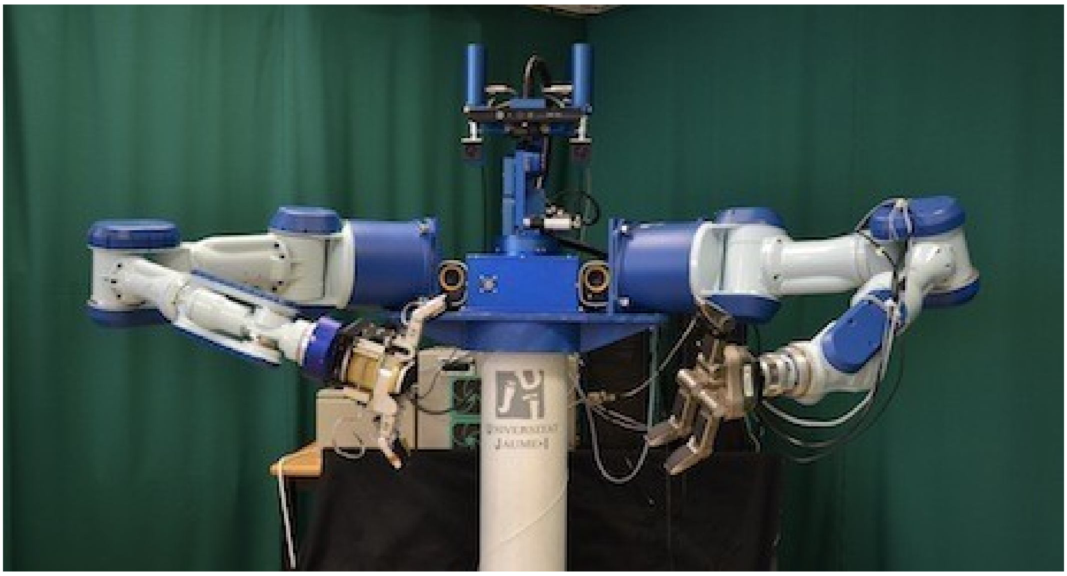


Figure A.1: Tombatossals: The UJI humanoid torso.

A.1 Tombatossals. The UJI humanoid torso

The humanoid torso is composed of two arms, two hands and a head for a total of 29 DOF. Three desktop computers are used for control and processing. The robot is depicted in Fig. A.1. This platform was built and enhanced during the development of this thesis and has been the main platform used to perform the research and the experiments presented through this thesis. All the chapters of this thesis have used this platform for experimental validation.

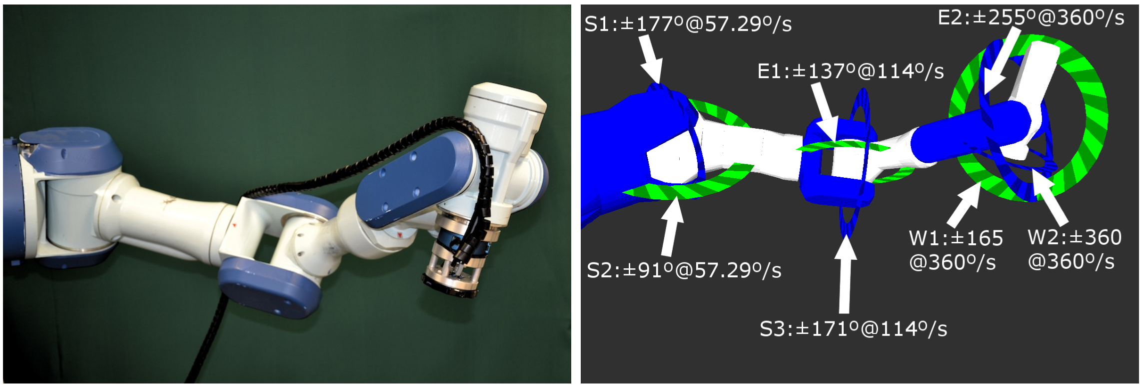


Figure A.2: Left: PA10-7C 7 DOFs arm. Right: Arm model and joints with their angle and speed limits.

A.1.1 The arms

Both arms are Mitsubishi PA10-7C, 7 DOF industrial manipulators with a position repeatability of ±0.1mm. Each arm weights 40Kg and has 10Kg payload. Taking into account the hands, force sensors and tool adapters, the remaining payload is 7.2Kg for the left hand and 7.8Kg for the right hand. Joints can be controlled in position, velocity and effort. The joint names, limits and speed are depicted in Fig A.2. The arms are placed in the same horizontal plane with an aperture angle of 120° (Fig. A.1). See [Elbrechter et al., 2012] for an alternative configuration using these same arms.

A.1.2 The hands and contact sensors

Barrett Hand

It is an under-actuated 3-fingered hand with 4 actuated DOF that can be controlled either in velocity or in position. Each finger has two coupled joints actuated by one motor. The other DOF drives the opposition of two of the fingers. The joint angles and actuation speed are depicted in Fig.A.3. Each finger has an integrated strain-gauge sensor that provides the torque applied to its distal phalanx.

Schunk SDH2 Hand

It is a fully actuated 3-finger hand with 7 DOF, 2 DOF for each finger and 1 DOF to pivot contrary-wise two of the fingers. Joint limits are ±90°for each joint and 210°/s speed. As it can be seen in Fig.A.4 the opposition of the fingers is limited to 90°. Thus, this hand can oppose two of the fingers but cannot perform a hook grasp.

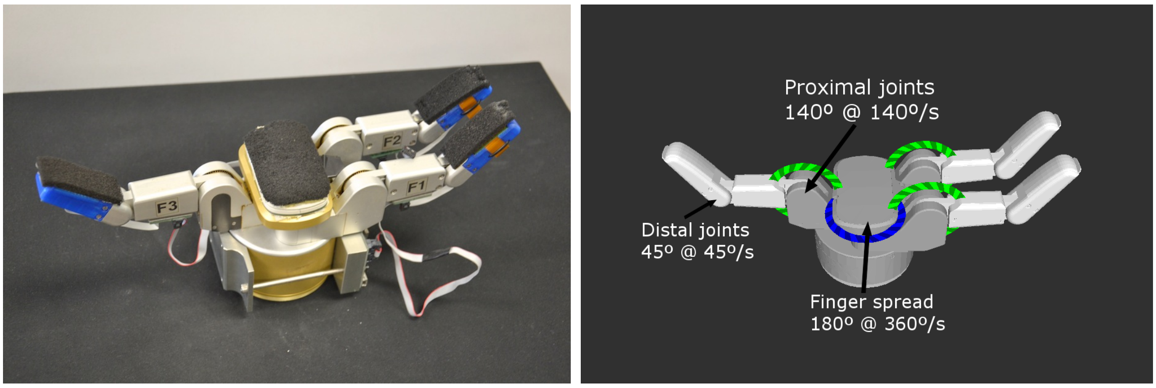


Figure A.3: Left: Underactuated 4 DOFs hand Barrett Hand upgraded with Weiss Robotics tactile sensors. The distal phalanxes are modified for a better integration of the sensors. Right: Hand model and joints with their angle and speed limits.

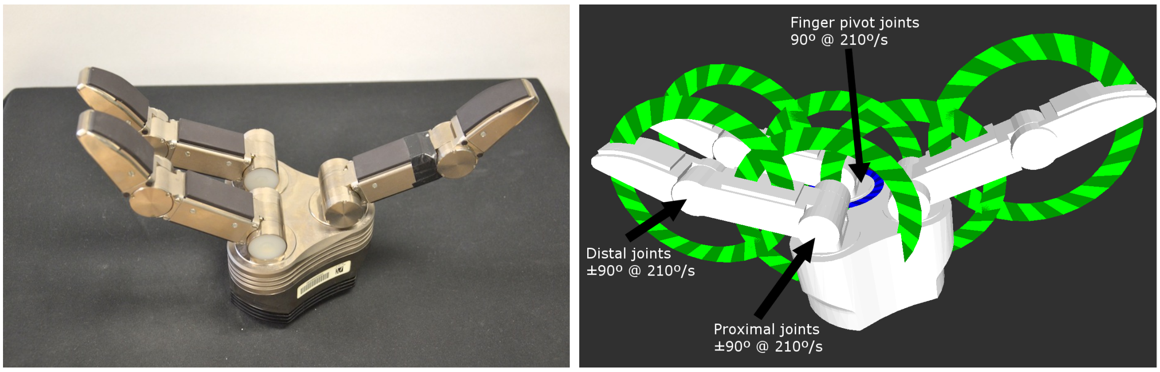


Figure A.4: Left: 7 DOFs Schunk Hand with Weiss Robotics tactile sensors. Right: SDH2 Hand model and joints with their angle and speed limits.

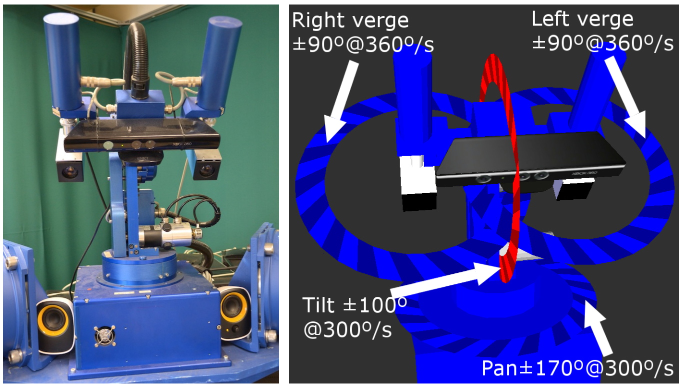


Figure A.5: Left: TO-40 pan-tilt-verge head. Right: Head model and joints with their position and velocity limits.

Sensors

The right hand (Barrett Hand) is upgraded with Weiss Robotics[1] resistive tactile sensors mounted on the palm and on the distal phalanxes. Tactile sensor pads are custom arrays of 5x8 pressure sensors for the phalanxes and 6x14 for the palm. The distal phalanxes are modified for a better integration of the sensors, (see Fig.A.3). The left hand (SDH2) has Weiss Robotics tactile sensors already integrated on the proximal and distal phalanxes. See black patches in Fig.A.4. Tactile sensors have a sampling rate up to 230Hz.

Between each hand and its arm there is a JR3[2] 6 axis force-torque sensor. The force-torque sensors on each wrist provide the other modality of contact sensing, their sample rate can be up to 200Hz.

A.1.3 The head and camera setup

The head is composed of a TO40 pan-tilt-vergence system and a Kinect™. Head joints are depicted in Fig.A.5. The TO40 is a 4 DOFs head with two DFK 31BF03-Z2 cameras. The motorized zoom allows the control of the focal length from 5mm to 45mm. The cameras have a resolution of 1024x768@30fps. The baseline between cameras is 27 cm. The Kinect ™ provides RGB and Depth images with a resolution of 640x480@30fps.

A.1.4 Computers

The robot sensors and actuators are connected to three different computers. The computers are physically connected to each other through a Gigabit Ethernet switch. The communication is handled by ROS, and the computer where the algorithms are running is transparent to the programmer. However, in order to balance the load, each computer

[1] Weiss Robotics sensors. `http://www.weiss-robotics.de/`
[2] JR3 Force-torque sensors. `http://www.jr3.com/`

Main task	Processor	RAM	GPU
2D Vision	Intel E8400 @3.00GHz	8Gb	560GTX 1Gb
3D Vision	Intel i5 650 @3.20GHz	8Gb	580GTX 1Gb
Control	Intel Q9550 @2.83GHz	8Gb	9800GT 512Mb

Table A.1: Hardware specs of each computer

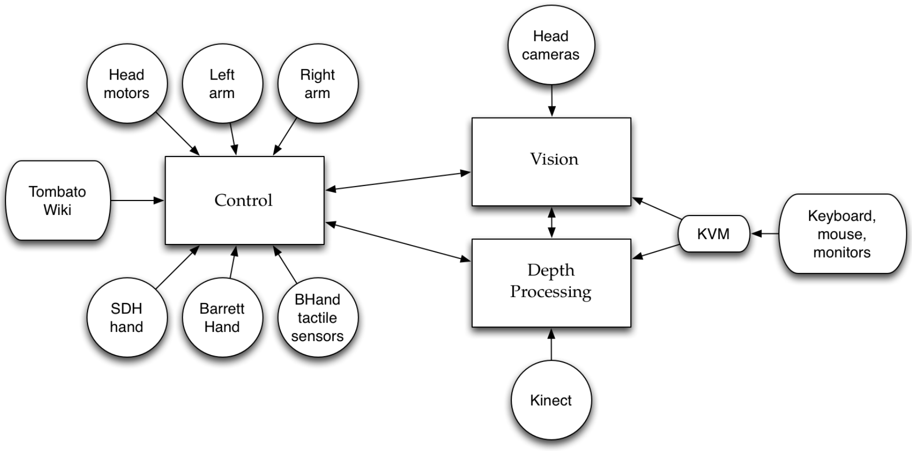


Figure A.6: Tombatossals computer layout. It is composed by three computers: Control, Vision and Depth Processing.

copes with a specific task. It is important that modules that require high bandwidth data sources (e.g. cameras, depth sensors) run on computers that have direct access to those sources. In Fig. A.6 we show how the sensors and actuators are connected and the role of each computer depending on the sensors that are directly available for that computer. However, other roles such as task management or visualization do not have a computer assigned and can be run transparently on any machine. The description of the computers and their main tasks are shown in table A.1.

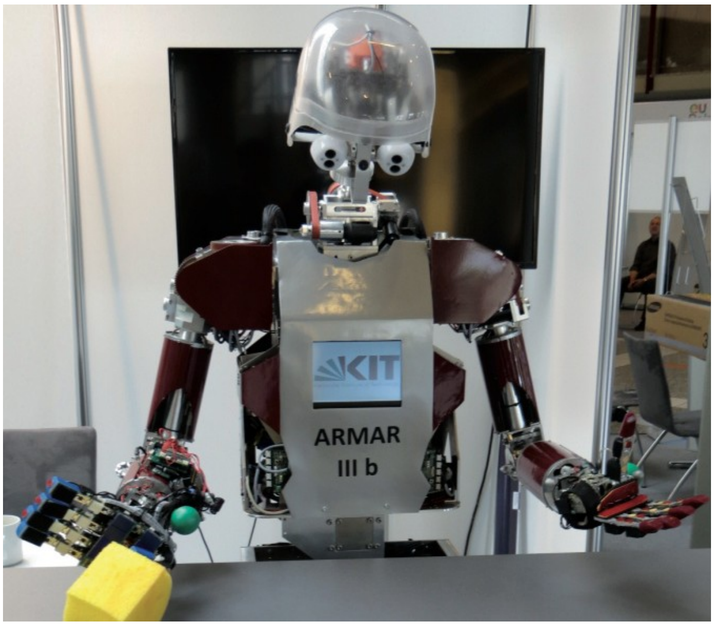


Figure A.7: ARMAR-IIIb a humanoid robot with 43 DOF.

A.2 ARMAR IIIb

ARMAR-IIIa was designed and built in 2006 by the Karlsruhe Institute of Technology, its design closely mimics the sensory and sensorimotor capabilities of the human.

The robot was designed to deal with a household environment and the wide variety of objects and activities encountered in it. ARMAR-IIIa is a fully integrated autonomous humanoid system. It has a total 43 DOF and is equipped with position, velocity and force-torque sensors. The upper body has been designed to be modular and light-weight while retaining similar size and proportion as an average person. For the locomotion, a holonomic mobile platform is used. Two years later, a slightly improved humanoid robot, ARMAR-IIIb (shown in Fig. A.7), was engineered. Detailed information about the robot can be found in [Asfour et al., 2006], where most of the information summarized in this section was extracted from.

This platform was used in this thesis for the research and implementation of the work presented in Chapter 4 during the 4 month research stay at the Karlsruhe Institute of Technology in 2012.

A.2.1 The arms

The arms are designed in an anthropomorphic way: three DOF in the shoulder, two DOF in the elbow and two DOF in the wrist for a total of 7 DOF. The design of the

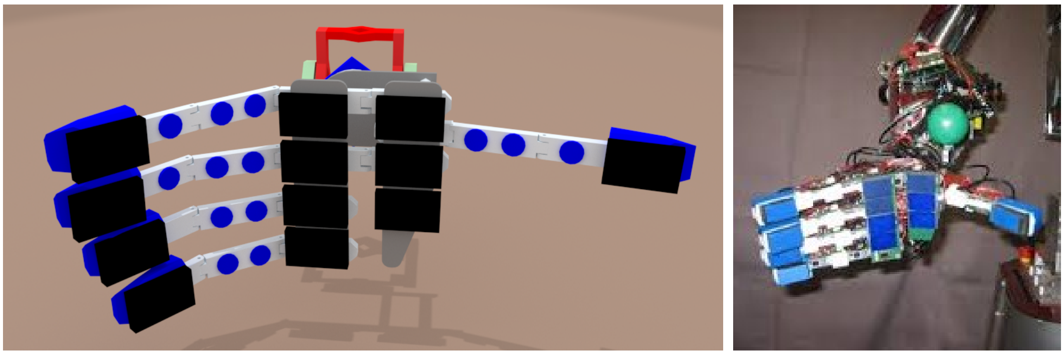


Figure A.8: The Karlsruhe Humanoid Hand. Left: Hand model with black patches showing the tactile sensors. Right: Hand picture.

arms is based on the observation of the motion range of a human arm. Motors can be position, velocity and torque controlled.

A.2.2 The hands and contact sensors

Each arm is equipped with a five-fingered hand with eight actuated DOF. The hand is under-actuated, each finger has 2 DOF and the palm another one. The thumb, index and middle fingers have their 2 DOF actuated, the ring and pinkie are coupled and only have 1 DOF, the last DOF controls the palm. The hand is actuated using compressed air and valves, the position of the actuated joints can be controlled using the feedback provided by the joint encoders. However, when grasping objects or applying forces to the environment with the fingers the exact position cannot be determined only by the encoders.

Sensors

For tactile feedback during manipulation operations, a former version of the Weiss tactile sensors mounted on Tombatossals' Barrett Hand are used in ARMAR-IIIb. The sensors are mounted on the distal phalanxes of each finger and on the palm as depicted in Fig. A.8. The detailed description of the tactile sensors developed for the robotic hand was published in [Kerpa et al., 2003], however the sensors were improved and the first commercial version was provided by Weiss Robotics GmbH & Co.KG[3]. Nowadays, these sensors have evolved and are used in many robotics applications in industry and research. In the wrist, 6D force/torque sensors from ATI Industrial Automation[4] are used.

[3]Weiss Robotics GmbH & Co.KG: http://www.weiss-robotics.de/en/
[4]ATI Industrial Automation: www.ati-ia.com

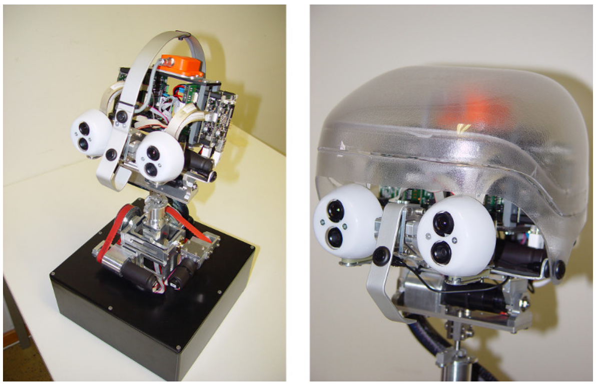


Figure A.9: The Karlsruhe Humanoid Head.

A.2.3 The head and camera setup

ARMAR-IIIb uses a Karlsruhe humanoid head. It possesses two cameras per eye with a wide-angle lens for peripheral vision and a narrow-angle lens for foveated vision. It has a total number of 7 DOF (4 in the neck and 3 in the eyes), six microphones and a 6D inertial sensor. Throughout Europe, there are already ten copies of this head in use. The details about the head mechanism, sensors and control are provided in [Asfour et al., 2008].

A.2.4 Computers

There are five computers inside the robot that are devoted to different tasks. The computers are separated in a three layered architecture: task execution, task coordination and task planning. Each computer has different roles assigned, audio processing and synthesis, visual perception, platform control and navigation, coordination, position and torque motor control. The computer layout is the same as detailed in [Asfour et al., 2008] but the computers have been recently updated to Intel i5 processors for powerful onboard computational capabilities.

The computers are running under Linux, with the Real Time Application Interface RTAI/LXRT-Linux. They are interconnected through a gigabit ethernet network. For the implementation of the control architecture and interprocess communications, the MCA2[5] framework is used.

[5]MCA2: `http://www.mca2.org/`

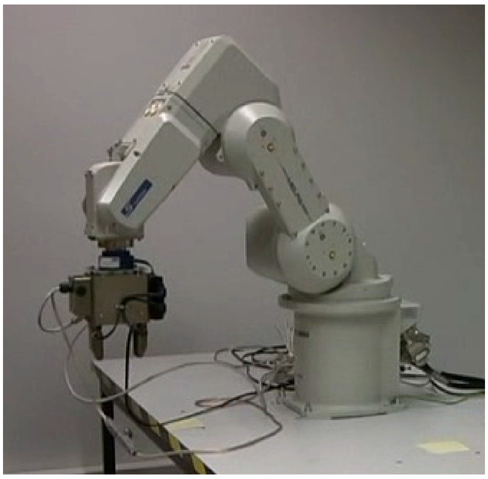


Figure A.10: Industrial manipulator setup composed of a 6DOF Mitsubishi Melfa RV-3SB 6DOF industrial manipulator and a Schunk PG70 2-Finger Parallel Gripper.

A.3 Mitsubishi Melfa RV-3SB arm

The robotic setup available at the Lappeenranta University of Technology (LUT), consists of a 6DOF Mitsubishi Melfa RV-3SB industrial manipulator and a WRT-102 gripper from Weiss Robotics, see Fig. A.10.

The Melfa RV-3SB is an industrial manipulator with 3Kg payload and a position repeatability of $\pm$0.02mm. It weights 37Kg and the speed of motion of the joints varies from 187 to 660 degrees per second depending on the joint. The WRT-102 gripper is based on the PG-70 2-Finger Parallel Gripper from Schunk but has tactile sensors on both fingers. Between the gripper and the arm there is a 6DOF JR3 force-torque sensor.

This platform was used for the embodiment abstraction experiments performed in Chapter 7 as one of the results of the GRASP Project funded by the European Commission under the FP7 programme.

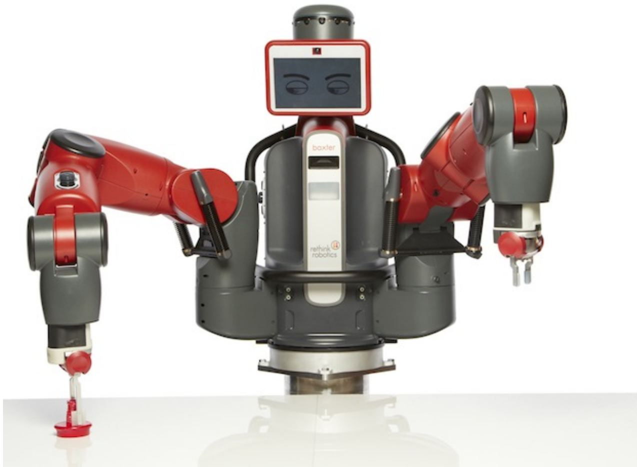


Figure A.11: Baxter collaborative robot.

A.4 Baxter

Baxter is a commercial compliant low-cost manipulator torso manufactured by Rethink Robotics. It features a dual-arm configuration very similar to Tombatossals. With a total weight of 138.79 Kg. This platform was used for the software architecture implementation presented in Chapter 6 and the participation in the APC 2015 by the RobInLab team.

A.4.1 The arms

The arms of Baxter (see Fig. A.12) weigh 21.3 Kg, have 7DOF and a payload of 2.2 Kg already taking into consideration the grippers included with the robot. Although, the manufacturer does not provide information about its position repeatability, it is well known that Baxter's arms are not precision manipulators, some users of the robot have reported that its repeatability is around $\pm$3mm. The arms are compliant and they have a safety mechanism that automatically loosens the arms when the perceived external force is over a certain limit. The joints can be controlled in position, velocity or torque.

A.4.2 The grippers

The gripper provided by the manufacturer has a very small range of movement and cannot grasp the wide variety of objects that are present in household scenarios. Given the 2.2Kg payload of the arms, using a commercial hand such as SDH2 or Barrett Hand, is not an option as they weigh around 2Kg. Inspired by the Festo Fin Ray gripper[6], we have developed our own low-cost and light-weight gripper for Baxter, see Fig. A.13.

[6]Festo Fin Ray gripper: `https://www.festo.com/cms/en_corp/9779.htm`

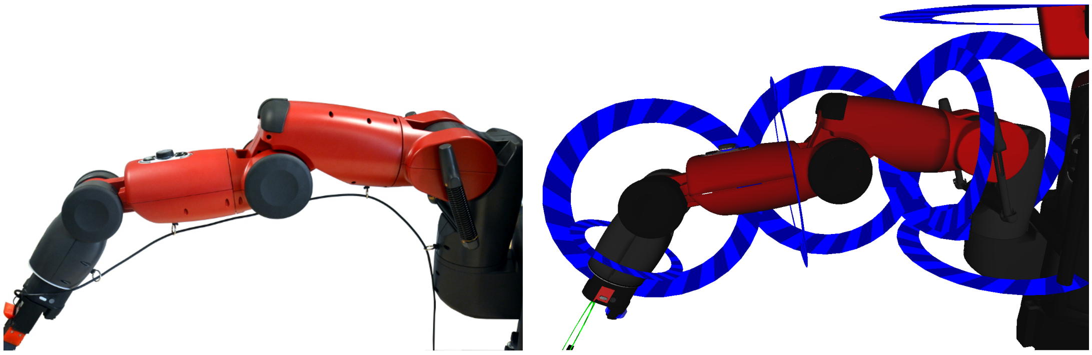


Figure A.12: Left: Baxter robotic arm. Right: Baxter robotic arm model and joints.

Sensors

The controller of the arms provides a virtual 6D force-torque sensor using the computed external forces at the end effector. Although the measurements are very noisy and not accurate, they are useful enough for contact detection and safety corrections. In each end effector there is an embedded fisheye camera that provides up to 1280x800 images at 30Hz and a IR range sensor.

A.4.3 Head and camera setup

The head consists of a screen attached to a pan and tilt mechanism. The pan joint angle can be controlled, however the tilt joint has only two positions, up and down. The screen has an integrated fisheye camera. On top of the head there is a ring of sonar distance sensors that are used to detect the presence of people in the vicinity, the robot head is depicted in Fig. A.14. In order to enhance the robot perceptual capabilities and be able to explore all the bins of the APC shelf, we developed a kinect adapter for the robot elbow.

A.4.4 Computers

The Baxter robot has an embedded computer with a 3rd Gen Intel Core i7-3770 Processor. It can work standalone but for research and more demanding applications it can be connected to an external network with a Gigabit Ethernet cable. The robot is controlled natively using ROS, thus a computer network like the one used for Tombatossals or ARMAR-IIIb can be easily set-up and used to distribute the computational expensive modules over different computers.

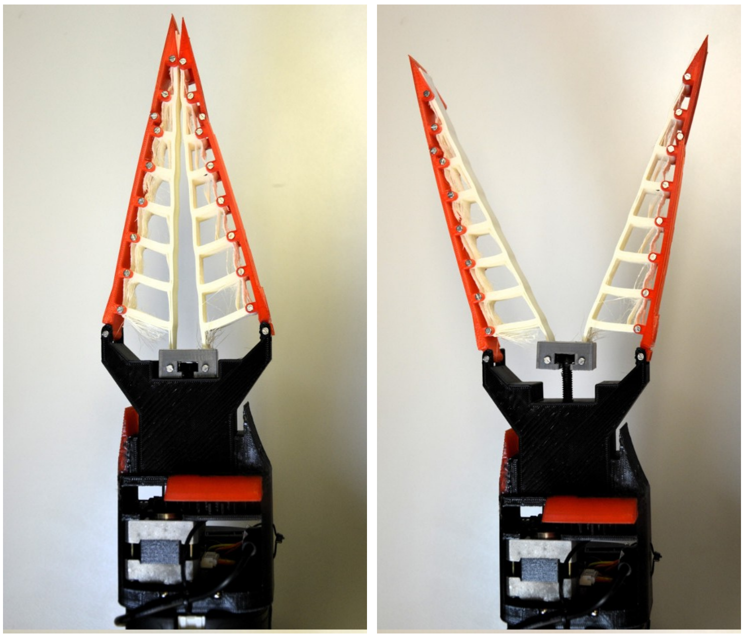


Figure A.13: Low-cost light-weight adaptive grippers for Baxter, developed for the Amazon Picking Challenge by the RobInLab team.

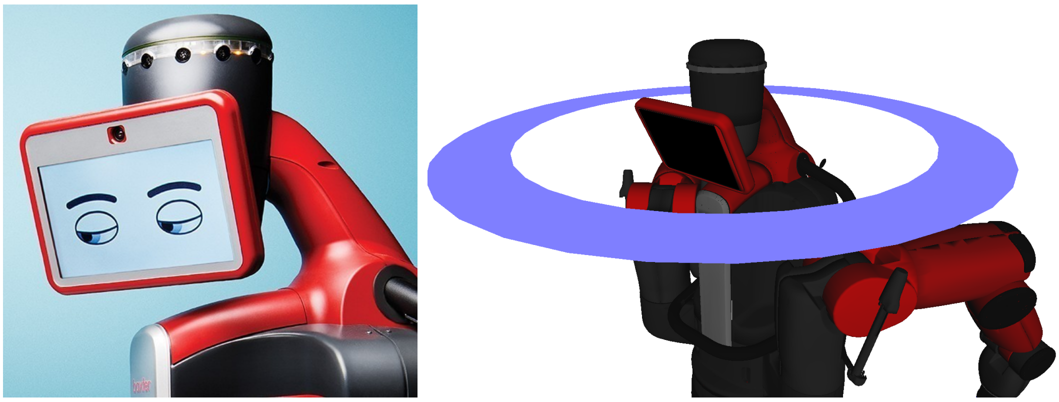


Figure A.14: Left: Baxter's pan-nod head. Mounted on the pan-nod mechanism there is a screen with a camera. On top of the head there is an array of sonar distance sensors. Right: Baxter head model and controllable pan joint.

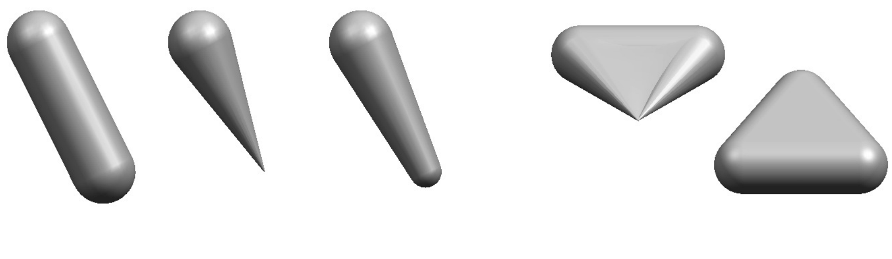
Appendix B

Robot spherical modelling

A geometric model of the robot can be used to reason about the space occupied by it and estimate contacts with objects. It is also a very useful tool to segment out the robot from an image or from a point cloud.

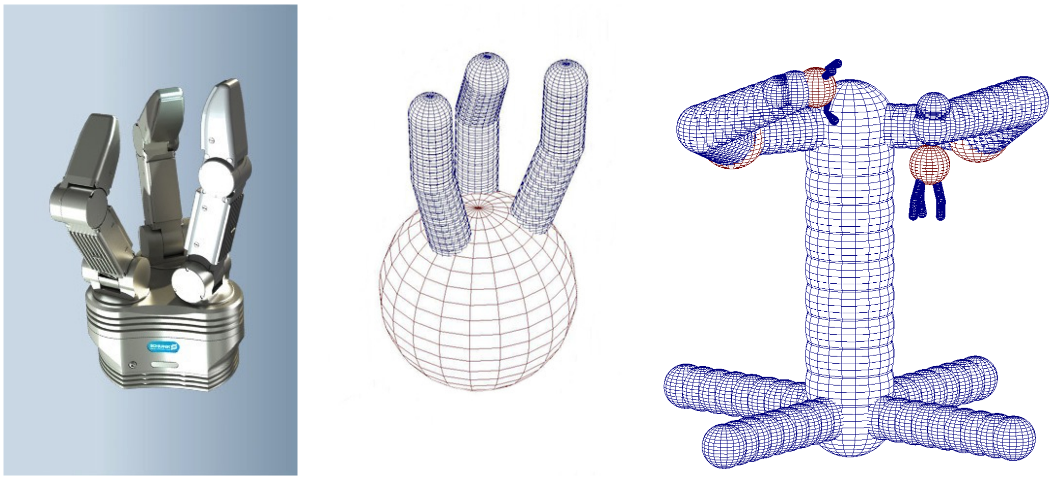
To model a robot, a model based in bounding volume primitives, can be used. For the model presented here, the spherically extended polytopes (*s-topes*) are used. This representation has been widely used [Tornero et al., 1991, del Pobil and Serna, 1995, Gilbert et al., 1988] because of its efficiency in distance computation, specifically in collision detection and path planning. An *s-tope* [Hamlin et al., 1992] is the convex hull of a finite set of spheres $s \equiv (c, r)$, where c is the centre and r its radius. Given the set of n spheres $S = \{s_0, s_1, ..., s_n\}$, the convex hull of such a set, S_s, contains an infinite set of swept spheres expressed by Eq. B.1. Where λ_i is the parameter that determines a specific sphere, radius and centre, of the whole set of spheres.

$$S_s = \left\{ s : s = s_0 + \sum_{i=0}^{n} \lambda_i (s_i - s_0), s_i \in S, \lambda_i \geq 0, \sum_{i=0}^{n} \lambda_i \leq 1 \right\} \qquad \text{(B.1)}$$



(a) s-tope with two spheres, bi-sphere (b) s-tope with three spheres, tri-sphere

Figure B.1: Examples of simple s-topes: bi-spheres and tri-spheres



(a) Shunk Dextrous Hand (SDH) (b) SDH spherical model (c) Spherical model of our robotic system

Figure B.2: Spherical model of hand and robot

To illustrate the previous equation, Figure B.1 depicts several examples of s-topes defined by two (*bi-spheres*) and three spheres (*tri-spheres*).

We have modelled our robot as a combination of s-topes. Each link is represented as a bi-sphere and some static parts (i.e. hand palm) as single spheres. In addition, each defining sphere has been attached to the corresponding frame of the kinematic chain. Figure B.2(c) depicts the complete model of our robot manipulator system and Figure B.2(b) illustrates a detail with the model of our three-fingered hand.

The distance of a point to the spherical model is calculated as the minimum distance from the point to all the s-topes that compose the robot model. Since our geometric model is composed only of spheres and bi-spheres, we need to apply only two rules to compute each distance. For a single sphere, the distance between a point p_i and the sphere $s \equiv (c, r)$ is computed using Eq.B.2, where c is the centre and r the radius:

$$distance = \|p_i - c\| - r \tag{B.2}$$

The distance between a point p_i and a bi-sphere is calculated as follows: first we need to determine the closest sphere center to the point among the infinite number which define the bi-sphere. Given a bi-sphere defined by the spheres $s_1 \equiv (c_1, r_1)$ and $s_2 \equiv (c_2, r_2)$, Eq. B.3 defines the rule to find the closest sphere $s_{min} \equiv (c_{min}, r_{min})$ to p_i. If $\lambda < 0$ the first sphere is used. Then, Eq. B.2 can be used to compute the distance.

$$\begin{aligned}
\lambda_{min} &= -\frac{(c_1 - p_i) \cdot (c_2 - c_1)}{\|c_2 - c_1\|^2}; \quad \lambda_{min} \in [0, 1] \\
c_{min} &= p_i - c_1 + \lambda_{min}(c_2 - c_1) \\
r_{min} &= p_i - r_1 + \lambda_{min}(r_2 - r_1)
\end{aligned} \tag{B.3}$$

Acronyms

AIP Anterior Intraparietal Sulcus. 160, 164

ANNs Artificial Neural Networks. 146

AOS Axis Orientation Selective. 164, 167, 172–176

APC Amazon Picking Challenge. 2, 5, 140, 194, *Glossary:* Amazon Picking Challenge

API Application Programming Interface. 103

AVs Approach Vectors. 135, 138

BSD Berkeley Software Distribution. 103, *Glossary:* BSD

CCG Combinatory Categorical Grammar. 147

CIP Caudal Intraparietal Sulcus. 162, 164, 172

CNS Central Nervous System. 18

COLLADA COLLAborative Design Activity. 103, *Glossary:* COLLADA

DMP Dynamic Movement Primitive (DMP). 30

DOF Degrees of Freedom (DOF). 4

DRC DARPA Robotics Challenge. 4, *Glossary:* DARPA Robotics Challenge

GPL General Public License. 103, *Glossary:* GPL

HMMs Hidden Markov Models. 146

ICP Iterative Closest Point. 81, 82

LOC Lateral-Occipital Complex. 161–165

MLS Minimum Least Square. 174

ND Normal Density. 174, 175

NM Nearest Mean. 174

ODE Open Dynamics Engine. 105

OGM Occupancy Grid Map. 79, 81, 82

OMPL Open Motion Planning Library. 134

PbD Programming by demonstration. 146

PCA Principal Component Analysis. 11, 135

RBFs Radial Basis Functions. 146

ROI Region Of Interest. 134

ROS Robot Operating System. 105, 106, 125, 126, *Glossary:* ROS

SOS Surface Orientation Selective. 164, 167, 172–176

V1 Primary Visual Cortex. 161, *Glossary:* V1

V2 Secondary Visual Cortex. 162, *Glossary:* V2

V3 Third Visual Complex. 162, 163, *Glossary:* V3

V4 Visual Area V4. 162, 163, 165, 166, *Glossary:* V4

YAML YAML Ain't Markup Language. 130

YARP Yet Another Robot Platform. 125

Glossary

action-phase controllers object manipulation tasks typically involve a series of action phases in which objects are grasped, moved, brought into contact with other objects and released. Each phase accomplishes a specific goal or subgoal of the task. 16

Amazon Picking Challenge a robotic grasping competition organized by Amazon. The robots, being in front of a shelf, like the ones used in Amazon warehouses, had to autonomously grasp a set of objects and place them into an order bin. The robot is given a file with a list of the target objects and it has to autonomously search, pick and place them into the order bin. There is a scoring system based on the number of objects retrieved, penalty points are received if the wrong object is picked or for each object dropped. More information about the rules and the past edition of the contest can be found at `http://amazonpickingchallenge.org/`. 2, 201

Biomimicry a field of study that not only takes inspiration from nature but replicates the mechanisms that the evolution has designed in order to provide solutions and improvements to current problems. 3

BSD a family of permissive free software licenses, imposing minimal restrictions on the redistribution of covered software. 103, 201

collaborative robotics a branch of industrial robotics where compliant robots are used to work shoulder to shoulder with humans. This robots are more failure tolerant and robust to environment changes and have the ability of dealing with a determined amount of uncertainty. 1

COLLADA defines an XML Namespace and database schema to make it easy to transport 3D assets between applications without loss of information, enabling diverse 3D authoring and processing tools to be combined into a content production pipeline. 103, 201

DARPA Robotics Challenge a competition of robot systems and software teams vying to develop robots capable of assisting humans in responding to natural and man-made disasters. More information can be found at http://www.theroboticschallenge.org/. 4, 201

FAI type I fast adaptation mechanoreceptors, a.k.a. Meissner corpuscles. Respond to stimulation with a burst of firing at the beginning and end of stimulation. Their receptive field is small and are located in the Dermis (just below the epidermis). Better respond to rubbing against the skin or skin movement across a surface. 14

FAII type II fast adaptation mechanoreceptors, a.k.a. Pacinian corpuscles. Respond to stimulation with a burst of firing at the beginning and end of stimulation. Their receptive field is large and are located in the Dermis (deep in subcutaneous fat). Better respond to non uniform stimulation like vibrations. 14

GPL the GNU General Public License is a free, copyleft license for software and other kinds of works. 103, 201

grip force force applied perpendicular to the fingertip surfaces. 18, 20

load force force applied tangential to the fingertip surfaces in order to lift a grasped object. 20

manipulation primitive a reactive controller, designed to perform a specific primitive action on a particular embodiment. 24

micro-neurography a neurophysiological method employed by scientists to visualize and record the normal traffic of nerve impulses that are conducted in peripheral nerves of waking human subjects. 12, 14

Open source refers to a computer program in which the source code is available to the general public for use and/or modification from its original design. 103

ROS a middleware that provides a message passing framework among other features. Its developers community provide a set of open source software libraries and tools oriented for robot applications. 105, 202

safety margin when grasping an object, the difference between the grip force and the slip force. The slip force is the minimum force applied before the object starts slipping. 18

simple tactile reaction time time of reaction to a tactile stimulus in the absence of any cognitive demand of the subject. 17

V1 a region of the functional model of the brain in charge of edge detection and global organisation of the scene. As information is further relayed to subsequent visual areas, it is coded as increasingly non-local frequency/phase signals. 161, 202

V2 a region of the functional model of the brain sensitive to orientation, spatial frequency, and color. 162, 202

V3 a ventral stream region of the functional model of the brain in charge of color extraction, shading and 2D orientation features. 162, 202

V4 a ventral stream region of the functional model of the brain, it is devoted to use the information extracted by V3 and produce viewpoint invariant data of the objects. 162, 202

YAML is a human friendly data serialization standard for all programming languages. 130, 202

YARP a robot middleware that supports building a robot control system as a collection of programs communicating in a peer-to-peer way, with an extensible family of connection types (tcp, udp, multicast, local, MPI, mjpg-over-http, XML/RPC, tcpros, ...) that can be swapped in and out. It also supports flexible interfacing with hardware devices. 125, 202

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