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Robot Simulation and Motion Planning

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B.Sc. Thesis

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Abstract

This document explains how to write IIS theses using the $\text{\LaTeX} 2_{\varepsilon}$ ‘iisthesis’ class¹, which is itself based on the $\text{\LaTeX} 2_{\varepsilon}$ ‘book’ class and is intended for compiling with pdflatex. This document does not tell you how to structure your thesis.

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Declaration

By my own signature I declare that I produced this work as the sole author, working independently, and that I did not use any sources and aids other than those referenced in the text. All passages borrowed from external sources, verbatim or by content, are explicitly identified as such.

Signed: Date:

Chapter 1

Introduction

Operating a robot and developing high level control code for it is a cumbersome task. Very often various groups of developers are working simultaneously on different parts of the software. But in most cases there is only one device that can be used for testing and so only one can run his/her code at a time. The others have to wait until they get access to the robot. Moreover, tests on real robots always come with a high level of risk. Incorrect algorithms can lead very fast to damages on robot components or their environment and entail costly repairs. In the worst case even people can get hurt by uncontrolled robot motions.

The solution to those problems is the usage of a simulator that mimics the robot components and their behavior as accurate as possible. It has to provide the same control interface so that each part of the software can get tested on the simulator before it gets utilized on the real robot. Those considerations motivated the first part of this thesis – the realistic replication of the IIS-Lab robot setup on a suitable simulation platform. This involves the creation of an exact model of the robot setup, containing the various robot components and their environment. The necessary steps are explained in Chapter 2.

The second part of the thesis is about motion planning. Moving the robot hand cannot follow any arbitrary trajectory towards a target pose. During that motion it might collide with itself or any other obstacle within its environment. That means those trajectories have to be planned carefully to avoid accidental collisions and to generate smooth and well controlled robot motions. This also involves to create and maintain an internal representation of the robot and its environment, a step that is common to the simulation part of the thesis. Chapter 3 shows the configuration and integration of the motion planning framework MoveIt into the IIS-Lab robot setup along with some usage examples.

Chapter 4 focuses on MoveIt's grasping functionality. It shows, how a reference 'Pick and Place' task can be planned with the planning tools and executed on the simulator and the real robot as well.

In Chapter 5, some test results will be presented, analyzing the quality of the various planning algorithms and approaches.

1.1 IIS-Lab Robot Setup

The robot setting, that was considered in this thesis can be seen in Figure 1.1. The main part of the robot setup in the IIS-Lab consists of an aluminium torso with two mounted KUKA light weight robot arms. Those arms have 7 degrees of freedom (DOF) each one can carry up to 7kg of payload. Additionally a Schunk SDH gripper can be mounted on each arm.

- **KUKA LWR 4+ arm**

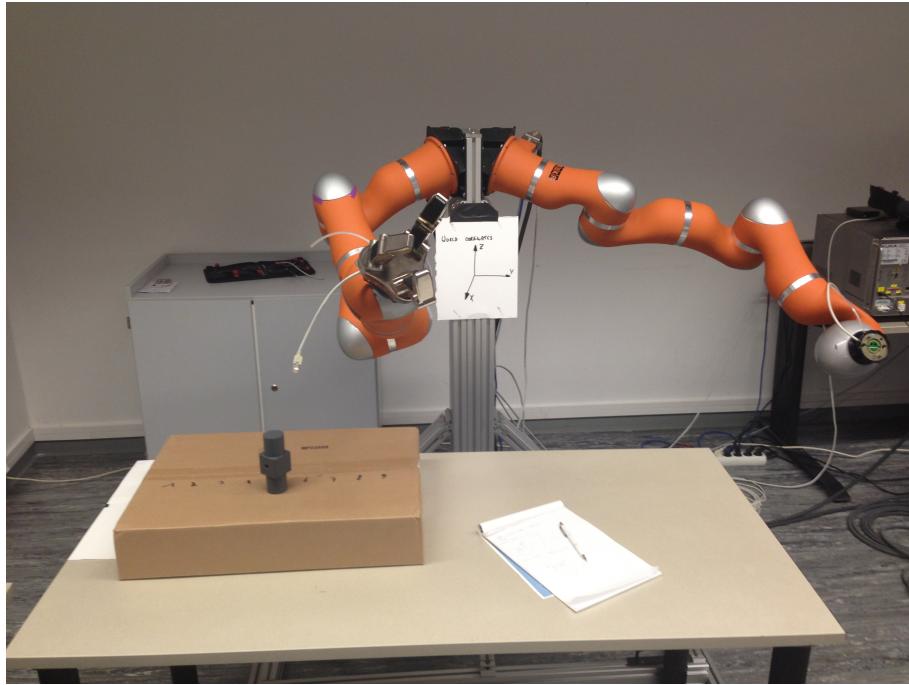


Figure 1.1: Current setup in the IIS-Lab TODO: provide more recent image

Description of the arm(7 DOF, max. 7kg payload, 16kg weight, very flexible,...

- **Schunk SDH gripper**

Description of the gripper(3-finger-gripper, different grasp types, as powerful as human hand, very sensitive)

- **Kinect camera**

Description of Kinect(RGB camera, Depth sensor, 3d data under any light conditions)

1.2 The Robot Operating System(ROS)

As the control of the robot components is based on ROS, a brief introduction shall be given here. As stated in Quigley et al. (2009), ROS is not an operating system in the classical sense. It can be seen as a communication layer, providing various mechanisms for inter process communication. A ROS system consists of a number of nodes. Each node is an independent computation unit and runs in it's own process, adding some clearly defined functionality to the overall system. For example one node can be responsible for planning, another one for perception or controlling the hardware. Nodes communicate with each other by passing messages, using the ROS communication infrastructure. Messages are strictly typed data structures that can be defined in a special message composition language. They can be composed of primitive types like Float, Integer or Strings and also of other message types. That makes it possible to define custom messages for each use case. Messages can be published to topics. A topic can be seen as some kind of address, consisting of a string. Topics can be organized in namespaces. If two instances provide the same interface, each one can be operated in it's own namespace. This is important, as for example the simulator should provide exactly the same interface as the real robot. Without namespaces it would not be possible to operate the simulator and the real robot in parallel. So Each node can publish and also subscribe to a number of topics. It is also possible

that more than one node publishes to the same topic. The organization of the nodes of a system can be visualized as a graph.

A node can also advertise a service. This is a special type of topic that allows a synchronized message exchange. In contrast to topics, a service with a given name can only be offered by one node. The service message is composed of a request and a response part. When a node sends a service request to another node it will block, until the advertising node has handled the request and delivers a response. The nodes that make up a ROS system can be located on different machines. One machine has to be the dedicated master that runs the roscore. Other machines can connect to the master via network. ROS also provides a centralized parameter server that can be used to store configuration data for the various nodes. A system usually consists of a large number of nodes that have to be configured and started. This can be done in launch files. Those are simple textfiles, holding startup information and configuration details for one or more nodes in an XML syntax. Using the roslaunch command, a set of nodes can be configured and launched at once. It is important to understand this terminology because especially the terms node, topic and message are heavily used throughout this thesis. A more detailed documentation can be found on the ROS website.

1.3 Project Targets

Both objectives

- **Simulation**

Realistic replication of the robot setup on a suitable simulation platform Generation of realistic sensor data Visualization of collisions Implementation of a ROS interface, corresponding to that one of the real robot

- **Motion Planning**

Configuration and integration of a motion planning framework Implementation of a benchmark pick and place task, executable on simulator and real robot Provide an easy to use interface to the planner Analyse the quality of the various planning algorithms

Chapter 2

Robot simulation

This chapter focuses on the simulation part of the thesis. The objective is the creation of a simulation model, particularly designed for the IIS lab robot setup. The model has to reflect the properties and behaviour of the contained robot components as good as possible. Certainly the simulated components have to provide the same control interface as their real counterparts, allowing to test and optimize control code on the simulator before utilizing it on the real robot. Preferably, the control code sees no difference about on which instance it is executed. The recommendations on such a solution can be summarized as follows:

- The simulator needs to be able to generate realistic sensor and feedback data that can be used by the control software. This includes forces and torques that are measured within force sensors, the current state of the various robot joints (position, velocity, effort), but also RGB and depth images, usually produced by Kinect cameras and vision sensors.
- The simulation solution has to provide exactly the same ROS control interface as the real robot. This interface essentially consists of a number of ROS topics, that can be used to send control commands to the various different robot components or to read actual joint states and sensor data.
- The utilized simulation platform has to provide a graphical user interface that allows to visualize the motions of the robot and its interaction with the environment. Possibly accidental collisions of robot parts have to be registered and should also be visualized.
- In order to be used by as many people as possible, it is very important that the solution is really easy to use and does not require a long lead time. Therefore it has to be put particular focus on usability.

The following sections explain in detail, how this goal was reached. At the beginning stands the process of finding a suitable simulation platform that meets the requirements and the considered criteria. After that, the chosen simulation platform V-Rep is introduced and an overview about how to design dynamic simulations is given, explaining some of the necessary terminology. Subsequent sections focus on the necessary steps to achieve the final solution, namely finding and modelling required robot components, assembling and configuring the final simulation scene and the implementation of the ROS control interface.

2.1 Choosing a suitable simulation platform

The tasks executed on the robot are in most cases variations of so called 'pick and place' tasks. An object gets picked up, lifted and placed somewhere else within the robot's workspace.

Therefore joint target positions are sent to the control interfaces of the various robot components and they execute the commanded motions if possible. The question, if the execution is possible at all and in that case in which velocity, is influenced by a number of dynamic parameters. The maximum effort of the motors in the joints is limited. If the force that acts upon a joint is higher than the maximum effort of the motor it will not be able to maintain its current position or to reach the desired target position. This can happen if the picked object is too heavy or if the robot collides with an immovable object in its environment. The forces that act upon each single joint are influenced by a number of parameters like the position within the kinematic chain of the robot, the summed own weight of the robot components and also the weight of a possibly additional payload.

The required solution should be able to provide a realistic simulation of those dynamic interactions. Therefore the utilized simulation platform has to take use of a powerful physics engine. A physics engine is a software component, that is capable of computing parameters of physical processes and the dynamic properties of the involved objects. Examples for such engines are the Open Dynamics Engine¹ (ODE) and Bullet physics². Some of the evaluated simulation platforms even provide a number of different physics engines to choose.

The candidates that have been taken into account were Gazebo³, V-Rep⁴, MORSE⁵ and Openrave⁶. After some investigation only two of them (Gazebo and V-Rep) had been evaluated in greater detail. Criteria for the selection had been:

- Which physics engine is used respectively is it possible to choose among various engines?
- Usability and stability
- Expandability
- Availability of required model components (arm model, gripper,...)
- Quality of the documentation
- Licence issues

Taking into account those criteria it went clear that V-Rep will be the simulation platform of choice. In some initial tests V-Rep seemed to be much more stable than Gazebo and the user interface is very intuitive. Another important point is that V-Rep ships with a fully functional model of the KUKA LWR4+ robot arm.

2.2 The Virtual Robot Experimentation Platform(V-Rep)

V-Rep is a powerful robot simulation platform, developed by Coppelia Robotics. The current version (V3.1.2) provides the ability to choose from three configurable physics engines (ODE, Bullet, Vortex – only trial version) for simulating dynamic processes. It also contains a very comfortable editor for modelling robot components and simulation scenes. In the *shape edit mode* it is possible to edit and simplify meshes. This is very important because for simulating dynamic processes only simple shapes with a low amount of vertices, edges and faces should be

¹<http://www.ode.org>

²<http://bulletphysics.org>

³<http://gazebosim.org/>

⁴<http://coppeliarobotics.com>

⁵<http://www.openrobots.org/wiki/morse/>

⁶<http://openrave.org>

used to reduce complexity. The contained model browser provides a rich set of different robot models, static objects and various sensors, ready to use. A powerful feature are V-Rep's so called *calculation modules*. They can be configured to provide additional calculation functionalities on groups of scene objects. The *collision detection module* is capable of detecting and visualizing all kinds of collisions within the simulation scene. The *inverse kinematics calculation module* allows to solve inverse kinematics problems for robot components. The behaviour of the simulator is highly customizable via a rich programming API for C++ as well as the scripting language LUA⁷. V-Rep is no open source software but it provides a free licence for educational units and can therefore be used for research purposes. A more detailed introduction to V-Rep can be found in Freese et al..

2.3 Dynamic simulations in V-REP

For a better understanding of the modelling process it is necessary to explain a few fundamental concepts about designing dynamic simulations in V-Rep. This section just covers those aspects that are important for the underlying project. A more detailed explanation can be found in the official V-Rep documentation⁸.

Each simulation scene in V-Rep is composed from a number of models that are arranged within the environment. A model consists of various scene object, combined in a tree like structure to mimic the kinematic chain of a robot component. Each model has a dedicated model base and constitutes a sub-tree of the scene hierarchy. The model base is the root element of the model tree. There are existing various types of scene objects within V-Rep, but only those, which are important for the implementation will be explained here.

- **Shape**

A shape is a 3 dimensional body. Shapes represent the visual parts as well as the dynamically enabled parts of the scene. It is necessary to distinguish between primitive shapes (Cylinder, Cuboid, Sphere, Plane and Disk) and complex shapes (triangle meshes). Primitive shapes are much easier to handle for the physics engine as there can happen a lot of optimization during dynamics calculations. Complex shapes usually look better and therefore they are used mainly as the visual part of the model but also by the collision detection module. Various shapes can be combined to groups and therefore treated as one single object. Shapes can be defined as *static* or *non-static* objects. The position of a static object is fixed relative to its parent node within the scene hierarchy and will not change during simulation. Non-static objects underlie gravity and will fall down if they are not constrained by a dynamically enabled joint or a force sensor connection. It is also necessary to distinguish between *respondable* and *non-respondable* shapes. Respondable shapes have a clearly defined mass and moment of inertia and therefore they create collision reactions when colliding with other respondable objects during simulation. Only respondable shapes are considered during dynamics calculation. Usually a model in V-Rep is composed of a visual part, consisting of complex shapes and a hidden part, consisting of groups of primitive shapes that are configured to be used for the dynamics calculations. This issue will be covered again when explaining the creation of the hand model. Each shape also has some additional flags, defining special attributes used by the *calculation modules*. The *collidable* attribute states that a shape has to be considered during collision

⁷<http://www.lua.org>

⁸<http://www.coppeliarobotics/helpFiles>

detection. The *renderable* flag marks a shape to be recognized by a *vision sensor*. There are more flags available but only those two were used within this project.

- **Joint**

A joint is a flexible connection between two rigid parts of a robot. It has to be distinguished between revolute or prismatic joints with one degree of freedom and spherical joints with three degrees of freedom. In the arm and hand model only revolute joints are used. Joints can be passive or actuated by a motor. The motor settings include maximum force or torque and velocity limits. If the control loop is enabled then a desired target position for the joint can be set. The controller will then try to reach this position, based on it's PID settings while respecting the motor limits. It would also be possible to program a custom control loop for each joint but for the current project this is not necessary. Joints can be operated in various different modes. A joint in *torque/force mode* is simulated, using the physics engine. This is the most realistic control mode. A joint in *inverse kinematics mode* is controlled by the inverse kinematics calculation module and if additionally the option *hybrid operation* is selected then the dynamic parameters of the joint are also taken into account. Operating a joint in *dependent mode* means that it's position depends on the position of another joint within the scene. How this dependency looks like can be configured by setting a *dependency equation*.

- **Vision sensor**

States a simulated image capturing device. A vision sensor can capture images of the simulation scene, depending on it's configuration. It can deliver RGB image sequences as well as depth images. Vision sensors are used in the Kinect camera model.

- **Force sensor**

A force sensor in V-Rep is a rigid connection between two dynamically simulated objects. The calculated forces and torques can be measured and visualized. It is also possible to define a maximum force the connection is able to bear. When this maximum value is exceeded, the connection will break.

- **Dummy**

Dummies are the simplest scene objects at all but they provide some important functionality, especially for the various calculation modules of V-Rep. They can be understood as the origin of a named reference frame with a configurable position and orientation within the simulation scene. Two dummies can be linked as *tip-target pairs* to be used by the IK calculation module. The importance becomes more clear when the construction of the simulation scene will be explained, particularly when configuring the inverse kinematics calculation module.

Groups of scene objects can be organized in *collections* and treated as one single entity. Collections play an important role in the collision detection module.

2.4 Designing the simulation scene

This section explains in detail the structure of the simulation scene and the contained model components. The setup contains three types of robot component - the Kuka LWR4+ robot arm, the Schunk SDH-2 gripper and the Kinect camera. For each one of them, a simulation model was required in order to be able to build up the scene. V-Rep ships with realistic and fully functional model for the Kuka arm and also for the Kinect camera. But as there is currently no

model for the Schunk gripper available, it had to be created from scratch. The necessary steps of the modelling process are explained in the next section.

2.4.1 Modelling the Schunk SDH-2 gripper

A model within a V-Rep simulation scene basically consists of three major parts. First there are the shapes that form the visual part of the model. Those shapes are triangle meshes for each single link of the robot component. Preferably they are not to complex, i.e. the amount of faces is not to high. The second part is formed by the joints that connect those shapes and allow to actuate the flexible parts of the model. The third part consists of the dynamically enabled parts of the model. These shapes form the body of the model, how it is seen by the physics engine. Those respondable parts are usually an approximation of the original meshes, composed from groups of primitive shapes. Those parts are very important as they make the model realistic and allow to interact with other respondable objects within the scene. Without them, the model would just move through other bodies as only respondable shapes are able to produce collision reactions. The steps, described within this section enclose the modelling of that three parts for the gripper model.

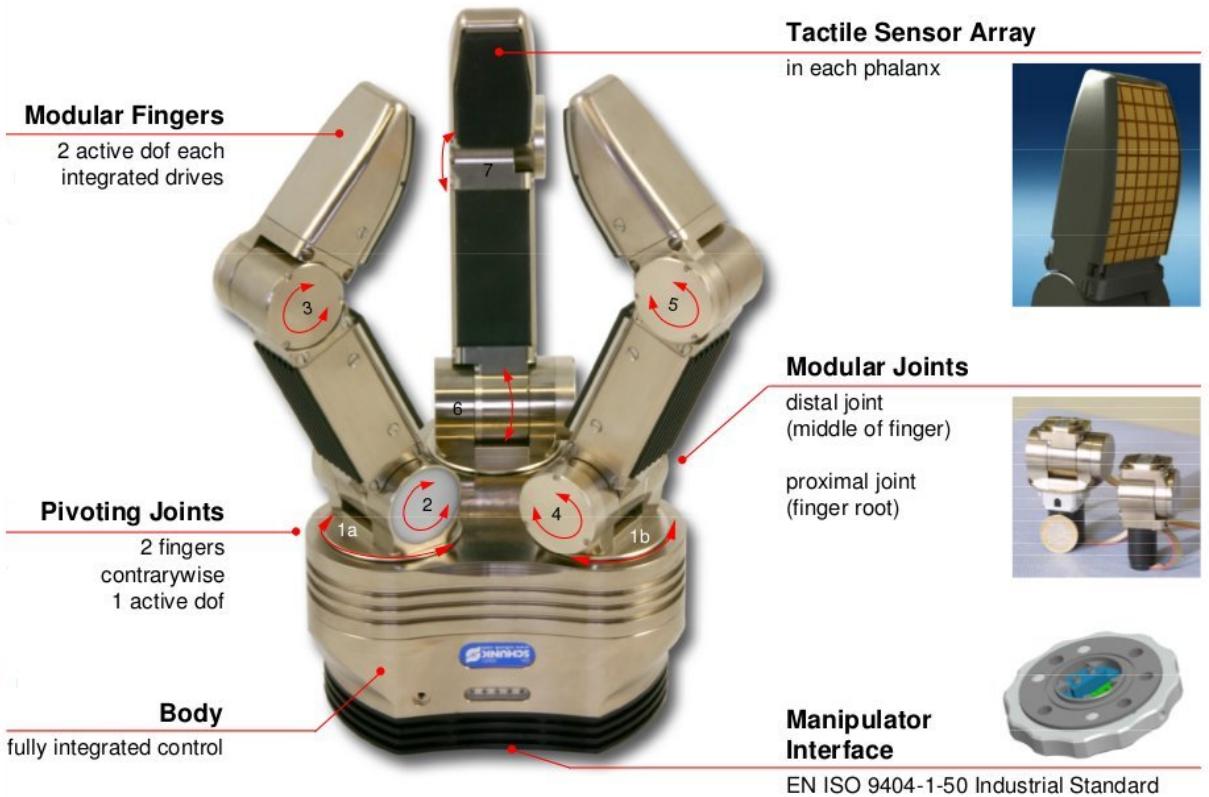


Figure 2.1: Schunk SDH-2 gripper

Figure 2.1 shows the Schunk SDH-2 hand. The gripper has 3 fingers, each one containing two modular joints. The joints located closer to the wrist are called the *proximal* finger joints whereas the joints, actuating the finger tips are called the *distal* finger joints. Two of the fingers can be rotated along their vertical axis but they are connected contrariwise. That means if one finger rotates to the left, the other one is rotated to the right for the same angle, actually adding

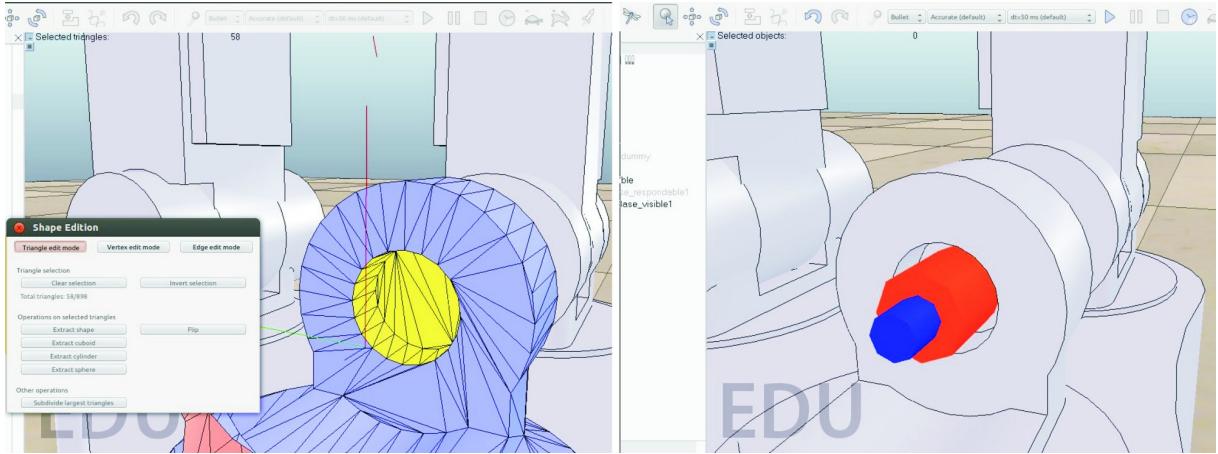


Figure 2.2: Placing a joint within the model

one additional degree of freedom. Those two joints are called the *pivoting* joints. The visual part of the hand model basically consists of 4 different shapes - the wrist, finger knuckles, finger links and finger tips. Suitable meshes were taken from the schunk_description⁹ ROS package and imported into the V-Rep robot editor. They have then been arranged according to the technical description. The next step was to insert and arrange the gripper joints on their appropriate locations.

Therefore it was important to determine the correct position and orientation for each single joint within the model to allow the correct movement of the fingers. This was achieved by using the *shape edit mode* and select the cylinder shaped area within the mesh, where the joint has to fit. From that selection a cylinder was extracted and the joint was then centred within this newly created cylinder. Those steps had to be repeated for all 8 joints. The placement process can be seen in Figure 2.2.

The left image shows the extraction on the target area. On the right image, the joint is already placed on its appropriate location.

After placing all the joints and links within the scene, the model tree was adjusted to form

⁹http://wiki.ros.org/schunk_description

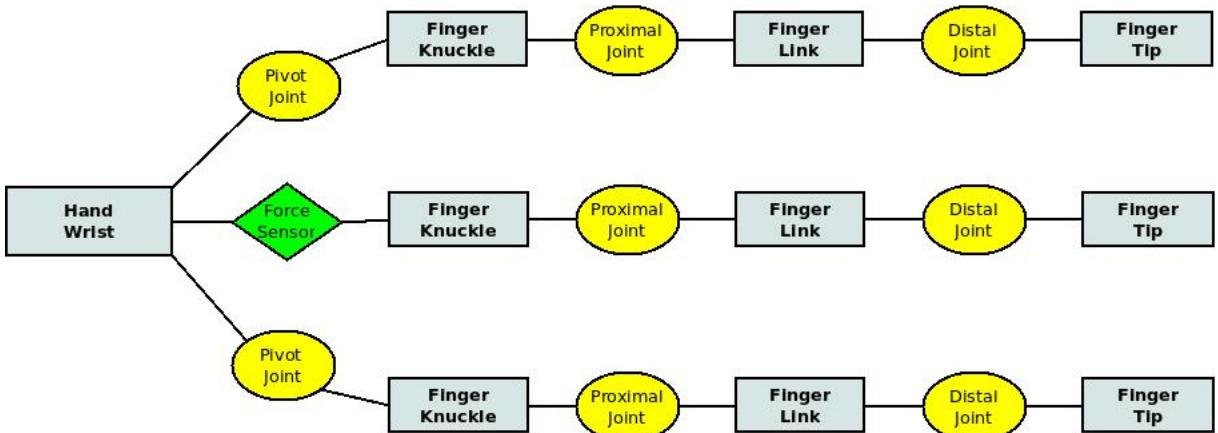


Figure 2.3: Kinematic chain of the Schunk gripper

the kinematic chain of the hand as can be seen in Figure 2.3. The dynamic parameters of the joints were set according to the technical description. Those parameters include the joint limits, maximum velocity and maximum effort. As the positions of the pivot joints are connected to each other, the configuration of the second finger's root joint looks slightly different. To achieve this mirroring behaviour the joint is operated in the *dependent mode*, which means it's position depends on the position of a connected joint and that dependency is expressed as *dependency equation*. The configured equation just copies the actual position but the joint is operated in opposite rotational direction.

The meshes only form the visual part of the model, but they are too complex to be used for dynamics calculations. So the shape of each link had to be approximated by groups of primitive shapes. This was achieved by executing the following steps for each single part of the model:

- Within shape edit mode locate parts of the mesh that could be approximated by a primitive shape (cuboid, cylinder), by selecting suitable groups of vertices
- Extract the primitive shape by using the corresponding editor functionality
- Repeat those steps until the most important parts of the link are approximated that way
- Group those primitive shapes to treat them as one single object
- Adjust the dynamic parameters (mass, material settings, inertial matrix)
- Adjust the local respondable mask
- Give the group the same name as the corresponding mesh, but with the *_res* suffix
- Remove the extracted shapes from the current visibility layer because they are just used for dynamics calculations

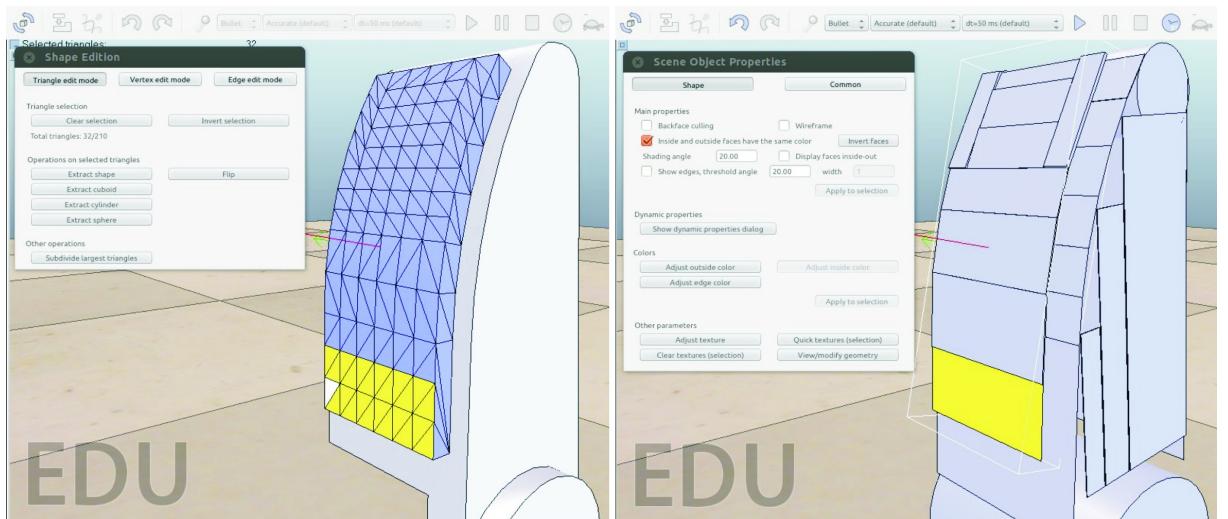


Figure 2.4: Process of approximating the original mesh with pure shapes

The extraction process is visualized in Figure 2.4. Dynamic parameters like mass and inertial matrix have been provided by Alex Rietzler. The predefined *highFrictionMaterial* setting was used for each single part of the finger because that showed better results when picking up objects

later on.

The last step of the modelling process was the adjustment of the model hierarchy. Root element of the hand model is the respondable part of the wrist which is also the dedicated model base. It is very important to follow the V-Rep guidelines for designing dynamic simulations because if the hierarchy is wrong, the model will simply fall apart when starting the simulation (detailed information can be found in the corresponding chapter¹⁰ of the V-Rep documentation). Each non-static and respondable shape has to be connected to its parent by a joint or a force sensor. The visual part of the link is always a child object of its corresponding respondable. That way, the kinematic chain of the gripper is formed.

2.4.2 Assembling the scene

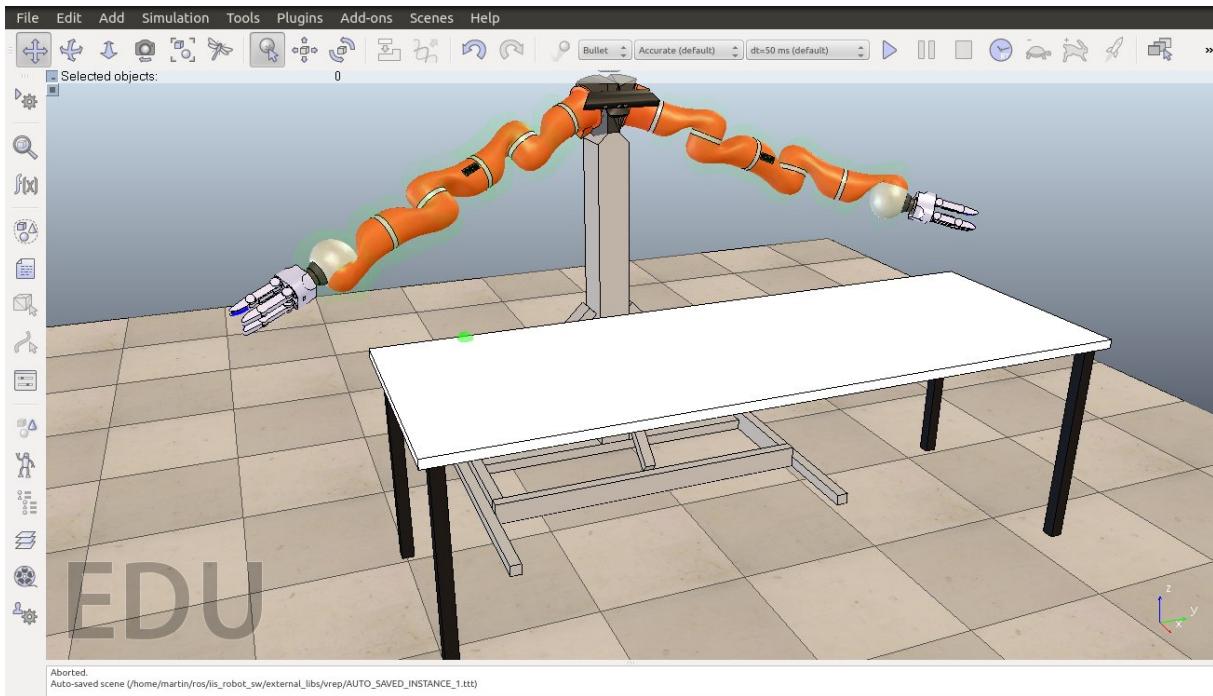


Figure 2.5: Structure of the V-Rep simulation scene

After finishing the gripper modelling process, each necessary component was available to build up the simulation scene as can be seen in Figure 2.5. The final scene consists of a model of the robot's torso, two KUKA LWR4+ arm models with attached grippers and a model of the table in front of the robot. The origin of the world reference frame is located on the upper left side of the table, indicated by a slightly green shimmering sphere. A dummy object called *ref_frame_origin* was placed at that location. Each position calculation later on will happen relative to that dummy element. If it is necessary to move the origin to another location within the workspace, this can simply be achieved by just moving that dummy to the required location. The position and orientation of the torso, the table and the two arms are set relative to the world reference frame. (TODO: transformation was provided - how was it achieved?). The grippers were placed on the tip of each arm. Within the scene hierarchy they are child elements of the last node in the corresponding arm tree. The correct rotation and offset was measured on the

¹⁰<http://www.coppeliarobotics.com/helpFiles/en/designingDynamicSimulations.htm>

real counterpart and then adjusted accordingly.

The plate and the legs of the table were modelled as group of primitive cuboids. The table is defined as respondable to ensure that it will produce a collision reaction if a robot component collides with it. But as it is a static object it's position will not be influenced by such a collision because it is fixed within the scene. The material setting is set to *highFrictionMaterial*.

The Kinect camera model was also taken from the model browser. As it's position and orientation in the real world is not fixed and might change from time to time, it's position within the simulation scene is just an approximation to reflect the real world setting as good as possible.

2.4.3 Configuring the collision detection module

One of the requirements to the final solution is the ability to detect and visualize possible accidental collisions of the simulated robot with itself or it's environment. Moreover it would be a convenient feature to have some kind of warning if some of the robot's parts come dangerously close to an obstacle during movement. This could be achieved by creating a *collision shield*, which means an enlarged version of the robot and do additional collision checking. These considerations lead to two different types of possible collisions. *Soft collisions* are collisions, detected on the collision shield of the model. They just indicate a warning that the robot comes very close to an object it is not allowed to touch. *Hard collisions* mean that a robot component directly hits another collidable object. This would be also a collision in the real world. The solution should be able to distinguish cleanly between those two types.

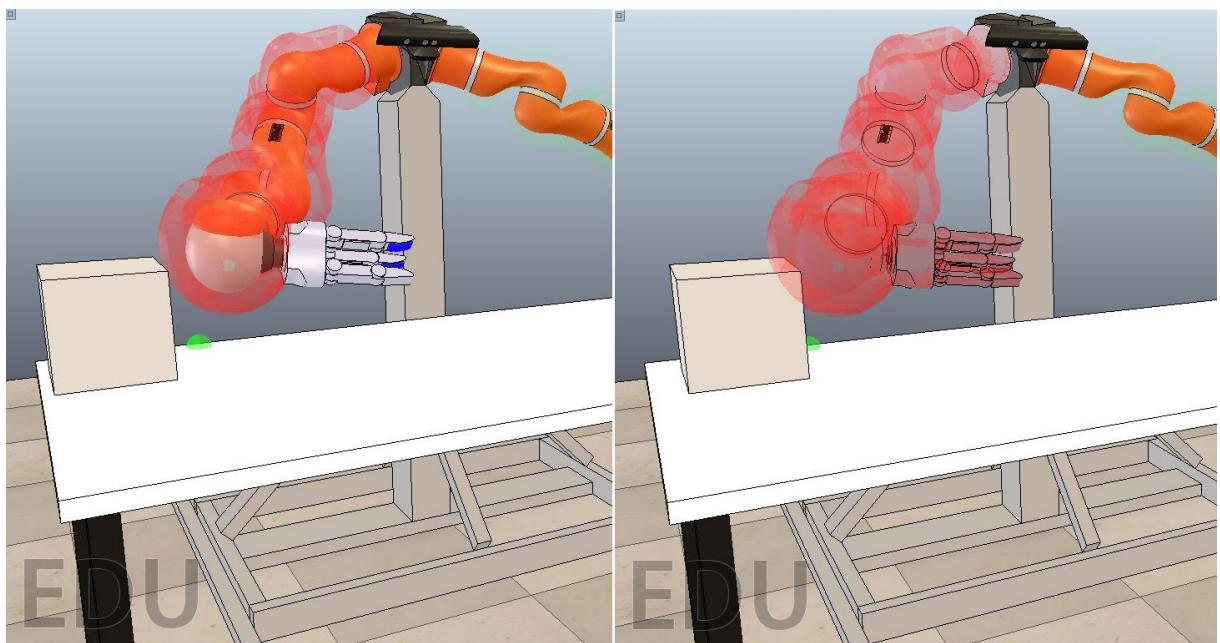


Figure 2.6: Collision detection and visualizing. The left image shows a hit on the collision shield, the right image indicates a direct hit.

That goal was achieved by using V-Rep's *collision detection module*¹¹. This calculation

¹¹<http://www.coppeliarobotics.com/helpFiles/en/collisionDetection.htm>

module is capable of detecting and visualizing collisions within the simulation scene by checking for interferences between *collidable* shapes. It is important to understand that the collision detection module only *detects* collisions. Producing *collision reactions* is the responsibility of the *dynamics module* and the chosen physics engine. Usually the shapes that form the visual part of the model are used for collision checking. The configuration is done by registering one or more *collision objects*. Each collision object consists of a *collider* and a *collidee*. Both of them can be single shapes or collections of shapes. The collidee settings also offer the option *all other collidable objects in the scene*. In that case, the collider is checked against all elements in $S = \{ s \mid s \in \text{scene} \text{ and } s \notin \text{collider} \}$. The big advantage in using collections is that they allow to exactly describe which shapes should be checked against which other ones. Detected collisions are visualized by applying different colouring either to the collider or to the collidee as can be seen in Figure2.6.

The first step during realization was to model the collision shield. Therefore it was necessary to create an additional shape for each link that is slightly larger than the original one. This modelling process started at the second link of each robot arm and for all subsequent links the following steps were performed:

- Create a copy of the shape that forms the visible part of the robot link
- Morph the copied object into a group of convex shapes to reduce complexity. This can be done by using the corresponding shape editor functionality.
- Ungroup the resulting group of shapes and merge them into one single shape
- Grow the resulting shape, but only in x and y direction of its own reference frame. The resulting mesh should be approximately 10cm larger but keep the same height.
- Adjust the outside color to make it green and nearly transparent. The collision shield should be visible but not occlude the original model.
- Apply a meaningful name to the newly created shape to be able to easily identify it within the model hierarchy. Here the name of the original shape with the '`_col`' suffix was used.
- Make the new shape a sibling of the original one within the model hierarchy.
- Adjust the shape object properties. Define the new shape to be *static* and *non-respondable*.
- Disable the *collidable* flag on the shape. This behaviour will be overridden in the collection settings later on when configuring the collision detection module.

This modelling process is visualized in Fig???.

The next step was to adjust the configuration of the *collision detection module*. Each arm requires two *collision objects*, defined as stated in Figure2.1. The first two collision objects are designed to detect direct hits on the corresponding arm. Therefore the colliders (collections *leftArm* and *rightArm*) are checked for collisions against *all other collidable objects in the scene*. This setting is only possible because the *collidable* flag is disabled within the scene object settings of the collision shield elements, which means that they are excluded from collision checking by default. The collision objects, named with the *Shield* suffix are responsible to check for hits solely on the collision shield elements. The colliders (collections *leftArmShield* and *rightArmShield*)

Collision object	Collider	Collidee
left_arm	leftArm	all other entities
right_arm	rightArm	all other entities
left_armShield	leftArmShield	exLeftArmShield
right_armShield	rightArmShield	exRightArmShield

Table 2.1: Configured collision objects

Collection	Definition
leftArm	$\{ s \mid s \in \text{subtree of left arm} \}$
leftArmShield	$\{ t \mid t \in \text{element of left collision shield} \}$
exLeftArmShield	$\{ u \mid u \in \text{scene and } u \notin \text{subtree of left arm} \}$
rightArm	$\{ v \mid v \in \text{subtree of right arm} \}$
rightArmShield	$\{ w \mid w \in \text{element of right collision shield} \}$
exRightArmShield	$\{ x \mid x \in \text{scene and } x \notin \text{subtree of right arm} \}$

Table 2.2: Collection definitions

consist only of the collision shield elements. As those elements were defined without the *collidable* flag, the option *Collection overrides collidable properties* is selected in the corresponding settings to explicitly enforce collision checking when using those collections. The collections, defining the collidees (*exLeftArmShield* and *exRightArmShield*) include all other objects except those, contained in the left/right arm's subtree. This exclusion is necessary because otherwise those collision objects would detect collisions between the shield elements and the other arm links. The collection definitions can be seen in Figure 2.2. All collision objects are defined not to be handled explicitly. This means that V-Rep does not check them automatically on each simulation pass. It has to be done manually and will be explained later on in the section about control interface implementation.

2.4.4 Configuring the IK calculation module

The ROS control interface needs the ability to set arm target positions in *joint space* or in *Cartesian space*, depending on the selected control mode. Joint space targets are relatively easy to handle as that only means to set the target position of each single joint. Setting targets in Cartesian space requires to solve the inverse kinematics problem for the corresponding robot component. Therefore V-Rep offers the *inverse kinematics calculation module*¹². This calculation module allows to define and register various *IK groups*. Each IK group has to contain at least one *IK element*, defining the kinematic chain, constraints and desired precision settings (linear and angular). IK elements can be configured to enforce position constraints and/or orientation constraints for each single axis. The kinematic chain is specified by selecting the dedicated base link and the tip. The tip is a dummy object, indicating the end effector reference frame. The IK target is defined by another dummy object. Tip and target have to be linked, forming a *IK, tip-target* connection by selecting the appropriate link type within the dummy object settings. Figure 2.7 shows a schematic description of that concept. The target pose is set by placing the target dummy at the desired location. The IK calculation model will then adjust the joint positions until the tip pose matches the target pose, respecting joint limits and configured constraints and tolerance values. The joints within the specified kinematic chain need to be operated in *inverse kinematics mode*, otherwise the module is not able to control them.

¹²<http://www.coppeliarobotics.com/helpFiles/en/inverseKinematicsModule.htm>

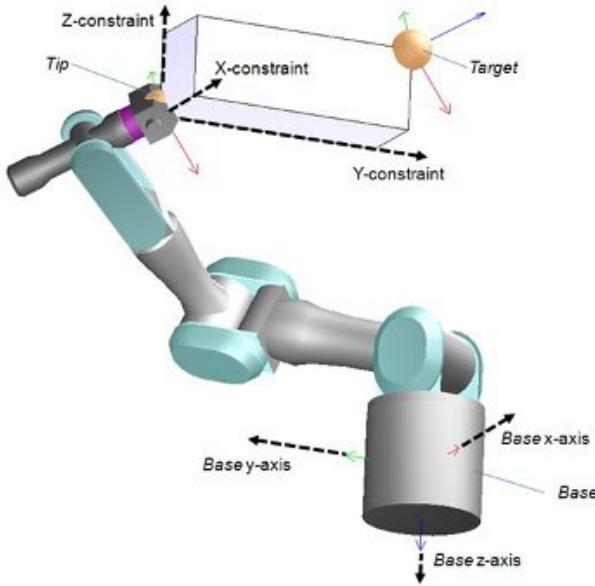


Figure 2.7: IK calculation module concept

The IK calculation module allows to define various IK groups for each robot component with differing configurations. Along the collection of IK elements, the IK group settings include the desired calculation method and the maximum amount of calculation iterations to use. Available IK calculation methods are *pseudo inverse* (PI) and *damped least squares* (DLS). As stated by Buss (2004), the PI method is usually faster than DLS. The tradeoff is that PI tends to be unstable in configurations where the target position is unreachable. That fact leads to a jittery behaviour of the manipulator. The DLS method provides higher stability in such situations but requires more calculation time.

IK group	Method	Iterations	Prec. lin/ang
left_arm	PI	9	0.001 / 0.1
left_arm1	PI	3	0.002 / 0.2
left_arm2	DLS	3	0.002 / 0.1
right_arm	PI	9	0.001 / 0.1
right_arm1	PI	3	0.002 / 0.2
right_arm2	DLS	3	0.002 / 0.1

Table 2.3: IK group definitions

Three IK groups have been created for each arm. The configuration settings are listed in Figure 2.3. They were chosen, following the guidelines from the V-Rep documentation. The first two groups use the faster PI calculation method. The first one allows a higher amount of maximum iterations while demanding stricter precision settings than the second one. The third one is designed to increase stability especially for positions close to singularities. Therefore the DLS method was chosen with an increased position tolerance value. That configuration is less performant because of the DLS calculation method and therefore it is only used if the other groups failed to find a solution. The IK groups are called sequentially until one of them is able to solve the problem. This process is explained in the ROS control interface section later on.

2.5 Implementing the ROS control interface

In the real world, each type of robot component has its own, clearly defined ROS control interface. Those interfaces are composed from sets of inbound and outbound ROS topics that allow sending commands and to retrieve state data. The simulated components have to provide exactly the same ROS interface as their real counterparts, using similar topic names and message types. The structure of this control flow can be seen in Figure 2.8.

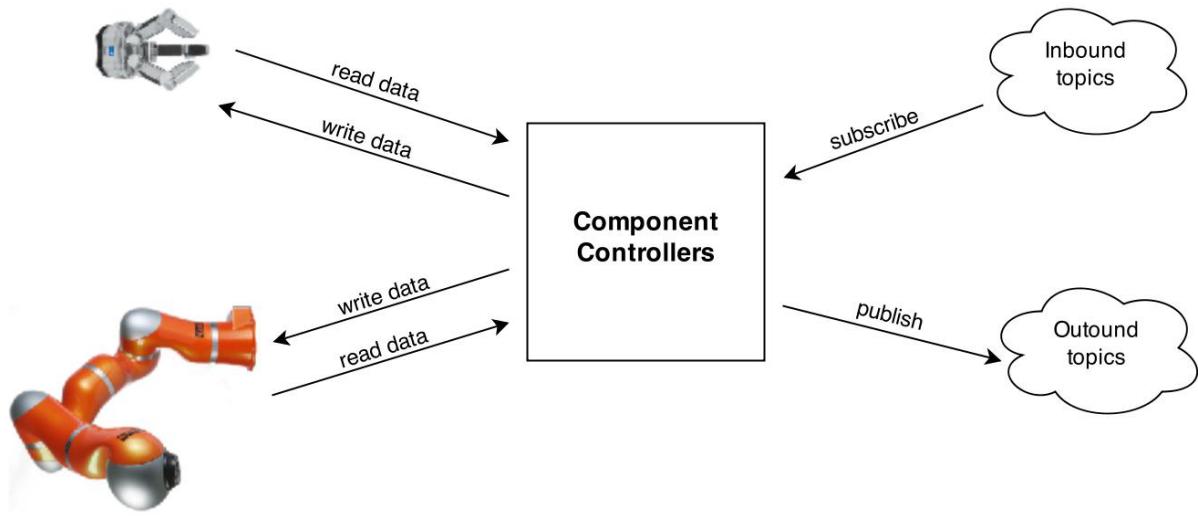


Figure 2.8: Control flow structure

The existing ROS interface that is part of the V-Rep distribution is not suitable as it only provides a very general approach for controlling joint values and reading state data. Therefore V-Rep provides various extension points, allowing to add custom functionality. The final solution was implemented as a *simulator plugin*, written in C++ and using V-Rep's *regular API*¹³. This approach states the most flexible solution as this API provides more than 400 functions that can be used to extend the simulator functionality. A plugin is a compiled library file, written in C++ that has to follow some V-Rep specific naming conventions and must reside in the V-Rep working directory. The library file gets automatically loaded on V-Rep startup and runs in the main simulation thread. The source code is located in the *iis_simulation* package that is part of the *iis_robot_sw* repository. The following section describes the design of the plugin architecture and the most important components within the package.

2.5.1 Plugin architecture

A plugin is a compiled library file, written in C++. This library needs to be placed in the V-Rep working directory and follow the V-Rep specific naming conventions. On startup, V-Rep looks for library files, prefixed with 'libv_repExt'. Matching files are automatically loaded. A plugin runs in the main simulation thread - that means it has to be programmed really carefully to avoid performance leaks during simulation. The plugin has to provide a clearly defined interface, consisting of 3 function definitions:

- `unsigned char v_repStart(void* reserved, int reservedInt)`

This function is called on V-Rep startup and is used to perform necessary initialization

¹³<http://www.coppeliarobotics.com/helpFiles/en/apiOverview.htm>

steps. A return value of zero indicates that the initialization process failed and the plugin gets unloaded immediately. The current solution depends on a running roscore during startup. If that is not the case it is not able to work.

- **void v_repEnd()**
Called before shutdown and is used to do some general cleanup and free allocated memory.
- **void* v_repMessage(int msg, int* auxData, void* custData, int* resData)**
This function is called very often during the whole V-Rep lifecycle and is therefore a very performance critical method. Via this function V-Rep notifies plugins about events like start/end of simulation, simulation step, scene content change, scene switch and more. The plugin code can react to those events accordingly. In the current implementation, those messages are just passed to the software components that are responsible to handle the specific action.

The plugin code is organized as can be seen in the UML diagram in Figure2.9. The major parts of the system are described in the subsequent paragraphs.

SimulationComponent A simulation component is a single, reusable model of a specific robot component that can be utilized in different environments. Each component provides its own clearly defined control interface. A simulation scene can contain multiple components from various types. The *SimulationComponent* class is the abstract base class for all simulation components. Currently there are existing two concrete implementations – the *LWRArmComponent* and the *SchunkHandComponent*. If the scenario should be extended and new components have to be introduced, it is necessary to create a new subclass of *SimulationComponent* and provide implementations for the abstract methods.

ComponentContainer This class represents the set of all identified simulation components within the current scene. On V-Rep startup an instance of *ComponentContainer* is created. Each time, the content of the current simulation scene changes, the method *actualizeForSceneContent* is triggered. This method then performs the following steps:

- It validates all currently registered *SimulationComponent* instances if they are still valid and present in the scene.
- It traverses the whole scene hierarchy to identify newly created components
- If a new component is identified, a corresponding concrete instance of *SimulationComponent* is created and added to the container.

The process of traversing the scene hierarchy and identifying components is explained in section2.5.2. During a running simulation, the *ComponentContainer* gets notified about each single simulation step. It simply forwards that message to all registered components. Those can then perform all necessary steps like triggering collision checking or handling IK groups.

ROSServer The *ROSServer* is a static class that encapsulates all ROS related functionality. It tries to initialize ROS on plugin startup, forcing a shutdown, if the connection to the master cannot be established. Otherwise it creates and maintains a ROS *NodeHandle* for the 'simulation' namespace. Each *SimulationComponent* can register *ComponentController* instances at the *ROSServer*. On simulation start it initializes all registered controllers with the maintained *NodeHandle*. The *ROSServer* gets also notified about each simulation step and forces the controllers to handle the received commands and publish all the necessary data. On simulation end it triggers the shutdown of all registered controllers.

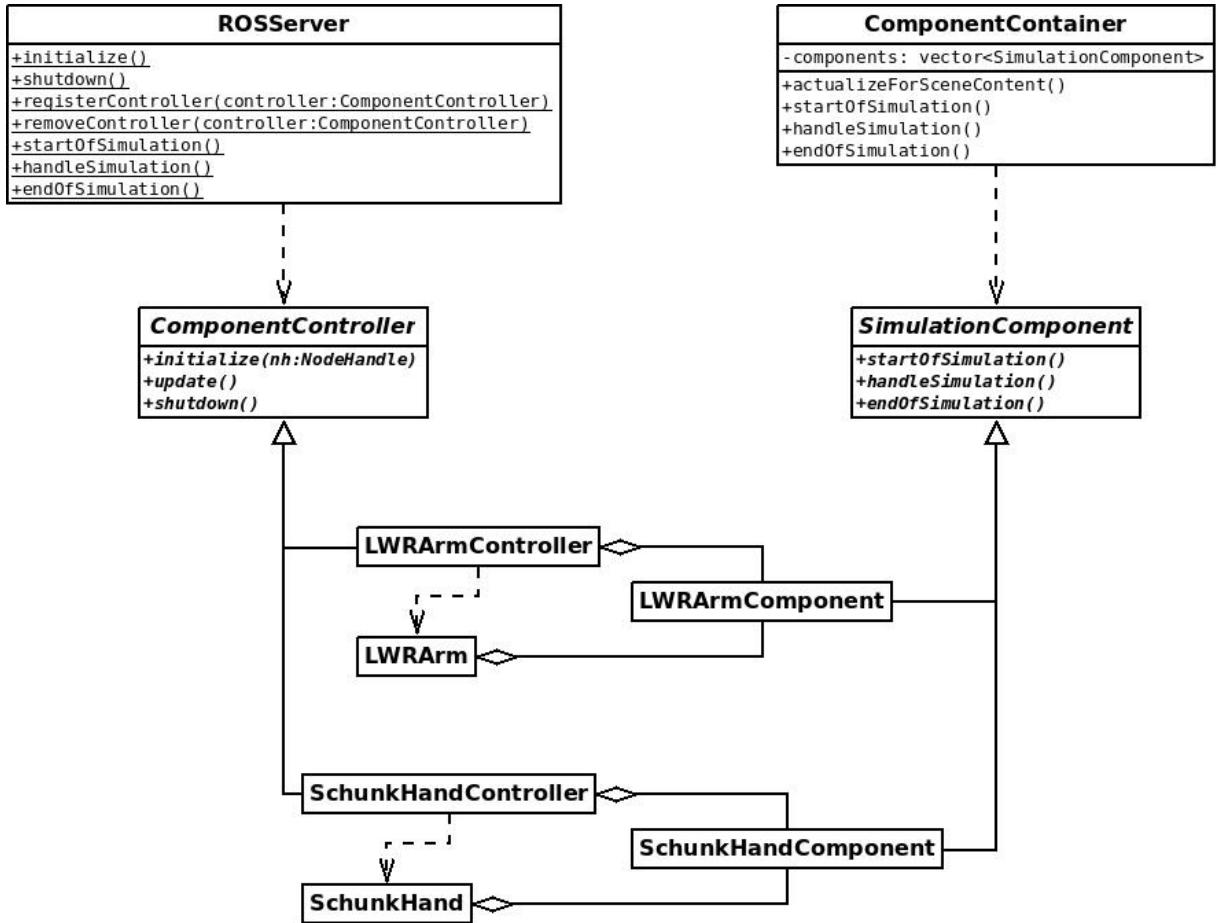


Figure 2.9: Simulator plugin architecture

ComponentController This is the abstract base class for all controllers. A controller actually represents the ROS interface of a specific simulation component, maintaining all the inbound and outbound topics used to control the simulated hardware. It is responsible for delegating commanded values to the underlying component as well as reading and publishing state data. Concrete implementations are the *LWRArmController* and the *SchunkHandController*. A *ComponentController* needs to be registered at the *ROSServer* and gets initialized on simulation start. Concrete implementations can use the provided *NodeHandle* to create all the necessary publishers and subscribers. The *update* method is called by the *ROSServer* on each simulation step and forces the controller to publish all the required data. The *shutdown* method is called by the *ROSServer* on simulation end, forcing the controller to shutdown all publishers and subscribers.

Explain naming strategy, how topic names are structured...

2.5.2 Identifying simulation components

The plugin functionality should not be tied to a specific simulation scene but to specific models of robot components. Each time a known component is added to the scene it should be recognized by the plugin and the corresponding instance of *SimulationComponent* has to be instantiated and added to the *ComponentContainer*. As visualized in Figure 2.10, each simulation scene is a tree structure, consisting of various different types of scene objects. It is necessary to identify

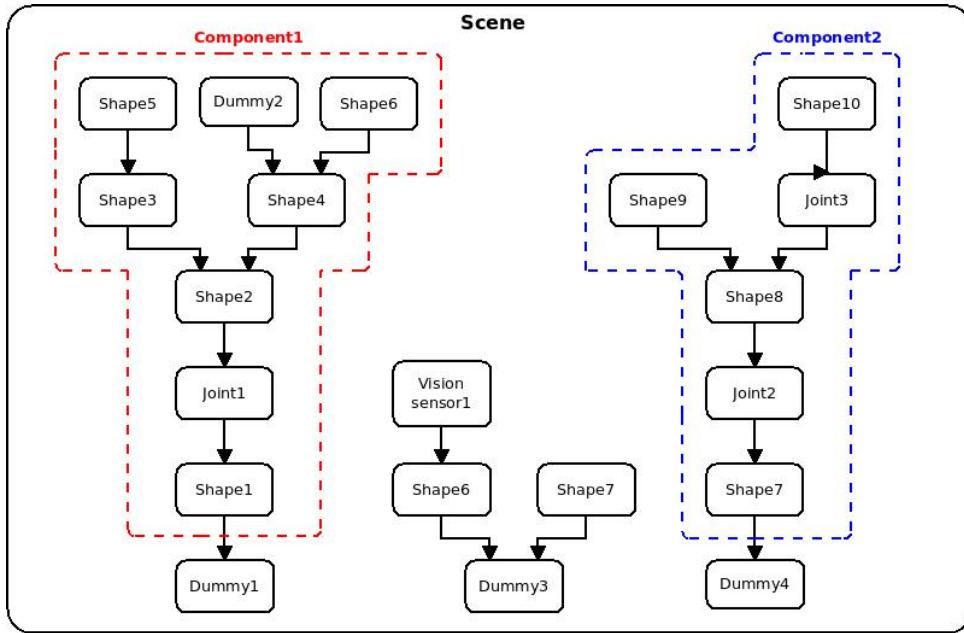


Figure 2.10: Sample scene hierarchy

subtrees within this hierarchy that belong to known simulation components and should therefore be handled by the plugin. If a component is identified, the plugin has to discover each single part of the model. Depending on the model this can be joints, force sensors, reference frame dummies, IK groups or collision objects.

One possible way would be to give each part a clearly defined, unique name and then search for those names within the scene. But this approach would require to hardcode each single joint name and this is not a preferable solution for this problem. If a user accidentally changes a name inside the model tree then the solution is broken because the plugin loses connection to the underlying object and cannot control it any more. Here V-Rep's custom developer data functionality comes into play. It is possible to put auxiliary data segments to each single object in the scene. Those data segments are serialized together with the object and can be read programmatically. Each data segment starts with a header number which is used to uniquely identify the data from a specific developer. A visualization of this concept can be seen in Figure 2.11.

As the format of the data can freely be chosen, it was decided to use string representations of key/value pairs, separated by a colon (:). The key is an integer number, used to determine the type of the tagged object. The value segment can be used to provide additional information, e.g. the name of a joint. The left arm's model base for example is tagged with the data segment 2497,1:left_arm. The number 2497 is the header that identifies the data segment to belong to this plugin. The data segment identifies that element as the model base of a *LWRArmComponent* (Key=1) with the name 'left_arm'. A complete list of all currently available keys can be found in the documentation, located in the appendix.

When actualizing for scene content change, the *ComponentContainer* traverses the scene hierarchy and looks for objects, that are tagged as known components. On success, it creates the specific instance providing the object ID of the underlying scene object. During initialization, the concrete *SimulationComponent* instance traverses the rest of the model subtree to extract all the remaining parts that belong to that specific model (joints, dummies, force sensors...), using the same mechanism. The implementations for arm and hand model provide feedback output

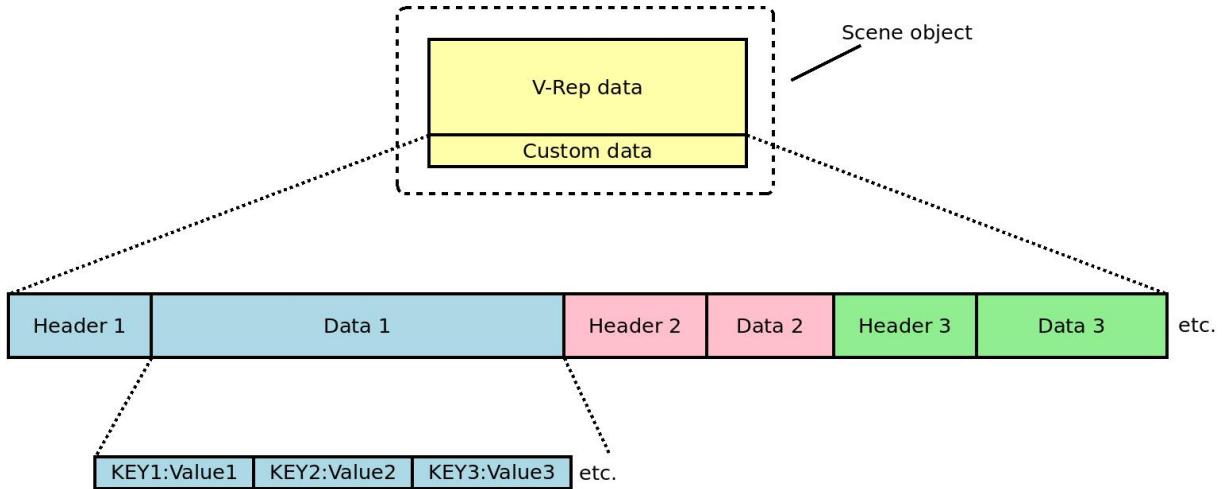


Figure 2.11: Custom developer data segments on scene object

on the console window about the success of this initialization process and provide meaningful error messages in case that not all necessary parts of a model could be successfully located.

2.5.3 The LWRArmComponent

Each SimulationComponent consists of two parts. The first one is a class that provides access to a concrete simulation component instance. The LWRArm class for example stands for a KUKA LWR4+ arm model in the scene. This class provides full access to the functionality of the underlying arm model.

The second part is a controller class for the component instance. This controller encapsulates the whole ROS interface to the simulation component and has to be a subclass of the abstract ComponentController class. On each simulation pass the controller publishes all the necessary state data to its various topics and sends incoming commands to the simulation component. The names of the various provided topics are composed from the overall namespace, the defined unique name of the component and the actual topic name. For example the joint control topic of the right robot arm evaluates to '/simulation/right_arm/joint_control/move'. Each SimulationComponent registers its ComponentController at the ROSServer and unregisters it when it is destroyed.

Description of the LWRArmComponent goes here...

- LWRArm This class provides access to a correctly configured LWR arm model within the simulation scene. To fulfill the requirements for the control interface, the arm has to be able to operate in joint control mode and in inverse kinematics mode. Initially the arm starts in joint control mode. All the joints are switched to torque/force mode and accept target positions to be set. The simulated PID controllers will try to move the joints to their designated target positions.

Switching to IK mode means to operate all the joints in IK mode and use the previously configured IK calculation module. Setting a target pose in Cartesian space means to bring the IK target dummy into the required pose. The IK calculation module tries then to bring the linked IK tip dummy into the same pose by commanding the robot arm's joints accordingly and satisfying the configured constraints and precision settings. At the moment, three IK groups are configured for each arm with different settings to achieve performant and stable solutions. Those groups are sequentially called until one of them is successful. The configuration of the first group focuses on performance but provides less stability. The last group uses a configuration

that is slower but provides more stability in positions closed to singularities. If none of the groups was successful it will result in an error message on the console, otherwise the arm will start or continue to move towards its target pose. When initializing the LWRArmComponent, it will search for IK groups that are named the same as the arm and with consecutive numbering (left_arm, left_arm1, left_arm2,...). That allows to reconfigure the IK calculation module and introduce additional IK groups without touching the plugin code. It is expected that at least one IK group is configured, otherwise an error message is written to the console.

The collision status of the arm is determined by using the configured collision detection module. On each simulation step the collision group that is responsible for detecting direct collisions is handled first. If that one detects a collision, a direct hit is reported and it is not necessary to handle the second group at all, because a direct hit always implies a hit with the shield as well. Only if no direct hit was detected, the second group is handled. The outcome can be queried as the current collision state of the arm. During initialization it is searched for a collision group that has the same name as the arm, responsible for direct hit detection and a group that is named with the naming pattern [arm_nameShield], responsible for shield hit detection. If one or both of the required groups cannot be detected, an error message on the console will be stated and the collision detection functionality will not work as expected. Collision state is evaluated on each simulation time step.

Additional items that have to be identified within the model tree are the 7 joints, the end effector tip dummy, the IK target dummy and the force sensor on the last link of the arm. The origin of the reference frame can be defined by creating a dummy object within the scene with the special name 'ref_frame_origin'. If such a scene object is found, all Cartesian poses are taken with respect to the reference frame of that object, otherwise the poses are interpreted absolute within the world reference frame. All the necessary data that is published by the controller can be accessed via this class.

- LWRArmController The LWRArmController provides the implementation of the Kukie interface. This interface is created by Simon Hangl especially for the KUKA arms in the IIS Lab.

2.5.4 The SchunkHandComponent

Description of the SchunkHandComponent goes here...

2.5.5 Publishing Kinect camera data

How is the integrated vision sensor configured? How are the RGB and depth images published? Explain usage of default V-Rep ROS functionality and how to enable publishers in LUA script.

2.6 Simulator startup script

Describe startup script, environmental variable (VREP_PACKAGE_PATH), launch file, how to use different simulation scenes.

Chapter 3

Motion planning

Chapter overview

3.1 Introduction

What means motion planning? What are the requirements?

3.2 The MoveIt! motion planning framework

MoveIt is an open source framework for motion planning. It is the successor of the previous arm navigation stack and is therefore fully integrated into ROS. MoveIt! was originally developed by Willowgarage(www.willowgarage.com) but since April 2012 it is maintained by the Open Source Robotics Foundation (OSRF). Figure blabla gives an overview about the system architecture of MoveIt!. The most important node is the move_group node. Configuration of that node happens via the parameter server. It requires a complete kinematic and semantic description of the robot setup in the urdf and srdf format and a lot of other configuration parameters which will be described later on. The move_group node provides a rich set of ROS actions and services which can be used to solve planning problems and execute the calculated motion plans on the connected hardware.

The most important parts of MoveIt are implemented as plugins which means that it is highly customizable. By default it uses KDL as IK solver and the Open Motion Planning Library (OMPL) as planning plugin but it is possible to replace them with custom solutions if necessary.

MoveIt! maintains a planning scene which is an internal representation of the world, including the robot and its environment. The base is a description of the robot and its various planning groups. To keep track of the current state of the robot MoveIt! needs to be informed continuously about the actual joint states. This is done via publishing the joint states to a specific topic. If there are additional objects within the robot's workspace they also have to be added to the planning scene. This can be done either by explicitly adding them via the corresponding topic or by integrating sensor information like Kinect camera data. MoveIt! can then take those objects into account during motion planning and avoid collisions. But some collisions are intended. For example if an object has to be picked up, the gripper has to get in contact to this object. Therefore collision checking for specific objects can be (temporary) disabled to allow those controlled collisions. Therefore MoveIt! maintains an 'AllowedCollisionMatrix' to which objects can be added or removed. The connection to the hardware happens via the FollowJointTrajectoryAction interface. Each robot component has to provide this interface if it

is intended to be control via MoveIt!. This interface consists of a set of ROS topics that provide trajectory execution functionality and also allow monitoring of the current execution status. The major contribution within this chapter to the whole project was to provide an implementation of this interface and connect it to the one that is currently available. (TODO: leave some words about OMPL!!!)

3.3 Creating the URDF model of the robot setup

The Unified Robot Description Format (URDF) is a markup language, designed to exactly describe robots. The description has to be done in XML formated text files. The exact specification can be found under (<http://wiki.ros.org/urdf/XML>). The most important elements in the XML specification are:

- **<link>**

Describes the all necessary properties of a specific robot link. Each link must have a unique name. The visual, inertial and collision details are configured in the corresponding subtags of the link element. The visual part as well as the collision model can either be composed from primitive shapes or from mesh files. If mesh files are used it is important that they are not to complex. Especially for the collision model it is recommended to use a simplified model to avoid a performance loss.

- **<joint>**

Describes the properties of a joint. A joint is a connection between two links, having exactly one parent and one child link. Each joint states a new reference frame for it's child link and it is positioned relative to it's parent frame. A fixed joint is a rigid connection between parent and child link. There are different types of joints available but for the current project only revolute joints are of interest. Details like limits, axis orientation and dynamic properties can be configured in the corresponding subtags of the joint element.

Those elements are used to exactly describe the kinematic chain of the robot components and their placement relative to each other. This description can get very large as a lot of different components are involved. So it is possible to organize it into a set of text files, each one describing one part of the whole. The 'xacro' ROS package provides the necessary functionality to combine all those text files into one XML string. XACRO stands for XML Macro and is designed to parse xacro files into one single XML document.

The URDF description of the IIS robot setup is located in the iis.hardware stack. The arm and gripper descriptions are located in seperate packages within this stack. The iis.robot package brings all the components together.

The modelling process started with the search for pre-existing URDF descriptions of the required robot components. A description of the Schunk SDH gripper was found in the schunk_description ROS package. A suitable description of the KUKA LWR arm was found in the git repository of the Robot Control and Pattern Recognition Group (RCPRG - University of Warsaw). The other parts of the model, namely the robot torso and the table had to be created. Each one is located in a seperate file within the uibk_robot package (torso.xacro and table.xacro). The mesh files, used in the description of the robot torso have been exported from the V-Rep simulation scene. For the visual part, the mesh was taken as it is. For the collision model, the width of the original mesh was increased to provide some safety padding. Moreover a cylinder with a diameter of 40cm was added in the head area to ensure that the planner avoids accidental hits in this sensitive region. The table was modelled from primitive shapes. It was taken care that the size of the table can easily be adjusted if it becomes necessary. The collision model of

the table is also slightly larger than the visual part to provide some safety margins. The offset between the gripper and the last arm link was not correct, because in the existing description the connector ring was missing. To correct that issue the file 'sdh_with_connector.xacro' was created.

The file 'iis_robot_table.xacro' draws all the pieces together. It describes the whole setup, consisting of the torso, two arms, two grippers and the table. The root element of the model hierarchy is a link called 'world_link'. Torso, table and both arms are positioned relative to that root link. Changing the world reference frame could easily be achieved by shifting the root link to a new position.

The robot model described within those files can be visualized using RViz. Therefore the launch file 'display.launch' was created within the 'iis_robot' package. When launching this file, the URDF description is uploaded to the parameter server and RViz starts, displaying the model. The collision model can be visualized by checking the 'Collision Enabled' checkbox in the 'RobotState' plugin settings. (TODO: show image, displaying visual and collision model) - additional setups available - can be visualized using launch file and 'file_name' parameter

3.4 Configuring the planning tools

The MoveIt configuration package was created, using the MoveIt Setup Assistant. Precondition for doing that is an existing URDF description of the robot setup which was created in the previous step. The setup process comprised of the following steps:

- **Computation of the self collision matrix**

The self collision matrix consists of pairs of robot links that can safely be excluded from collision checking. Neighbouring links for example are in permanent collision. Collisions between other links can never happen because they are simply too far apart. The Setup Assistant calculates a large number of different robot configurations and tracks for link pairs that are mostly always in collision and pairs that are never in collision. The self collision matrix can be adjusted manually if necessary. Excluding a large number of link pairs raises performance during motion planning because collision checking is an expensive process.

- **Defining the planning groups**

Each planning request in MoveIt is done against one of the defined planning groups. A planning group is a group of links and joints within the model that comprises a single robot component. Planning groups are defined for each arm and gripper. There is also defined a planning group called 'both_arms'. That group can be used later on if a planning request should be done for both arms simultaneously.

- **Defining the end effectors**

The end effectors are the left and the right gripper. Each end effector has a name and consists of one of the predefined planning groups, a parent group and the parent link which is the last link in the kinematic chain of the parent group.

- **Generate the configuration files**

After completing all the configuration steps the configuration package can be generated. Therefore a target directory has to be specified which was set to 'uibk_robot_moveit_config'.

After completing the last step, a ROS package was created, containing all the necessary configuration and launch files for the given robot setup. The outcome can be tested, using the 'demo.launch' file from the configuration package. The setup can be modified by launching the Setup Assistant again, using the 'setup_assistant.launch' file from this package.

3.5 Connecting MoveIt to the existing robot control interface

Now MoveIt is configured and ready to handle planning requests for the IIS robot setup. This can be tested, using the 'demo.launch' file of the 'uibk_robot_moveit_config' package. This starts a move_group node, using the previously created configuration files and starts an instance of RViz together with the motion planning plugin. There it is possible to switch between the planning groups, set start and target configurations, do planning requests and visualize the outcome. But the execution of the calculated trajectories is still impossible because of the missing connection between MoveIt and the involved robot hardware. Each component needs to provide a FollowJointTrajectory action interface, defined in the 'control_msgs' package. This is a special kind of ROS interface, designed to send trajectories to robot components and monitor the execution status. The existing control interface of the IIS robot components does not fulfil those requirements and so there had to be found a way to 'translate' those JointTrajectory message into something compatible.

A is a set of waypoints (joint configurations). Each waypoint has to be reached at a certain time. Those waypoints mark the important points along the path, the manipulator has to move. The controller has to be able to move the robot from point to point, satisfying the time constraints defined in the motion plan. This involves to interpolate between those trajectory points over time and calculate intermediate positions, depending on the loop rate of the control cycle. Those positions can then be sent to the robot, using the joint_control/move topic (TODO: provide images to make that point more clear!!!). This interpolation is a difficult task and the implementation would be far beyond the scope of this project. Luckily the required functionality is already available within the 'ros_control' stack (wiki.ros.org/ros_control). Those packages are created to integrate and control robot hardware in a generalized way. This facilitates the usage of existing controllers on various different robots (TODO: provide image overview of ROS control architecture and hardware adapter concept).

3.5.1 Overview ROS control stack

The infrastructure that is necessary to use the generic controllers from the 'ros_control' packages is mainly provided by two components:

- **RobotHW**

This is the abstract base class for robot hardware abstraction. It's purpose is to send commands to the hardware and retrieves state data. Each generic controller needs a special kind of interface for controlling joints or read their current state. Concrete implementations of that class register those interfaces, based on the way how the hardware is actually controlled. For retrieving state data, a JointStateInterface is required. Controllers using that interface can query it for a specific joint and ask for the current state (position, velocity, effort). Sending commands to the joints is done via a type of the abstract JointCommandInterface, for example the JointPositionInterface which is used within this project. Other implementations are JointEffortInterface and JointVelocityInterface. Which interfaces are provided depends on the way how the concrete hardware is controlled.

- **ControllerManager**

The controller manager provides a ROS interface to load, start and unload controllers and for switching between them. The control cycle is intended to run in real time and the managed controllers are updated periodically (TODO: provide image showing the control cycle). The main loop periodically forces the *RobotHW* class to read the current state from the hardware, updates all active controllers and forces the *RobotHW* to send the commanded values to the hardware. This should happen in real time when interacting directly with the hardware. Controllers are usually configured on the parameter server and loaded on demand, using the ROS interface of the controller manager. Custom controllers can be created by inheriting from the abstract *ControllerBase* class.

3.5.2 Designing the hardware adapter

The idea of the hardware adapter is to be the connection between MoveIt and the simulated or real hardware. Therefore the necessary infrastructure for using the generic controllers from the `ros_control` packages has to be made available. The figure ??? gives an overview about the concept of the hardware adapter. The `UibkRobotHW` handles the connection to the involved robot components via their ROS interfaces. Therefore it maintains a set of `JointStateAdapters`, each one responsible for the communication to one robot component. A `JointStateAdapter` reads the current robot state from the configured '`joint_state_topic`' and sends the commanded values to the configured '`joint_command_topic`'. The adapter configuration is done via the parameter server. On startup, the hardware adapter loads the configured `JointStateAdapters`.

The `UibkRobotHW` inherits from the abstract `RobotHW` and represents the connection to the robot. It maintains the current state of all connected components. Therefore it maintains a set of `JointStateAdapters`, based on the configuration files. Each `JointStateAdapter` states a connection to one specific robot component. During the control cycle the `JointStateAdapter` reads the current joint states from the configured joint states topic and updates the received values accordingly. Commanded positions are sent to the configured joint command topic. The `UIBKRobotHW` also maintains a set, containing all the information about each single robot joint. The joints are identified by a unique name. During initialization, the `JointStateAdapters` are created, based on the `adapter.config` file. After creation, each `JointStateAdapter` waits a certain amount of time for an initial joint states message. If it does not receive such a message before timeout, it will automatically shut down for safety reasons and report an error. This is very important as the `JointStateAdapter` will immediately begin to send joint positions after the initialization. The position to be sent is initially the current position, as long as no other positions have been commanded by the controllers. Therefore the initial position always has to be known, otherwise dangerous and rapid robot motions could occur.

For the controllers, the `UIBKRobotHW` class provides a `JointStatesInterface` and a `JointPositionInterface`. The controllers will use those interfaces to access the current state and for commanding target positions.

The required configuration parameters are:

- **adapter_list**

Contains a list of all `JointStatesAdapters` that have to be created. For each adapter name mentioned in this list a detailed configuration is required.

- **joint_state_topic** The name of the topic where the adapter listens for joint states. The message type of that topic has to be '`sensor_msgs/JointStates`'. This parameter is mandatory

- **readonly** This parameter is optional. If true then the adapter will only listen for joint states but not publish commanded values.
- **joint_command_topic** The name of the topic the adapter should use to publish the commanded values to. The message type, the adapter uses is 'std_msgs/Float64MultiArray'. This parameter is necessary if the adapter is not configured to be read only.
- **joints** A list of joint names that should be controlled by the adapter. The order in this list also determines the order of the values in the published message.
- **joint_name_prefix** This parameter can be used to uniquely identify joints. For example both arms are using the same joint names (arm_0_joint, arm_1_joint,...). But the MoveIt requires joint names to be globally unique. Therefore the prefix can be used to prepend the original name to achieve uniqueness. A value of 'right_' for example will lead to the joint names (right_arm_0_joint, right_arm_1_joint,...).

As the topic names, used by the JointStateAdapters can be configured, the UIBKRobotHW class is able to interact with the simulator and the real robot as well, as both of them provide exactly the same ROS interface.

During hardware adapter startup an instance of the UIBKRobotHW and ControllerManager is created from configuration. The control cycle runs in it's own thread, currently at a loop rate of 100hz. On each iteration the exact time since the last step is calculated. The ControllerManager then updates all registered controllers based on current state and time since last iteration. After handling the controllers, the JointStatesAdapters are forced to send the commanded values to the hardware. The ROS spinning and all the callback functions are handled in the original thread.

3.5.3 Launching the hardware adapter

For starting the hardware adapter, a launch file (hardware_adapter.launch) was created in the 'uibk_moveit_adapter', package that handles the necessary configuration parameter upload and starts the required nodes. As it is designed to be used with the simulator and the real robot as well, it provides the 'config_name' parameter that can be used to switch between both namespaces. Possible values are 'simulation' and 'real'. For example 'roslaunch uibk_moveit_adapter hardware_adapter.launch config_name:=real' starts the hardware adapter for the real robot. The launch file uploads the URDF robot description, the adapter and controller configuration to the parameter server. After that it runs the hardware adapter node and forces the ControllerManager to load and start the configured controllers via a ROS service call. The controller gives a lot of state information about the state and errors during the startup process. Simulator or real robot have to be launched before starting the hardware adapter, otherwise the adapter will not be able to work because of the missing initial joint states. After launching the hardware adapter, the additional controller topics can be found in the corresponding namespace, along with an additional 'joint_states' topic that publishes the whole state of the robot at once as it is required by MoveIt.

3.5.4 Adjusting the MoveIt configuration

The prerequisites are now made for connecting MoveIt to the (simulated or real) robot. The last remaining step is to adjust the MoveIt configuration for establishing a connection to the JointTrajectoryControllers. Therefore the configuration file 'controllers.yaml' was created. It contains a list, describing the available controllers. For each controller description contains the

name of the controller, it's action namespace, the type and a list, containing the names of the controlled joints.

Joint states are expected to be published via a topic named 'joint_states'. This is done automatically by the JointStatesController.

For starting MoveIt, the launch file 'moveit_planning_execution.launch' was created. This file is intended to start a move_group node either for simulated or real robot. The namespace can be selected using the boolean parameter 'simulation'. 'roslaunch uibk_robot_moveit_config moveit_planning_execution.launch simulation:=false' starts the moveit configuration in the 'real' namespace, connecting the move_group instance to the real robot. The launch file starts the move_group node along with the hardware adapter and all the necessary configuration parameters. It can be chosen whether to launch it within the 'simulation' or 'real' namespace by setting the 'simulation' parameter to true or false. The launch file also starts an RViz instance configured with the motion planning plugin. This is used for visualizing the planned trajectories. It can also be used to test the connection to the robot by making a planning request and execute the resulting trajectory.

3.6 Usage examples

3.6.1 Capabilities

3.6.2 Modifying the planning scene

3.6.3 Planning and executing trajectories

3.6.4 Running the planning tools in different namespaces

How to use MoveIt with the simulator or real robot in parallel

Chapter 4

Pick and place

The implementation of a benchmark pick and place task, executable on simulator and real robot as well, states one of the objective targets of this project. The implementation heavily uses major parts of MoveIt's planning functionality. The overview at the beginning of this chapter gives some general information about pick and place tasks, explaining the process step by step and describing the single stages that have to be performed. The second part focuses on the pick and place functionality of MoveIt and discusses the involved action servers, topics and messages. The third section explains the implementation of the benchmark pick and place task in greater detail and demonstrates how that functionality of MoveIt was used. The last section describes some observations that have been made during the implementation process.

4.1 Overview

A pick and place task is the process of grasping an object, lifting it and dropping it somewhere else. Humans do that permanently, without even think about it. But when teaching a robot to perform a pick and place action, it shows how difficult and complex this task is and how much planning is involved to achieve the desired result. The planner requires exact knowledge about the robot and its environment, including the objects to grasp and possible obstacles. Accidental collisions have to be avoided but other collisions are mandatory when the robot has to get in contact with the world. The gripper definitely collides with the object to pick, but only during grasping and holding. Therefore there has to be a mechanism to explicitly tell the planner that specific collisions are allowed during particular stages of the operation. Moreover, after grasping an object it has to be considered as an additional part of the robot during subsequent planning requests. That means that it must be attached to the manipulator temporarily and removed, after releasing the object. As long as the object is part of the robot, it possibly increases the size of the end effector.

Stationary objects usually stand or lie on a surface, called the *support surface*. During the interaction with an object, possible collisions with the support surface have to be taken into account. It is also possible that the whole process underlies additional constraints, so called *path constraints*. This type of constraint has to be enforced along the whole path, the grasped object takes during the operation. For example when carrying a glass, filled with liquid it has to stay in an upright position, otherwise the liquid is lost. That means, the glass has to be held in a specific orientation during the whole task. This can be described as *orientation constraint* which is a special type of path constraint. The planning solution has to provide mechanisms to define and enforce such types of *path constraints*.

Pick and place tasks can be split into two independent phases, each one composed from a number of trajectory stages:

- **Pickup phase**

This phase starts at an arbitrary robot configuration. In the first stage, the manipulator has to be brought into a position closed to the object to grasp, but in a distance that allows the gripper to open safely without touching the object. This position is called the *pre-grasp pose*. The next stage is to set the gripper into *pre-grasp posture*. That means, bring it's fingers into an open configuration that allows to completely enclose the object (or at least that part that is used to clutch it) after approaching towards the final *pose*. How this configuration looks like depends on the shape of the object to grasp and the structure of the gripper. Further on, the gripper has to be moved towards the *grasp pose* using the correct approach direction. This is the place where the robot gets in contact with the object. The gripper moves it's fingers into the *grasp posture* - a configuration that encloses the object and applies as much force as necessary to be able to take and hold it. The resulting collisions between the gripper links and the object have to be ignored. At that point the object has to be attached to the gripper and further on treated like an additional link of the robot although still being in collision with the support surface. The pickup phase completes after lifting the object along the retreat direction. The object is now part of the robot and no collisions should be tolerated any more. Figure 4.1 shows the stages of the pickup phase.

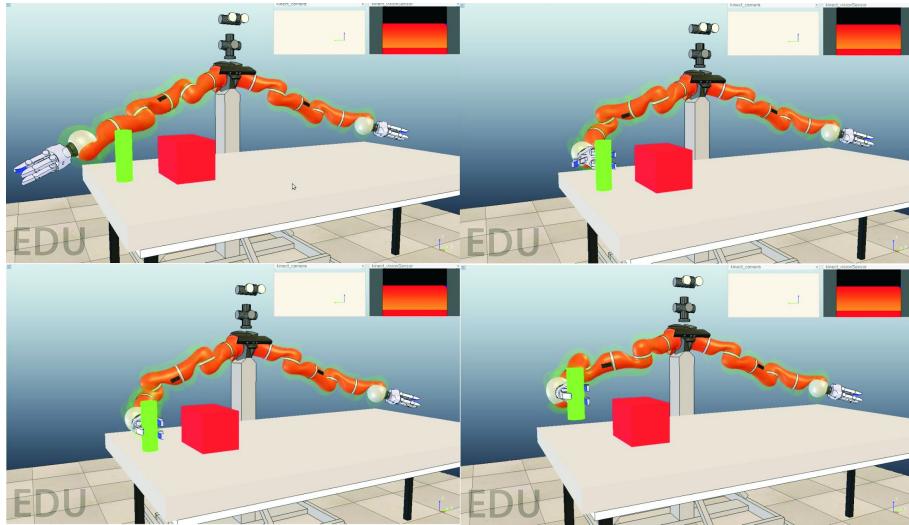


Figure 4.1: Stages of the pickup phase in the simulator

- **Placement phase**

The placement phase starts after a successful pickup. The grasped object is enclosed by the gripper and considered to be part of the robot. Now the manipulator moves towards the *pre-place location* - the place where the final approach towards the goal starts. The easy way is to just drop the object at that point. In that case, the placement phase completes after bringing the gripper fingers into the *post-place posture* (opening it) and detaching the object from the robot.

If the object should be placed carefully, the gripper has to approach from the *pre-place location* towards the final *place location* along the specified approach direction. Here has to be considered that the object will get into contact with the support surface again when it's final position is reached. At that stage the gripper can open and the object has to be detached from the robot. From that point, the object needs to be treated as obstacle again which means the planner is forced to avoid collisions with it. The placement phase completes after the manipulator has moved away from the object along the specified retreat direction. The stages of the placement phase can be seen in Figure 4.2.

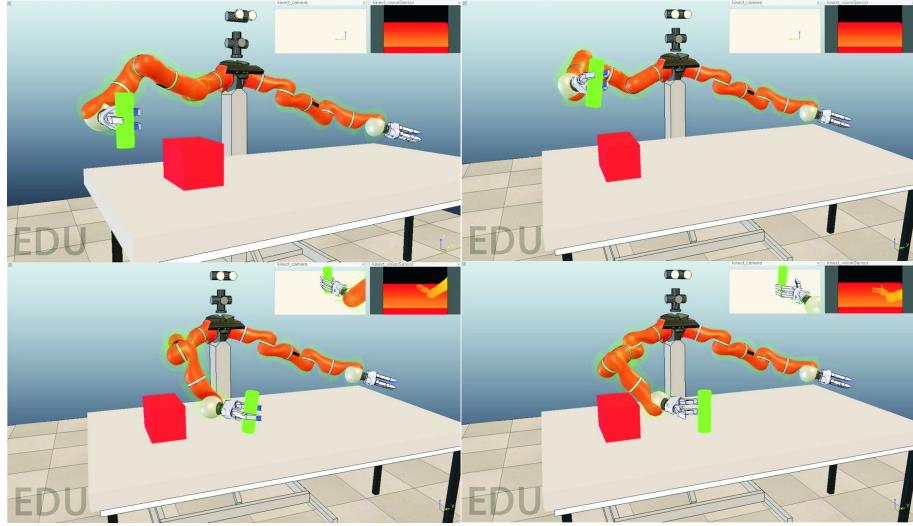


Figure 4.2: Stages of the placement phase in the simulator

Both phases of the task are only considered to be complete if each single stage has successfully been executed. The necessary planning parameters like pre-grasp and grasp pose, gripper postures and approach and retreat directions are usually provided by a *grasp planner*. This is an additional node within the planning pipeline that identifies objects in the environment of the robot, usually based on 3D sensor data and calculates the necessary grasp parameters. Explaining the functionality of grasp planners is far beyond the scope of this project though the section about implementing the reference task discusses the used parameters in greater detail and shows what would be usually delivered by the grasp planner.

4.2 Pick and place tasks in MoveIt

During the various stages of the pickup and placement phases a lot of motion planning is required. Each single stage requires to plan a trajectory that is free of accidental collisions while respecting the limits of the robot and enforcing possible additional constraints. Each phase can only be considered executable if a valid motion plan for each single stage exists. Planning all the subsequent stages one after the other would be a cumbersome task. Therefore MoveIt provides a set of messages and action servers that greatly simplify those planning tasks.

The *PickupAction* server handles the planning and optionally execution of all required stages during the pickup phase at once. Pickup requests are done, using a *PickupAction* client to send *PickupGoal* messages to the server. The request message is composed of all the parameters that are necessary to completely describe the planning problem. Picking up an object can always be done in several ways. Depending on the shape of the object there hardly always exist a lot

of possible poses where the gripper can safely approach and grasp. Therefore MoveIt allows to provide a set of possible grasp definitions for a pickup request. There is also a quality parameter that can be used to tell the planner, how ‘good’ a specific grasp is compared to other ones. MoveIt can then favour grasps with higher quality if several valid solutions are found by the planner. Providing a number of different grasps increases the probability for the request to be successful. The grasp definition is composed of the pre- and post grasp postures for the gripper, the final grasp pose and the approach and retreat vectors. As MoveIt needs to know which object should be picked within the planning scene, it is also necessary to include the ID of the object to grasp.

The *PlaceAction* server is responsible for planning the whole placement phase. Therefore same concept is used as above - a set of possible place locations can be provided to increase the probability of a successful planning attempt. The parameters that are used to describe a place location include the post-place posture of the gripper along with its target pose, and vectors, describing the pre-place approach and the post-place retreat.

Pickup and placement requests as well require a number of additional parameters that are explained in greater detail within the section about benchmark task implementation.

Objects contained in the task environment have to be brought to MoveIt’s attention. This can be done either by manually adding them to the planning scene, using the corresponding topics or by configuring MoveIt to be aware of sensor data. As the integration of depth information from the Kinect camera did not work stable during the evaluation phase, that possibility is not covered within this thesis and all involved objects were added manually.

Pickup- and place action servers provide the ability to choose whether to execute motion plans immediately or to do just the planning and return the outcome. In that case the execution has to be handled manually later on. The first method is much more comfortable as MoveIt executes the trajectories and also handles additional requirements like attaching and detaching the grasped object in time. The drawback is that also possibly weird trajectories get executed immediately as they might be valid solutions for the given planning problem though they are obviously unsuitable. So an additional safety mechanism needs to be introduced that allows to interrupt the execution when facing any problems. The second method allows to visualize the resulting trajectories and then decide whether to execute them or not. But then each single trajectory stage has to be executed manually which also includes attaching or detaching objects to the manipulator. The advantage of this method is the clean separation between planning and execution, allowing maximum control over the execution flow. Therefore this method was favoured during benchmark task implementation.

4.3 Implementation of the benchmark task

This section describes the implementation of the benchmark pick and place task in greater detail. The source code can be found within the ‘uibk_moveit_tests’ package. The workspace is the table in front of the robot covered with a 9cm thick foam mat. This mat will be declared as the support surface later on. The object to grasp is a cylinder with 4cm radius and a height of 25cm. This corresponds to the size of a usual SIGG bottle which can be used to run the benchmark task in the real world. The cylinder is located on a fixed, known position. There is also a box shaped object located within the workspace that acts as an additional obstacle. The goal of the task is to pick the cylinder up, using the right arm of the robot and place it at the goal location without colliding with the obstacle or other parts within the robot’s environment. The implementation makes use of MoveIt’s pick and place functionality. The necessary steps

are explained in the following subsections.

4.3.1 Creating the environment

As MoveIt is currently not configured to use sensor data, it has to be notified about the task environment. The table and the surface mat are already part of the URDF description but the cylinder and the obstacle have to be added to the task environment. This is done utilizing the `planning_interface::PlanningSceneInterface` class that provides functionality to manipulate the current planning scene. The same effects can be achieved by manually publishing to the '/collision_object' topic but using the convenience class saves a lot of boilerplate code. The `CollisionObject` type is used to describe those objects. Both of them are primitive shapes. Necessary parameters are the shape type, dimensions and the target pose. Additionally each `CollisionObject` needs a unique ID which is used to identify the shape within the planning scene. After adding the `CollisionObjects` to the collision world, they are visualized in RViz. The image in Figure 4.3 shows the task environment after adding the `CollisionObjects`.

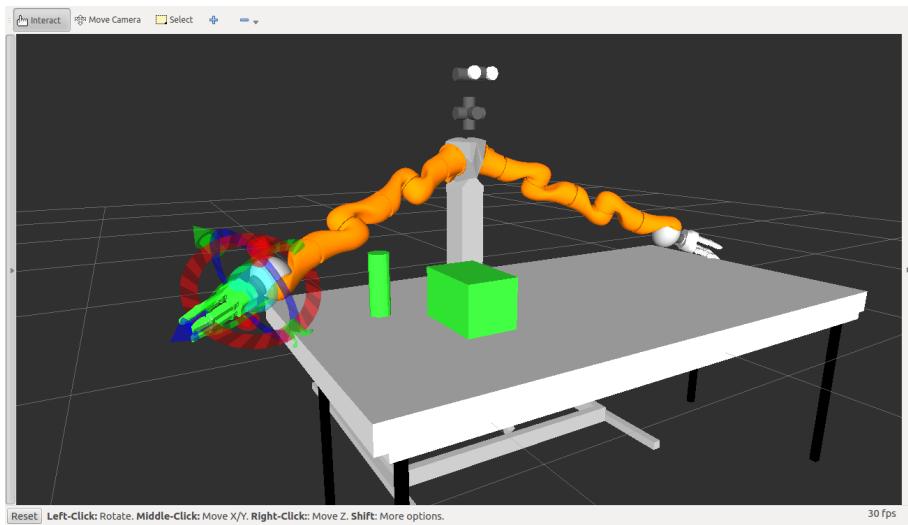


Figure 4.3: Planning scene after inserting the collision objects

4.3.2 Generating possible grasps

Before calling the pickup action server it is necessary to generate a set of possible grasps for the object to pick. This information is usually provided by a grasp planner. The sample task encapsulates the grasp planner functionality within the `generateGrasps` method. This method takes the current pose of the cylinder as input parameter and calculates 10 possible grasp poses along a semi circle around the cylinder location. Pre-grasp and grasp postures are joint trajectories for the gripper, containing just one trajectory point stating the target configuration for the gripper in the opened respectively the closed state. The pre-grasp approach and the post-grasp retreat are defined as `GripperTranslations`. This is a special message type that describes the direct gripper movement from one position towards a target. The direction is defined as a three dimensional vector. The length of the translation can be set in a flexible way by specifying a desired distance and a minimum distance. Experiments showed that the success rate is much better if the grasp parameters allow some flexibility to the planners. The approach vector depends on the grasp pose and points along the z-axis of the end effector frame towards the object. The desired distance between pre-grasp and grasp pose is set to 20cm while the minimum

distance is 10cm. The gripper retreat vector points up, along the z-axis of the world. Desired and maximum distances are also set to 20cm respectively 10cm. As no one of the generated grasps should be favoured among the others, the `grasp_quality` parameter of each grasp is set to 1. This means that they are equal in quality. The last necessary parameter is a unique identifier for each grasp. As usually a lot of different grasps are provided for each pickup request, this ID can be used to identify, which one was finally used to solve the planning problem.

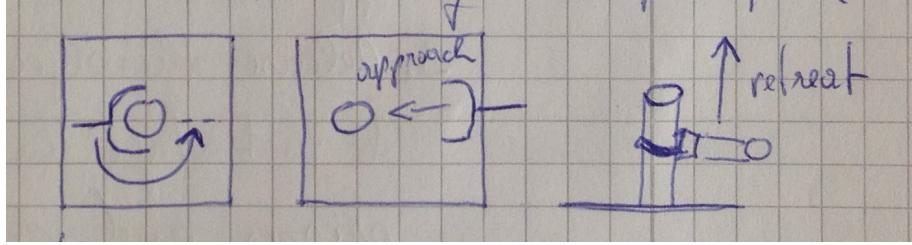


Figure 4.4: Grasp poses, gripper approach and retreat

4.3.3 Planning and executing the pickup

After generating the set of grasps, the planning request can be sent to the pickup action server. As there is a lot of boilerplate code necessary, a reusable helper class was created that can be used to simplify all kinds of planning requests. The utility class is called `PlanningHelper` and can be found within the '`uibk_planning_node`' package. A call to the pickup action server is done by using the '`plan_pick`' method of the helper class. This method takes a set of possible grasps and the ID of the object to pick as parameters. The outcome is a pointer to an instance of `PlanningResult`, a structure that contains all the necessary information about a planning attempt. Success or failure is indicated by the '`status`' parameter. On success, the parameter '`trajectory_stages`' holds a vector, containing the resulting trajectory stages. The actual call to the pickup action server is done by defining the `PickupGoal`, using the predefined grasps. Additional parameters are the ID of the object to pick, the name of the chosen planning group and the name of the link within the robot model that acts as the support surface. Optional parameters are among others the ID of the planner to use and the maximum allowed planning time. The parameter '`plan_only`' within the planning options is set to true to avoid the immediate execution of the planned trajectories. This allows a visual verification of the planning outcome before execution. The resulting robot path is shown in RViz. If the solution is satisfying it can be executed, passing the `PlanningResult` to the corresponding method of the `PlanningHelper` class. This method uses the '`/execute_kinematic_path`' service provided by the '`move_group`' node. The service sends a given trajectory to the responsible controller and provides feedback information about the execution status. The '`PlanningHelper`' also takes care to attach the picked object to the gripper after the grasp stage. The pickup phase completes after successful execution of all trajectory stages.

4.3.4 Planning and executing the placement

The placement phase is planned and executed in a somehow similar manor. The cylinder has to be placed on a specific location within the workspace in an upright position - the rotation around the z-axis doesn't matter. Therefore a set of possible place poses is generated in 20 different orientations around the z-axis. This again gives some freedom to the planner as it can choose which one to use (TODO: provide image that shows the principle). The final approach towards the goal location is specified as `GripperTranslation`. The direction vector points down

along the z-axis of the world. Desired and minimum distances are set to 20cm respectively 10cm, allowing some flexibility during that stage. As post-place posture for the gripper, the same configuration is used as for the pre-grasp posture. The last required parameter for a place location is the *GripperTranslation* that describes the retreat after releasing the object at the goal location. The direction depends on the chosen orientation and points towards the negative z-axis of the gripper reference frame.

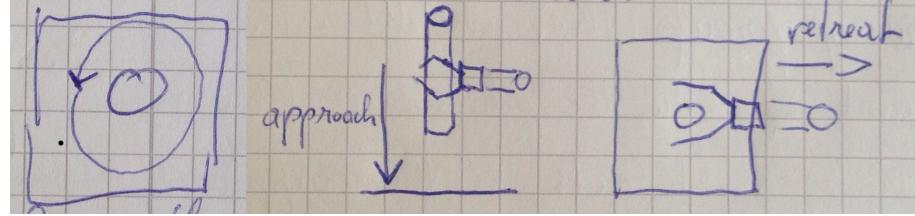


Figure 4.5: Place locations, pre-place approach and post-place retreat

The call to the place action server is again handled by the formerly mentioned planning helper class. The ‘plan_place’ method takes a vector of the predefined place locations and the ID of the object to place as input parameters. The actual call to the place action server is done, defining a *PlaceGoal* message. The most important parameters are the ID of the object to place, the name of the planning group and the set of possible place locations. Optionally can be specified which planner to choose and also the maximum allowed planning time. The method returns the result of the planning request. On success, the resulting trajectories are again visualized in RViz and can then be executed the same way as during pickup phase. After the execution, the task is considered to be complete and the picked object is detached from the gripper and again part of the collision world.

4.4 Executing the benchmark task

The benchmark task is designed to run on the simulator and the real robot as well. The sample program only depends on a running ‘move_group’ instance. The easiest way to run the sample is to start MoveIt in demo mode (demo.launch) and then execute the sample code, using.

```
rosrun uibk_moveit_tests sample_pick_place
```

This demonstrates the functionality but only executes the trajectories on the fake controllers provided by MoveIt. If the sample should be executed on the simulator or the real robot, the corresponding namespace has to be specified before running the code. This can be done by setting the ‘ROS_NAMESPACE’ environment variable to either ‘simulation’ or ‘real’, within the terminal. For example

```
export ROS_NAMESPACE=simulation
rosrun uibk_moveit_tests sample_pick_place
```

runs the benchmark task on the simulator. Of course it is necessary to start the simulator and launch the corresponding MoveIt instance before doing that. After creating the environment and adding the objects to the planning scene the pickup phase gets planned. The outcome can be seen in RViz and the program will ask if the resulting trajectory is ok and should be executed. A negative answer will force the program to replan the pickup and ask again, otherwise the trajectory gets executed. After successful execution, the place phase gets planned. The resulting plan also is visualized as well and execution needs confirmation again. The program exits after successful completing the placement phase.

4.5 Observations

This section gives an overview about the most important observations that have been made during the implementation of the sample task:

- It is very important to provide some degree of freedom to the planner at various points. Major points are the amount of different grasps or place locations and the allowed range within the defined gripper translations. Very strictly defined planning requests are very likely to fail whereas requests with a higher degree of flexibility drastically raise the overall success rate.
- Working with path constraints drastically drops the success rate because the high complexity of the planning problem. Enforcing path constraints requires much more allowed planning time and a very fast IK solver because of the large number of necessary IK requests. Maybe a faster IK solution than the one available could help to solve the problem but that is not guaranteed. Therefore there are no path constraints used within the sample task.
- Planning requests often fail due some MoveIt-internal issues and not because planning is not possible at all. Therefore it is necessary to repeat failed requests because it is very likely that planning succeeds on subsequent attempts. In the sample task implementation, the planning requests are done within a loop. If a request fails, it gets repeated. A successful request breaks the loop and continues the execution flow.
- Resulting trajectories should always be visualized in RViz before confirming the execution. The calculated motion plans might be valid but sometimes they are a bit confused and therefore unsuitable. Moreover, the planner can only take into account what it knows about the robot's environment. Especially in the robot lab there is equipment mounted in the area above the robot, that is not taken into account during planning. Therefore the visual validation is necessary to avoid damages on the robot and its environment.

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