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Chapter 1

Executive Summary

The main contribution of this deliverable is the implementation of a proof of concept example, which links the different contributions of the project together and demonstrates several aspects of structural bootstrapping in the context of the task "prepare the dough" on the humanoid robot ARMAR. In this context, we show how unknown actions in a plan can be inferred and replaced based on human observation where a human provides alternative solutions. As such the video **Proof-of-Concept.mp4** demonstrates a first implementation of structures and processes associated with structural bootstrapping by integrating contributions from all work packages towards an implemented architecture which exploit structural bootstrapping mechanisms based on Object-Action Complexes as underlying grounded representations of sensorimotor experience. The demonstration has been implemented using the proposed architecture in WP1 and to integrate action representations developed and evaluated in WP2, bootstrapping mechanisms discussed in WP3 and planning aspects of WP4. We consider this effort of integration as an important step towards a complete robot systems with advanced exploration, learning, planning, prediction and reasoning capabilities. The description of the scientific contributions have been described in **D1.2.1, D2.2.2, D3.1.2** and **D4.2.4**. The entire demonstration was performed at KIT on the humanoid robot ARMAR-III.

In addition to the demonstration described above, we show the execution of a tightly coupled cooperative-interaction task, where two robots are coupled by tightly holding a rigid object and are at the same time guided through interaction with a human operator. Video **CoupledDMPs.mov** shows how the robot execution is modified to reach the box and fit the lid. This experiment benefits from our theoretical work on coupled motor representations as detailed in deliverable **D4.1.2**. Furthermore, video **DMPcoaching.mp4** shows how visual feedback can be used to adapt trajectories by coaching with hand gestures. The experiments were performed on the JSI humanoid robot platform and on humanoid robot CB-i available at our collaboration partner ATR, Japan.

Chapter 2

Structural Bootstrapping: Proof of Concept

As shown in the video **Proof-of-Concept.mp4** and discussed in deliverable **D3.1.2**, the task of the robot to prepare the dough by mixing two ingredients. For this the robot has the required knowledge to do it in one specific way (by using an electric mixer) but it fails to generate a plan because of the missing mixer in the current scene. This failure is resolved by observing a human demonstrating the task and providing an alternative plan (mixing with the whisk). The human demonstration provides a sequence of actions together with the world state before and after the execution of each action. These actions are compared with existing knowledge represented in an OAC library to identify similarities of observed actions with already known actions. Based on the segmented actions and how they change the world state, the most similar action from the OAC library (the wiping action) is selected to execute the task.

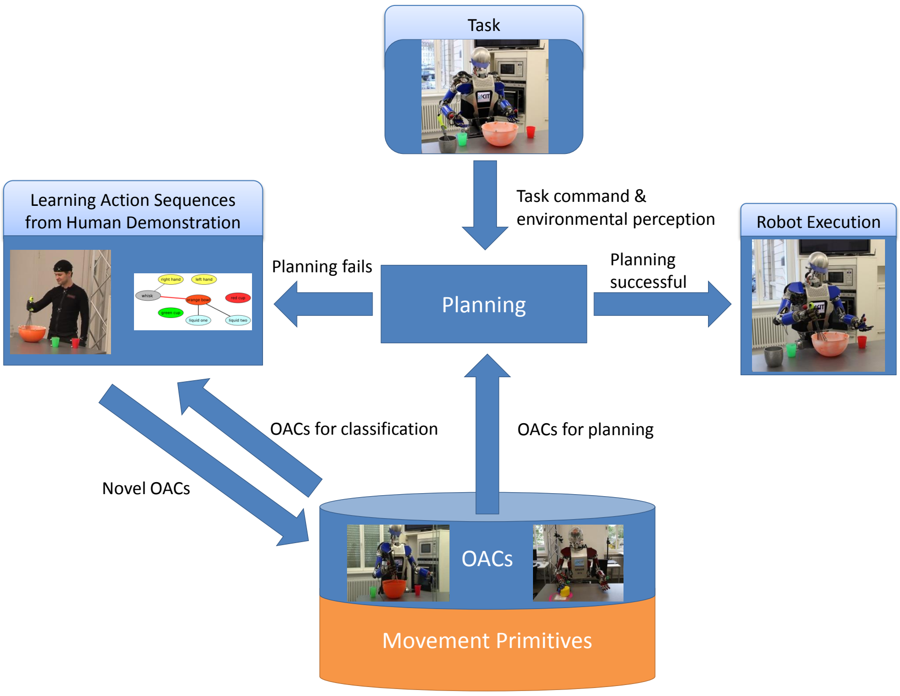

Figure 2.1: Concept of the implementation of structural bootstrapping mechanisms based on prior knowledge represented in an OAC library, planning and human demonstration in the context of the task prepare the dough.The demonstration has been implemented using the proposed architecture in WP1 and to integrate action representations developed and evaluated in WP, bootstrapping mechanisms discussed in WP3 and planning aspects of WP4.

For the scenario of preparing dough, human demonstrations are captured using the VICON marker-based tracking system. Methods for task segmentation, action recognition, and action replacement were developed to provide the required information to enable the robot to provide solutions for the given task considering the current situation.

The execution on the robot is realized based on Object-Action Complexes (OACs) stored in the OAC library. These provide the information about preconditions that must be fulfilled for a successful execution and prediction functions of the OAC effect on the world. In addition, they contain the required information on how to perform a specific action on sensorimotor level. Technically, the OACs are implemented as hierarchical statecharts, which can be parametrized according to object- and task-specific constraints.

Chapter 3

Additional Demonstrations

3.1 Bimanual Interaction

The proposed approach is described in deliverable **D4.1.2**. Video **CoupledDMPs.mov** shows the adaptation of movement of two robotic arms encoded by two coupled DMPs when the human coworker guides them by force interaction to teach a new behavior with changed environment conditions. The task of the robots was to help the human coworker to place a lid on a large box. When the box is moved, thus simulating a new batch of boxes of a different size, the operator can teach the robots how to move with the changed size of the box. No reprogramming of the production line is needed. The movement was repeated several times and adapted to minimize the force with respect to the coworker and with respect to the interaction with the box. After 8 repetitions, the human worker only feels the weight of the lid and the robots practically guide the human in placing it. It is important to note that the algorithm practically converges to the desired zero-force interaction, despite unrepeatable human input. Inconsistency in the exerted force by the human is the reason that the convergence is not ideal.

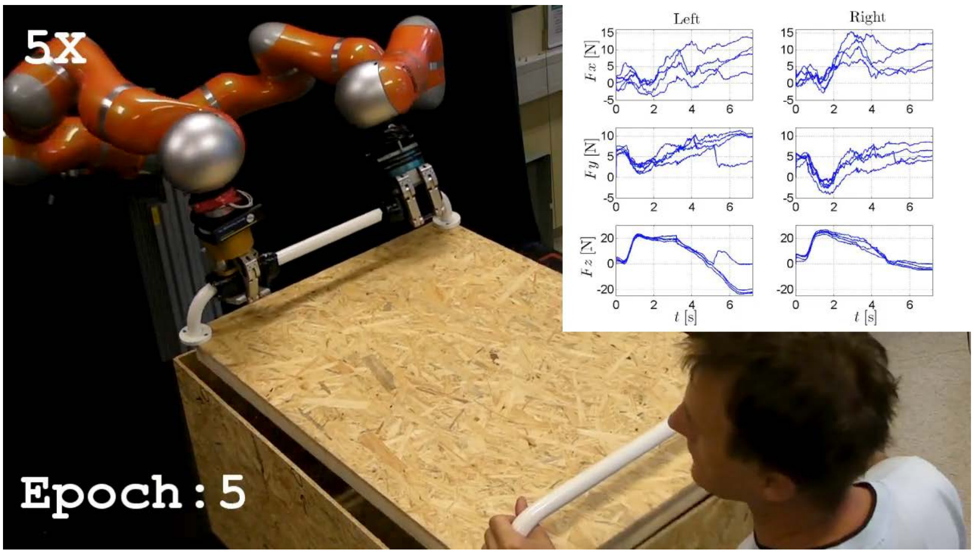

Figure 3.1: The arms were trained to place the lid with minimal force arising between them. When the box is moved, the human coworker guides the robots by force interaction. The force is minimized in several iterations (in this case 8) and then practically the robots lead the worker.

3.2 Interactive Motion Adaptation using Coaching

In order to adapt previously learned robot trajectories, we proposed an approach for altering the existing behaviors online through coaching, where a human coach interactively changes the robot motion to achieve the desired outcome. The video **DMPcoaching.mp4** shows a human coach transferring knowledge through coaching. Several motion trajectories were modified using this approach. The approach is based on hand gestures, with which the human coach can specify the desired modifications to the previously acquired behavior. A virtual force field surrounding the human hand is affecting the movement. A recursive least squares technique is used to modify the existing movement with respect to this virtual force field. The movements stay modified, i. e. they are learned after the coach finishes with coaching. The approach is applicable for both periodic and discrete motions.

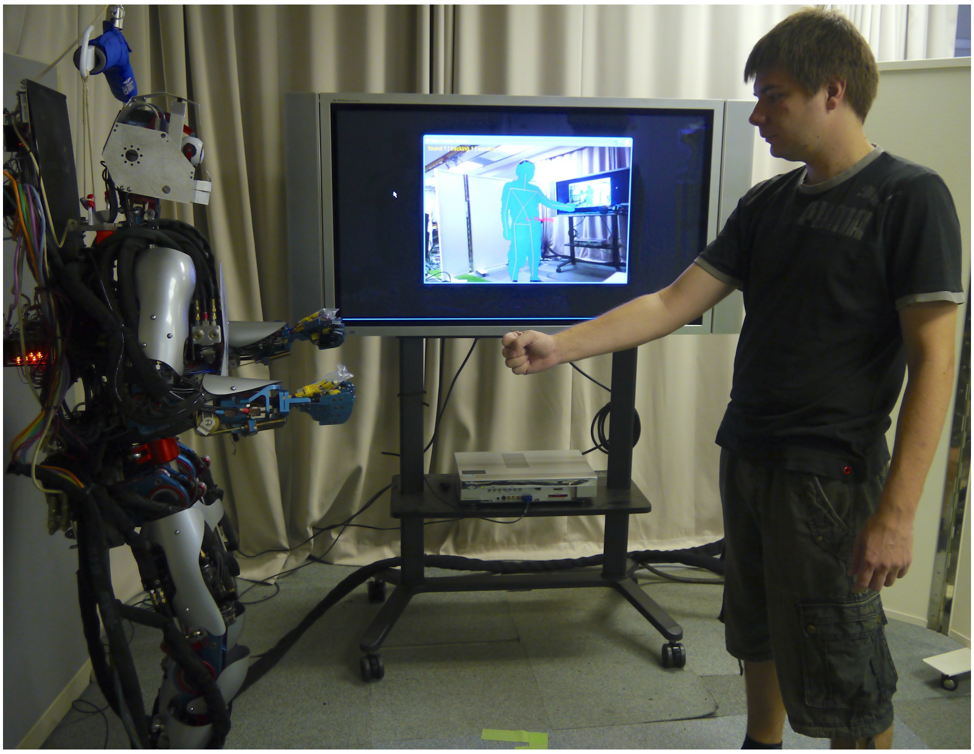

Figure 3.2: Human coach is modifying the Cb-i humanoid robot arm motion. The human coaching gesture is captured using the Microsoft Kinect sensor; its output and tracking results are displayed on the screen in the background.