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Chapter 9
Conclusions

The fundamental hypothesis that "*there is a need for intelligent physical compliance* was formulated in the introduction of this work, in order to account for the shortcomings of today's service robots. The hypothesis builds on the notion that particularly non-traditional robot tasks outside factory buildings demand compliant interaction capabilities in combination with advanced cognitive reasoning skills. However, this constitutes a need which is not even covered for application in laboratory environments. To overcome this issue, intelligent decision making strategies for compliant manipulation tasks have to be developed. That is, a robot has to process diverse task knowledge to *plan* effect-oriented actions, parameterize and *execute* these actions accordingly, and eventually *interpret* the outcome of the actions on a high-level of abstraction to estimate the task performance qualitatively. In order to facilitate this reasoning, suitable *representations* that incorporate the properties of physical compliant interaction have to be provided.

These aspects substantiate the hypothesis of a need for Intelligent Physical Compliance, which emerges from the hypotheses that "*there is a need for artificial intelligence*" and "*there is a need for physical compliance*" in order to fulfill society's "*need for service robots*". This motivation is well captured in the example of collecting leaves (cf. Fig. 1.1). The artist's conception illustrates Rollin' Justin deployed as a public service robot. It executes the recurring task of collecting leaves in a park area by the use of a rake. Among others, raking lines up with several tasks that are typically considered laborious and futile. Accordingly, the workload of many people could be relieved by delegating this task to a commercial service robot. However, unlike most commercially available robots, Rollin' Justin possesses joint-torques sensors that allow for soft physical interaction with the environment. This allows it to guide the rake compliantly over the rugged cobblestone without loosing contact or damaging itself. Moreover, feedback-driven control strategies allow Rollin' Justin to constantly monitor the applied contact force and adapt to uncertainties. Nonetheless, compliant robots are not yet deployable as universal service robots. This is mainly due to the fact that the complexity of the problem grows with the capabilities of the robot. In this regard, stiff industrial robots are mainly utilized to execute rather simple actions as they are observed in pick-and-place tasks. These tasks can be represented by means of discrete changes to the world, i. e. the relocation of objects can be represented by homogeneous transformations. In contrast, the task of collecting leaves in a park requires a much richer process model. A robot must reason about the interaction of the rake and the leaves in an effect-oriented manner. It has to predict the effects in advance and estimate the real task outcome after execution. To achieve this, the robot requires qualitative representations of the effects, the actions, and the objects participating in the task execution. That is to say, the cognitive load for compliant manipulation tasks is much higher than it is for traditional robot operations, which explains the need for AI.

This final chapter summarizes the investigations conducted in this work in Sect. 9.1. General conclusions are drawn w. r. t. the research fields of robotics and AI in Sect. 9.2. Afterwards, the disclosed research questions are highlighted in Sect. 9.3. Finally, the hypothesis about a need for Intelligent Physical Compliance is discussed in the outlook given in Sect. 9.4.

9.1 Manuscript Summary

The combination of AI-reasoning methods and compliant robot control constitutes one key point for the developments conducted. In the introductory chapter, two hypotheses have been formulated to introduce the divergent viewpoints of the two research domains. The statements were intentionally formulated to be only partial correct, in order to illustrate the limited perspectives on the research question. However, the findings presented in this work confirm that the views on the problem are *not contradictory, but complementary* to each other such that they describe the whole problem in a deductive manner. Both statements are repeated and listed for direct comparison. This section summarizes the manuscript with reference to these statements and highlights the immediate contributions.

AI Research

"First of all, the domain of the problem needs to be defined by means of an ontology. For example, one has to specify that a rake is a tool to collect leaves and it has to be carried by the robot to do so. The effect would be that the leaves are accumulated afterwards. Knowledge-based reasoning strategies have to be applied to infer that a rake has a certain probability to be picked up from a garden shed. A logic planner can schedule the actions accordingly."

Robotics Research

"Sweeping motions can be realized by means of whole-body impedance control. The tool motion would thereby be described by a moving virtual equilibrium point for the tool center of the rake. A virtual potential force aligns the tool w. r. t. the curvature of the target surface. Defining an appropriate Cartesian stiffness at the end-effector results in compliant contact behavior that allows to cope with environmental uncertainties and external disturbances."

Starting from the high-level AI perspective, it was first stated that an ontology has to be defined in order to describe the domain of the problem. This has been done in form of the classifications conducted in Chap. 3. In order to generate a comprehensive classification of compliant manipulation tasks, the taxonomy was developed based on the nature of contact that can be observed during physical interaction between a hand/object system and the environment/target system. The classification terms describe the contact behavior during interaction, i. e. contact or no contact with the environment, the relevance of friction, the presence or absence of deformations, and the occurrence of penetrations. By further deepening the investigations, it appeared that especially wiping tasks are of great importance for service tasks in domestic and industrial settings. To that end, a detailed classification of wiping tasks was conducted based on the definition of tool-medium-surface tuples. This classification serves as the foundation of the reasoning methods developed. It included the prototypical tasks of absorbing, skimming, collecting, emitting, distributing, processing, scrubbing, grinding, and decomposing. Altogether, the taxonomy would provide a guideline for future researchers, on how to analyze compliant manipulation tasks and how to derive generic process models from this analysis.

With regard to the necessity of an ontology, it was further argued that a robot would require representations to describe objects, actions, motions, and effects of manipulation tasks. The manuscript covers this request in Chap. 4. Based the insights of cognitive science, it was derived that an object-centric representation is a natural approach to imitate human-like cognitive reasoning capabilities. As a consequence, all knowledge required to solve robotic manipulation tasks was arranged w. r. t. the hierarchical representation of functional object classes. Among others, this would involve geometric information such as CAD data, mass information, and visual features, but also symbolic knowledge including logic predicates and even handling instructions for robots in form of Action Templates developed in this work.

Action Templates represent a fundamental concept to describe the symbolic meaning of an action in combination with the geometric nature of the process model. They enable a robot to ground symbolic plans into executable robot commands by means of robot independent operations. In order to generate wiping motions based on generic process models in form of Action Templates, the so-called Semantic Directed Graphs (SDG) have been developed which represent Cartesian wiping motions on two-dimensional planes. In addition, a particle distribution model was developed to represent the effects of wiping actions. Altogether, the developed representations allow a robot to envision a problem mentally which is one of the most important skills for human-like problem solving.

The proposed representations provide the means to develop planning methods for everyday manipulation tasks. This complies with the final sentence of the AI statement, stating the need of knowledge-based reasoning strategies and logic planning to solve abstractly defined manipulation tasks. Chapter 5 is concerned with this issue and answered the elementary question on how high-level action definitions can be mapped on low-level robot manipulation skills, to eventually bridge the gap from AI research to robotics research. In particular, an object-centered hybrid reasoning framework was developed that utilizes Action Templates as fundamental building block for automated robotic manipulation. The framework is based on hybrid reasoning, i. e. the combination of symbolic planning and geometric planning. As such, the approach facilitates symbolic and geometric backtracking with integrated whole-body mobile manipulation planning capabilities based on reachability analysis. The framework has been extended toward effect-space planning methods for autonomous agents. That is, SDGs were combined with the particle distribution model to plan goal-oriented wiping motions based on abstract goal definitions for a certain medium. It was shown how the effect of these actions can be predicted qualitatively, in order to select the best available strategy in advance for a given scenario. The approach has been successfully applied to the tasks of absorbing, skimming, and collecting. The developed reasoning methods are based on the generic concept of effect-space planning, which is well suited to investigate automated manipulation in general.

The dependency and relationship between the two research domains became immediately evident with the second introductory statement, that is anticipated through system identification and problem analysis from the control engineering perspective. While it has been stated how sweeping motions can be realized, it has not been mentioned how these motions could be generated. In fact, it is often implicitly assumed that they are given to the closed-loop system based on the outcome of high-level planning methods. Nonetheless, the controller has to be parameterized in order to execute the motions correctly. This procedure was captured in Chap. 6 along with the execution of the motions. In particular, it was argued that complaint contact behavior would be best realized by means of hierarchical whole-body impedance control. This approach would allow to resolve the highly redundant null space of humanoid robots while it is additionally possible to satisfy secondary control tasks such as self-collision avoidance, singularity avoidance, and gravity compensation. To this end, an approach to integrate the whole-body controller of Rollin' Justin into the developed high-level reasoning framework has been formulated. The approach was validated in three elaborate experiments, namely, scrubbing a mug with a sponge, skimming detergent off a window, and collecting shards of a broken mug with a broom. The experiments revealed that it is not always straightforward to design the desired in-contact motion for a given scenario. However, it was confirmed that it would be possible to exploit the compliant contact behavior of the robot. Notably, it was recommended to design the actual tool motion as a sequence of translations only and introduce rotations by means of low rotational stiffness settings to comply with the curvature of the target.

The roboticist's argumentation continues with the noteworthy fact that the compliant contact behavior realized with impedance control would allow to cope with environmental uncertainties and external disturbances. While this is most desirable for human-robot collaboration, it is especially this feature that makes impedance control nondeterministic w. r. t. the task performance. Moreover, closed-loop system are typically unaware of the purpose of the generated motions, neither are they aware of the resulting outcome. To overcome this issue, an effect inference approach based on haptic feedback has been developed in Chap. 7. The approach is based on the analysis of episodic memories recorded during prior task executions. In particular, the recorded end-effector positions are referenced to the recorded Cartesian controller force to interpret nominal contact conditions, contact loss, and external disturbances. A probabilistic model has been applied to assess the quality based on the previously introduced particle model. In case of unpredicted disturbances, the robot is able to apply the reasoning methods introduced in Chap. 5 to plan additional motions in order to improve the task performance. In addition to the qualitative investigations, the tasks have been analyzed semantically by means of the openEASE framework, which is able to relate narratives to the logged sensor stream. Based on this data, this manuscript offers future researchers the possibility to investigate the conducted experiments to foster the development of novel reasoning methods.

Finally, the developed methods have been applied to a relevant scenario, i. e. robotic planetary exploration. While this type of task might be beyond the scope for most humans, space exploration was one of the first areas to utilize unmanned space crafts and rovers for the gain of knowledge. For this reason, the humanoid robot Rollin' Justin was initially developed as space robot assistant. In Chap. 8 it was outlined how the robot was utilized within the METERON project with the aim of advancing the remote control concepts for future robotic space exploration missions. In particular, it was shown how the concept of Action Templates contributes to the SUPVIS Justin experiment, in which Rollin' Justin was controlled by means of high-level commands issued by a tablet computer interface aboard the ISS. With this, Rollin' Justin could be considered *the first cognitive robot to co-operate with an astronaut*. As the mission of the robot was to maintain a solar power plant, the task of cleaning a solar panel was conducted for evaluation. The purpose of the last chapter was to emphasize the relevance of the conducted research w. r. t. the needs of society, and thus conclude the argumentation of this work.

9.2 Discussion

The aim of this work is the generic implementation of human-like cognitive reasoning skills to enable robots to reason about compliant physical interaction. While the main evaluation toward this goal has been conducted w. r. t. particular problem of wiping tasks, conclusions of general relevance can be drawn based on the obtained insights.

One key concept of this manuscript is the application of an object-centric perspective for the development of reasoning methods. This design choice is based on the mindset of affordances (Gibson 1986), which formulates a cognitive science approach to explain the subconscious mental perception of manipulation possibilities with objects. With reference to this, it can be related that object-centric examination of manipulation tasks has an immediate influence on the development of process models in form of Action Templates. Instead of focusing on the robot, a programmer would transfer the problem onto higher levels of abstractions (i. e. the interaction of objects), which leads to more generic solutions. Moreover, the representation of actions and their effects can be separated from kinematic reachability constraints (cf. Sect. 4.4), the description of process models can be designed independently of robot-specific capabilities (cf. Sect. 5.1.1), the controller can be natively parameterized in the Cartesian object-space (cf. Sect. 6.1.2), and the performance of the task execution can be related to object-specific spatial coordinates (cf. Sect. 7.1.2). In this context, objects serve as a well suited common ground to merge high-level reasoning methods and low-level control strategies.

During the elaboration of this manuscript, it has been observed repeatedly that impedance control poses a suitable approach to perform compliant contact. Evidence can be found in the successful execution of several wiping tasks as part of the experiments conducted with the humanoid robot Rollin' Justin. Impedance controlled motions enable a robot to adapt locally w. r. t. the target surface and even comply with uncertainties. The global motion planning problem can this way be reduced to rather simple motions consisting mainly of translations in the object-space. A well parameterized Cartesian stiffness can eventually introduce the necessary rotations to align with the curvature of the target. In this sense, one should exploit the local intelligence of the control level whenever possible, in order to reduce the load for the high-level reasoning framework.

Another major insight is based on the role of effect-space planning, which describes an attempt to represent effects such that planning methods can be developed to explicitly manipulate this representation. In the presented work, this approach has been applied to the domain of wiping tasks. In particular, a particle distribution model has been developed to enable the generic generation of wiping motions w. r. t. abstract goal definitions for the particles. The resulting approach is primarily independent of kinematic reasoning and thus applicable to any robot that is equipped with a manipulator. The proposed planning methods take the actual distribution of the particles into account in order to compute the most efficient tool motions. The quality of the planned motions can therefore be assessed for each step of a plan. This becomes especially valuable if the information is accessible via narrative-enabled episodic memories as it is possible with the openEASE framework. As a result it can be inferred that effect-space planning is of utmost importance for the generic development of robot manipulation skills.

Moreover, effect-space planning constitutes a necessary skill to master everyday manipulation tasks. This became evident ever since it turned out that the particle model is not only able to predict effects, but also to infer the effects of real world wiping motions. This feature would become one of the most compelling characteristics of the newly developed representation. In fact, the combination of planning methods and evaluation methods based on a shared effect representation is of great potential. In the particular case discussed in this work, it allows to assess the efficiency of wiping actions executed by the robot and improve them directly in the effect-space. This feature leads to a significant quality boost as the robot is made aware of its own performance. As a consequence, the robot may put the quality of its own motions into question, especially if it identifies a failure situation, such as the collision with a human. Generally speaking, it is recommended to develop effect representation in such a way that they incorporate both a forward model to predict effects and an inverse model to infer effects likewise.

Finally, it can be confirmed that haptic feedback is a valuable, yet underestimated source of information. It has been shown that a compliant robot can estimate the quality of wiping motions purely based on haptic perception, i. e. the combination of proprioception and contact force information (Gibson 1966). This is especially interesting for scenarios that lack sufficient visual perception due to bad lighting conditions or invisible materials such as liquids or small particles. In spite of the fact that vision is often considered to be the primary sense in robotics, it is highly recommended to fuse visual perception with haptic perception in order to get more reliable data. Accordingly, the application of haptic perception by means of torque sensors, force sensors, and tactile skin should be taken into account whenever possible.

9.3 Open Research Questions

The conducted research disclosed three major open challenges in the context of Intelligent Physical Compliance and robotic manipulation in general. At first, the proposed approach covers the symbol grounding problem for actions in a generalized form. However, a general solution to the symbol grounding problem for effects remains an open problem. This imbalance originates from the fact that actions can be described as a sequence of atomic operations, while it is hardly possible to describe an effect by a set of atomic effects. Moreover, purely symbolic effect descriptions cannot be evaluated in a generic fashion. As a result, one may have to examine each task family individually in order to derive locally generic effect representations, as it was done for wiping tasks in this work.

Second, it is difficult to model actions and effects in such a way that they match every possible instance of a problem. Accordingly, the model parameters for a particular class of tasks have to be fine-tuned for every single trial. However, this is not sufficient for the general deployment of future service robots. These robots will have to optimize model parameters online by means of machine learning algorithms in order to be truly advantageous. This is both desired for the forward model (i. e. the action model) as well as the inverse model (i. e. the effect model). This way, robots may be able to continually improve their effectiveness and eventually catch up with human skill level.

The third research question constitutes on of the most difficult open problems in robotic manipulation, i. e. the detection, isolation, and recovery of arbitrary failure states. This is particularly complicated as the possible failure states exceed the number of nominal states by far. It is unpredictable which kind of error may occur during a task execution. Moreover, there is no generic fallback strategy available to recover from arbitrary failure states. In the worst case a robot may have to replan from scratch or maybe even abort the task execution completely if the task becomes unfeasible. It remains an open question how the required perception and reasoning methods can be integrated into a generic robot control program.

9.4 Outlook

Considering the short-term goals, it is of great relevance to generalize the developed approaches for other manipulation tasks that require both physical compliance and intelligent behavior. One particular example is found in cutting vegetables and other food products with a knife as it was presented by Lenz et al. (2015). The contact force and the cutting motion show a relation that is comparable to that of wiping actions. Therefore it is likely that assertions about the cutting performance can be made based on episodic memories in order to enhance the task performance by adapting the parameters of the controller.

For the long-term, the findings of this work will be utilized to advance the development of cognitive robots. However, before these robots become available for the general public, they will most likely emerge in more distinct domains such as space exploration, healthcare applications, and industrial manufacturing.

The industrial sector has already adopted some of the features of modern robotics. The current trends of the *Internet of Things* and *Industry 4.0* show that the future of manufacturing will be highly concerned with the representation and processing of big amounts of data. The knowledge system developed within this work is capable of handling this demand in a small scale experiment (Nottensteiner et al. 2016). It remains to be seen how semantically annotated episodic memories (e. g. represented as openEASE logs) can be utilized to continuously monitor the task performance of industrial robots by means of haptic effect inference, how the performance can be enhanced, and how failure situations can be detected and predicted, respectively. With this in mind, it will be investigated how the concept of Intelligent Physical Compliance can be adapted for assembly tasks.

The healthcare sector is especially interested in semi-autonomous robotic manipulation w. r. t. the aid of severely impaired persons. People suffering from neuromuscular diseases, stroke, or trauma are often unable to manage their daily life independently and become reliant on 24-h care. In this situation, an assistive robotic manipulator mounted on a wheelchair can provide help and relief. It has been shown that a *Brain-Computer Interface (BCI)* (e. g. surface electromyography electrodes) can be utilized to control such a device, yet it is arduous and difficult (Hochberg et al. 2012; Vogel et al. 2013). To overcome this issue, the reasoning methods developed in this work are currently being adapted to augment the continuous commands of a BCI in order to guide the user in its intended action (Hagengruber et al. 2017). According to the demands of potential users, the most desired tasks for such a robot include physical contact with the person itself, such as eating and drinking, body posture adjustments, and personal hygiene. This close contact to humans makes it mandatory for these robots to react safely at all times, which requires compliant control and intelligent decisions, i. e. Intelligent Physical Compliance.

This work has already contributed to the space sector by providing a novel, context-sensitive UI based on high-level commands within the METERON SUPVIS Justin experiment. Rollin' Justin can be commanded from aboard the ISS to maintain a solar panel farm located on Earth in this fashion. It has been proven that this type of interface is ready to be utilized in future space exploration missions. The necessity for Intelligent Physical Compliance is grounded in the nature of the unknown environment and the delicate instruments. More experiments are scheduled to be conducted in the future to identify the limits of this approach w. r. t. the usability and reliability in case of higher delay and lower bandwidth, the complexity of the task, and the number of simultaneously controllable robots exceeding the maximum cognitive load of an astronaut. The findings may one day contribute to the exploration and colonization of Mars and beyond.

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