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A Cloud-based Control Architecture Design for the Interaction of Industrial Robots with Soft Objects

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Abstract—**In order to control the interaction of industrial robots with soft materials many computationally-intensive subtasks have to be performed in parallel, such as material simulations, control policy optimization or path planning among many others. Since the robot control cannot process the amount of information needed for those tasks, the whole system needs to be split up in two parts: the physical system and the computationally demanding software that runs exclusively in a cloud environment. We analyse the requirements, make the assumptions and define the scope of the system before proposing a novel cloud-based control architecture for industrial robots to manipulate soft materials. A system is set up and evaluated with future challenges identified for the further specification and implementation of the proposed control architecture.**

I. INTRODUCTION

Soft materials are characterised not only by their low stiffness, but also highly nonlinear behaviours [1]. This is why an efficient, robust and safe interaction between robots and soft objects has not been as highly automated as it is for an industrial robot to manipulate hard objects. A multibody system that consists of a robot and soft object cannot only be defined by structured geometries, contact position and contact forces like those for rigid bodies. To achieve an efficient, robust and safe automation, a better understanding of the behaviours of soft materials related to the robotic motion planning and control is in order. Furthermore, the traditional local control concepts show weaknesses in handling tasks with soft objects: they are mostly designed for one special task and do rarely use any information of the object to manipulate [2].

Simulations of the robot-soft-object interaction could provide new insights in interaction mechanisms and manipulation requirements, which would further be used for simulation-based trajectory planning, control optimisation or reinforcement learning of gripping strategies. The simulation itself, as well as the tasks that use it, require a lot of computation power, especially when the constitutional models of the soft materials need being simulated. To take advantage of the additional information, a cloud-based robot control setup is considered, where the overall control architecture is split up in one computationally expensive part in the cloud and the local robot-gripper control system. Due to the flexibility of cloud services, the computing capacity can be scaled with the requirements.

To further elaborate those questions, the Integrated Research Training Group (IRTG) Soft Tissue Robotics has been set up as a multi-disciplinary joint research programme between the universities of Auckland and Stuttgart, where this project is a part of. Within the three main categories *simulation*, *automation* and *biological technical concepts* soft material behaviour and interaction will be investigated, especially focused on biological soft tissues and technical applications with soft materials. Interdisciplinary approaches will be used with the connection of different participating research fields to overcome problems in soft objects handling not with specialised solutions as kinematics, rather with a general understanding of the underlying problem.

Applications of the interaction with soft materials may lie in gluing of door seals in car manufacturing and cable handling, as well as fruit harvesting or meat processing. Also, wiring processes in switch cabinets, currently taking on average 50% of the total building time, may profit from automated handling with the explicit consideration of deformable materials [3].

The rest of the paper is organised as follows. As a preliminary step the related literature is reviewed in context of this project part in Section II. The system architecture concept and requirements definition are specified in Section III. Finally, some concluding remarks and an outlook on the future intentions of this project are given in Section IV.

II. LITERATURE REVIEW

The following section gives a short overview over recent literature in the fields of soft materials modelling, industrial robots control and cloud-based control that are directly relevant to the proposed project.

A. Soft Materials Modelling and Simulation

There exist two distinguished methods to describe the behaviour of soft materials, which are model-free and model-based approaches. Model-free methods have to compensate the lack of a model with utilisation of sensor data in observers, as e. g. in [4], [5]. Model-based methods can be formulated as continuous system or discretised in space. Continuous approaches, based on different assumptions of continuum mechanics, result in constrained partial differential equation (PDE) systems [6]–[8]. Since mostly unsolvable analytically, they have to be discretised either in space with finite element method (FEM) [9], [10] or finite difference method (FDM), and then treated as coupled ordinary differential equations (ODEs) systems [6], [11]. Also, directly discretised, heuristic methods exist as [12] or mass-spring models with optimised meshes [13], or even through discretisation of autowave propagation in the material [14].

Grouping of soft materials through classification is introduced to later generalise tested solutions. Firstly, this can be done by distinguishing the underlying material properties as elasticity (elastic, inelastic, elastoplastic), time-dependency (time-variant, time-invariant) and isotropy (isotropic, anisotropic) [7]. Secondly, the distinction can be made by geometry dimensions. A one-dimensional object like a rope may be modelled with a PDE where the local derivation is one-dimensional, too, whereas a soft body's local derivations depend on all three spatial dimensions. This is inherently done e. g. in [15]–[17]. A third, heuristical method for classifying soft tissues is introduced by Heinrich et al. by distinguishing different regions on a force-deformation diagram which are adapted dependent on the executed task [18].

B. *Control architectures for industrial robots*

In current industrial robotics a common control architecture, pictured in Fig. 1, has been well established and is widely used with minor modifications. Current efforts affecting this common architecture are on one hand made in the direction of multi-robot cooperation [19], where the robot control (RC) is used for the actuation of all participated robots. Single modules of this scheme are further improved, as for the joint control e. g. in [20], [21].

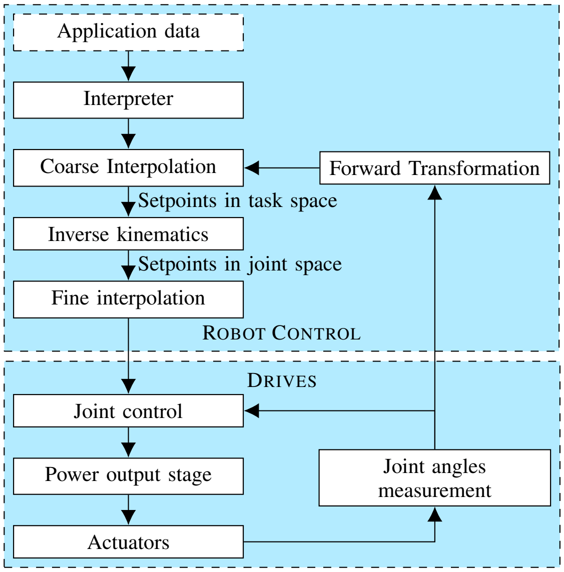

Figure 1. Signal flow diagram of a common robot control architecture, cf. [22].

Reasoning in robot abstraction and a resulting layered system architecture can be seen in [23]. Here, system parts are consequently encapsulated to meet the requirements of formulating complex tasks on task-level. Furthermore, the modular approach decouples the general solution of a task from the underlying robot. Further extensions of this approach into the field of service-oriented and cloud-based control architecture are described in the following section.

C. *Cloud-based control architectures*

Cloud-based control architectures are primarily in the focus of research with the topic of smart manufacturing [24]. An overview over challenges and requirements of cloud-based manufacturing is given in [25], where the basic mechanisms of cloud-computing are transferred to the field of cloud-manufacturing and essential foundations for *manufacturing as a service (MaaS)* are formulated.

Early research in cloud robotics has been done in the robot brain project [26], even before a concrete definition of the term *cloud* has been defined. A generic robot cloud storage has been developed with RoboEarth [27], a cloud communication platform with binding to the open-source robotics platform robot operating system (ROS) has been realised with Rapyuta [28]. But generally, the additional benefit examined in research for cloud robotics is primarily concerned with common data access and knowledge sharing. Recent service-oriented approaches go beyond and offer cloud-based path-planning [29] and even cloud-based control, where the robot control part from Fig. 1 is externalised to a cloud-environment [30], [31]. Since control as a cloud-service requires short cycle times and the theoretical signal speed is limited by the speed of light in optical fibres, the distance to used cloud servers becomes important. This leads to the use of location-aware cloud servers called *fog cloud* [32].

Recent work at our institutes has focused on cloud-based machine tool control [33], [34], robot control with an integrated robot simulation [35], production management [36], developing an ontology for service-oriented business interactions data model [37], [38], assembly optimisation [39], MaaS [25], [40] and the communication mechanisms that form its basis [41].

III. CONCEPT FOR A CLOUD-BASED CONTROL ARCHITECTURE

Based on the literature review from above, this section formulates a concept for the new control architecture. This is accomplished by deriving system requirements in Subsection III-C from the use cases defined in Subsection III-A and the scope of the proposed system, which is outlined in Subsection III-B. A usecase example of cable handling with a robot arm is described in Subsection III-D.

A. *Use cases*

Two main categories of use cases, also shown on the UML diagram in Fig. 2, are to be considered. The first one consists of *motion planning*, where the internal forces and deformations of the soft material have to be predicted beforehand, or accurately estimated online and used for control. Goals of this use case may be to plan a motion around obstacles for a soft object handled by a robot with, additionally to traditional collision avoidance problems, neither damaging the object nor the obstacles, even under dynamic deformation of the objects during the task. This may be the case for transporting cables from one point to another, where swinging of loose ends has to be considered in trajectory planning. The second use case aims for different *control tasks* that may be formalised with the soft material, where the soft object may be treated as an extension of the robot geometry. This includes the requirement of bringing static poses (pose: position and orientation) on a soft material close to a pose in task space ($\subset \mathbb{R}^6$). The target pose may be static or moving itself for a motion control application, also the poses on the soft material may move on the local coordinate system of itself, as it is the case for gluing, where the location to glue moves on the object during the process. Moreover, this use case contains the control of forces at points on the border of soft materials, which is relevant for tasks as inserting a cable into its connector where force sensitive handling is required.

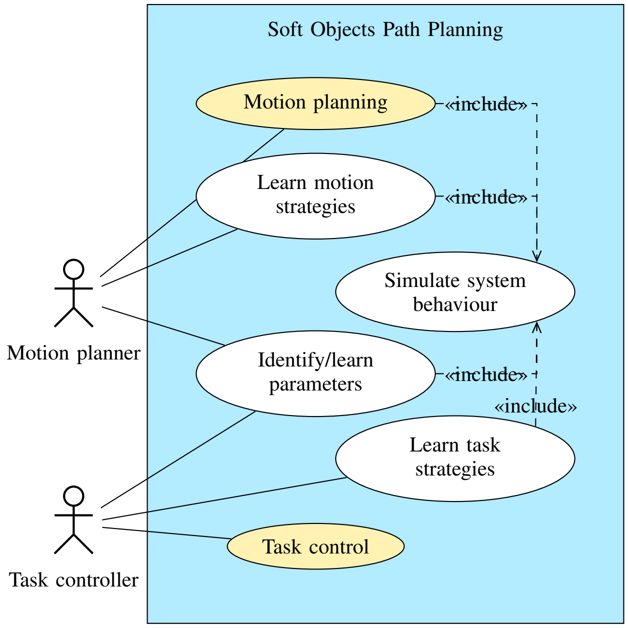

Figure 2. UML use case diagram of central use cases for path planning soft objects. Implicitly contained is the need for a simulation environment. The central use cases, motion planning and task control, are highlighted.

The main use cases, motion planning and task control, are common in that they do not modify the behaviour of the RC rather set the trajectory of the robot-material system. The difference between them is mainly characterised with the knowledge of internal state variables in motion planning. The motion planning also may access information from the soft object simulation, whereas the task control solely relies on feedback. This is also shown in Fig. 2, where the task control does not need to include the system's simulation.

Both main use cases require knowledge about the behaviour of the material. This may be represented in variously detailed models of the soft materials, beginning from simple material parameter sets, such as shear modulus and modulus of elasticity, up to complex FEM models. Motion planning algorithms may directly use the model information to predict the material's behaviour during the planned motion. In order for task control algorithms to use the model information to access directly non-accessible state variables of the soft object, such as internal stress and strain, the real-time requirements due to the cycle times of the task control have to be met. This implies the requirement of simple and real-time capable models for soft objects. If and for which classes of soft materials such drastically reduced models exist and are feasible with current technologies is still not clear today and also the research topic of another project within the IRTG Soft Tissue Robotics. Hence, the inclusion of simulation information in task control algorithms will not be investigated for now.

Once a model is parameterised and evaluated against the real soft material it can further be used e. g. for extracting and testing strategies for gripping or motion planning. As such applications also need a simulation model of the robot and gripper, the latter ones also have to be included in the simulation environment. This simulation setup allows to run many simulations in parallel at the same time to shorten the duration of all not real-time processing tasks (e. g. trajectory planning) with the number of simulation instances used.

B. System boundaries and assumptions

Since the overall goal lies in advancing the soft material interaction with non-specialised robots, the chosen scope excludes inter-company and planning aspects of cloud computing, such as ordering mechanisms, billing and resource planning tasks.

The robot chosen is restricted to traditional serial kinematics. For simplicity reasons, the RC together with the basic kinematics of the robot (including the gripper) are regarded as a black-box system, taking external trajectory signals and following them with sufficient accuracy under the assumption that the given trajectory is realizable with respect to the chosen robot kinematics and dimensions, e. g. the maximum acceleration of the joints is never reached. Thus, the RC-robot system's dynamics, also shown in Fig. 3, do not have to be simulated and a simulation of the soft object including the constraints of gripper trajectories is sufficient.

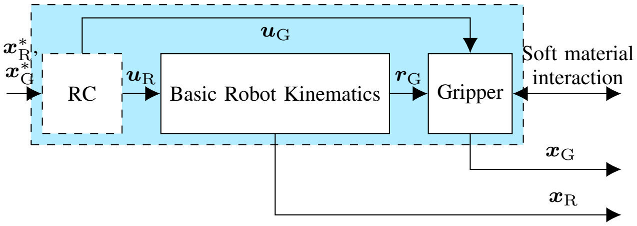

Figure 3. System boundary of neglected dynamics between robot and RC with desired robot/gripper states $\boldsymbol{x}_\mathrm{R}^*/\boldsymbol{x}_\mathrm{G}^*$, real robot/gripper states $\boldsymbol{x}_\mathrm{R}/\boldsymbol{x}_\mathrm{G}$, control inputs for robot and gripper $\boldsymbol{u}_\mathrm{R}$ and $\boldsymbol{u}_\mathrm{G}$ and gripper pose $\boldsymbol{r}_\mathrm{G}$.

Furthermore, to focus on soft objects handling the connected research topics of real-time cloud-control, human-robot interaction are not treated within this project.

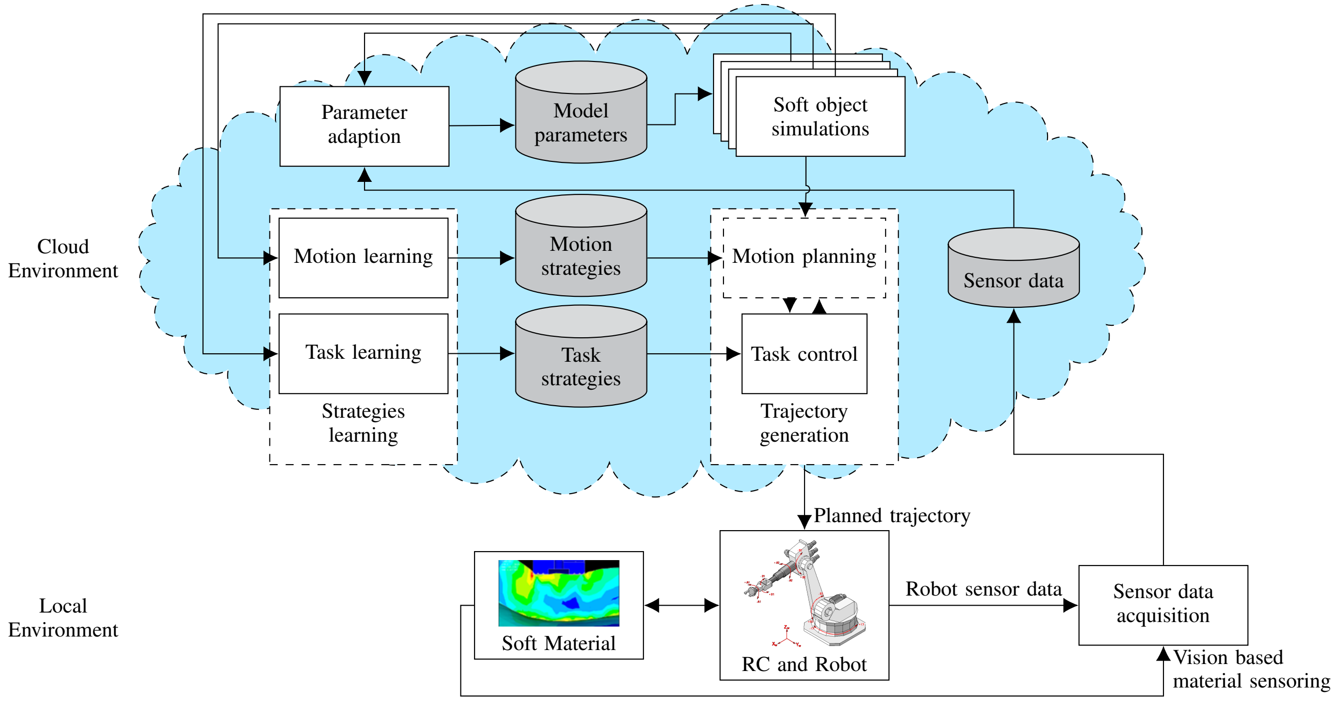

Figure 4. Overview of the communication flow of the planned system setup for handling Soft Tissues with a serial robot kinematics. Non real-time components are outsourced to a modular cloud environment.

C. System setup

The general system architecture is derived from the use cases and system boundaries of the previous sections, as well as general cloud architecture concepts proposed in [25], [42]. The main novelty of this setup lies in the integrated soft material simulation, which is accessed by other system components to interact with soft objects without the need for a special robot kinematics. A diagram of the overall system's communication is shown in Fig. 4. Robot sensor data, as joint angles and image-based sensor data of soft object position and deformation are processed in the sensor data acquisition and stored in a database. The parameter adaption component optimises the model parameters of the simulation by validation against stored sensor data. Strategies can be learned with multiple soft-object simulations whose outcomes are subsequently evaluated with respect to a policy function. Afterwards, they build a rule set for task-planning in the trajectory generation. Task planning for the robot motion is then accomplished by the two general use cases motion planning and task control identified in Subsection III-A. The motion planning task also runs simulations for accessing the internal material state, whereas the task control does not. Since some tasks require both, motion planning and task control, they are planned to be interoperable.

System components to be outsourced to the cloud are determined by their need for real-time computation. Every component, that does not need to be run cyclic in real-time runs as a service in the cloud. Since the trajectory generation component is planned to make use of the (non real-time capable) soft material simulation it can be realised as a cloud component itself. As communication times cannot be guaranteed in this case, the possibilities of the trajectory generation are also limited to either a fully offline generation of the whole trajectories before the robot's task or a quasi-static approach with enough trajectory values buffered in a look-ahead storage such that the execution can be ensured under usual network conditions. Still, in case that the network latency is higher than planned, the execution of the task may have to be interrupted with the quasi-static approach.

To meet changing requirements of components, the system has to be designed extensible and modular. A loose coupling between the different modules is intended to minimise the communication effort and simplify the exchanging of modules.

The communication itself can be realised with decentralised machine to machine protocols. Recent protocols, such as Open Platform Communications Unified Architecture (OPC UA) [43] support a publisher subscriber model, where participants are able to subscribe for specific information channels. Data to be exchanged in the communication process have to be specified, which is challenging for the dynamic contact points between the gripper and the soft object.

Finally, the interfaces that will be provided by system parts have to be developed in a way that enables their easy exchange. Different abstraction layers are introduced in each component as suggested by [23], [25] and sketched in Fig. 5. Software and hardware elements as well as their capabilities are abstracted by the *resource layer*, where common interfaces for higher level access are provided. The *virtual service layer* integrates different resources to services that can be accom-

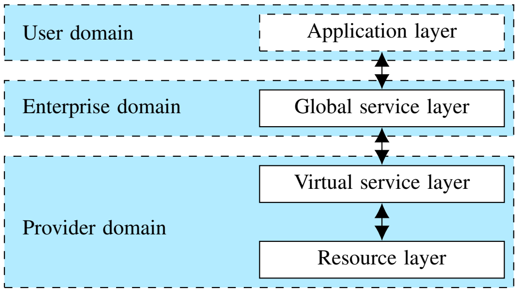

Figure 5. Layered architecture layout for abstraction and encapsulation of system components as described in [25].

plished with their use. For example, the parameter adaption from Fig. 4 is provided in the virtual service layer and accesses components from the resource layer, such as the model parameters database and different soft object simulations. In addition, available participants in the resource layer have to be detected and integrated into the overall system, which is also a task of the virtual service layer. The *global service layer* operates the overall interaction of the cloud. Offering services to its users and role-management is part of it as well as management of computation resources and accounting tasks as billing of customers for their used services, which will not be part of this project. The application layer connects to the services offered by the global service layer and provides applications directly to the user.

The software components may be virtualised by running them either in virtual machines or in containersproviding a packaged version of the software itself and all of its dependencies. Such virtualised components may be cloned for running the same simulation in multiple instances and can be integrated in different cloud server environments without much additional effort. Furthermore, multiple components are able to run on the same computer for optimal processing load and, together with a decentralised network communication protocol, also for shorter inter-component communication times since messages on the same computer can be passed via local loopback.

D. Application on a wiring setup

The scenario of a robot arm with a wiring task, e. g. for a switch cabinet, is described subsequently to exemplify the general system setup, where the soft objects to handle are cables. A first step consists of a visual detection of the cable to handle and the determination of suitable grasping points. The grasping motion is planned and executed. The only part needing knowledge of the cable's material properties is the closing motion of the gripper that has to be force controlled to avoid slipping or cable damage.

As soon as the robot holds a cable, the cable's simulation is incorporated as a key part in the system. The two typical tasks after gripping are laying the cables in cable channels and inserting a cable end into a connector. Cable laying is a control task in which the target point is moving along the material's length coordinate as the point to lay down next changes over time, cable end insertion is a control task with fixed point of interest. To reach the start pose for the control tasks, motion planning is used, which may be under several constraints as minimizing the transition time and simultaneously considering the kinematic and dynamic capabilities. Since the cable ends protrude from the gripper, its motion is to be considered in any planning step. Strategies for those tasks and the required motion planning are calculated with multiple instances of the cable simulation beforehand and are applied to the current situation. Sensor data is collected and stored simultaneously to task execution to improve the accuracy of the cable simulations via machine learning.

IV. CONCLUSIONS

An approach for a service-oriented clod architecture tailored for the interaction of industrial robots with soft objects has been presented as thematic positioning of this project part within the IRTG Soft Tissue Robotics research programme. Since the main topic of the IRTG lies on a better understanding of the behaviour of soft materials, the central element of the proposed system setup is chosen to be a simulation, which is able to predict the material's behaviour needed for robot motions provided by motion planning or learning constituents. Massive parallelisation in the cloud is brought up to reduce calculation times. Abstraction and virtualisation are introduced as architecture methodology for defining replaceable and exchangeable software and hardware components, which have to be integrated in the cloud environment. Additionally, these concepts allow to later extend the system to adapt to further requirements.

A. Outlook

The next steps lie in concretizing the control architecture regarding the definition of single system components and interfaces and embedding them into their according abstraction layers of Fig. 5.

Together with other IRTG projects concerned with machine learning and object localisation we intend to advance in the direction of handling tasks with deformable linear objects [15], [17], as cables and wiring applications at first, where the principal location dependency in the underlying partial differential model equations is only one-dimensional. The overall concept is however planned to be kept as universal as possible, that the general approach can be transferred, e. g. to agricultural and biomedical use-cases.

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