Simulation in Produktion und Logistik
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From space to manufacturing industry: New approaches of eRobotics to serve todays and future manufacturing needs

Aus dem Weltraum in die Industrie: Neue Ansätze der eRobotik, um heutige und zukünftige Anforderungen der Industrie zu erfüllen

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Abstract: This work presents our current efforts in the development of a comprehensive, versatile and holistic simulation platform to address robot-related issues in manufacturing. Along the lines of research of eRobotics that effectively extends the well-known virtual test-bed concept, we shift robotics into virtual reality. We adequately couple different multi-body modelling and robot control paradigms to provide efficient, flexible and sustainable solutions to torque based motion planning, motion control and compliance control of robot manipulators regardless of their generation or deployment areas. The approach is particularly useful as it enhances the reliability of predictions, and offers unique possibilities to get novice users very early familiar with recent advances in service robotics. To this end, the proposed simulation approach also supports natural and intuitive interfaces, which become an effective surrogate for complex control panels, leading to a user-friendly robot manipulation.

1 Introduction

3D Simulation technology is widespread in manufacturing today. Particularly in robot-assisted manufacturing, it is usually the method of choice to quickly pre-configure a work-cell or to plan tasks (see Tokunaga et al. (2005)). However, there is often a considerable gap between the objectives that motivate the utilization of simulation in manufacturing and the outcomes driven by the simulation. Specifically, the reliability of predictions and the capability to facilitate the integration and manipulation of new generations of robot manipulators are significantly altered by different factors, stemming from the conceptual limits of the simulation approach and the lack of versatility to swiftly adapt to recent advances in service robotics. These factors include the difficulties to provide a simulation that closely reflects the dynamic behaviour of real robot manipulators during manufacturing tasks and to cope with new demands (see Tincknell and Radcliffe (1996)) in manufacturing.

Interaction capabilities are very crucial for the feeling of involvement of humans into simulated scenarios. Humans can interactively experience and manipulate disparate objects and the simulation system responds to their actions. However, using proprietary control panels might sometimes require some technical expertise, therefore being too complex for novice users. The support of natural, flexible and intuitive interfaces (see Fig. 1) can mitigate this issue, improving the immersion and proficiency of any user, and allowing the interactive assessment of core technologies such as compliance control at a high level of safety and flexibility.

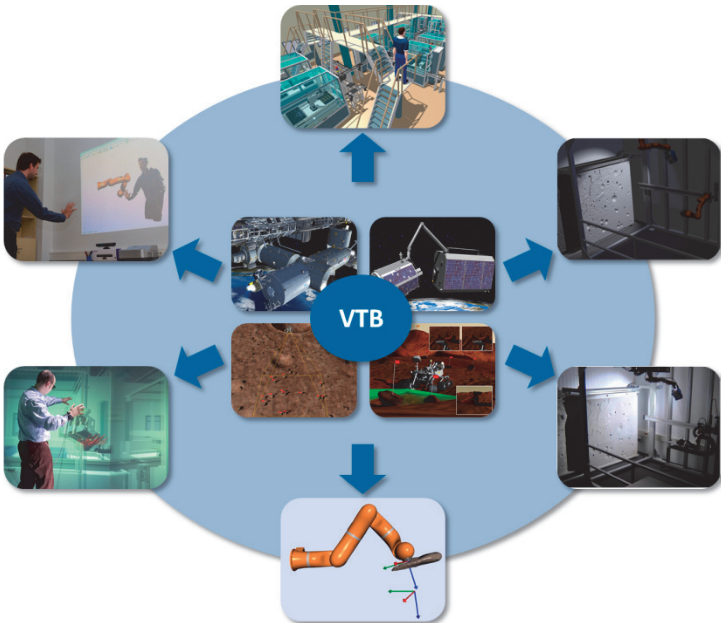

Figure 1: *Know-how gained from space robotics is transferred to manufacturing. Intuitive interfaces (left), real (bottom right) and simulated (top right) robots, simulated compliance control (bottom) and virtual factory (top).*

This work presents our current efforts in developing a simulation platform aiming at filling these niches. Our contribution is twofold. At first, along the lines of research of eRobotics (see Rossmann and Schluse (2011); Rossmann et al. (2012)) that effectively extends the well-known virtual test-bed concept and transfers experiences gained in space robotics into other areas including manufacturing (see Fig. 1), we present a realistic robot simulation that integrates kinematic robot motion planning and dynamic robot motion control down to actuation. Also, we highlight and exemplify the benefits of shifting robotics into virtual reality as a means to support the integration of new robotic technologies in the manufacturing industry and to enhance the ease of use of robot manipulators.

The remainder of the paper is structured as follows. Related works are presented in section 2. The key ideas behind eRobotics as the foundation stone for efficient and sustainable solutions in robot-assisted manufacturing applications are introduced in section 3. Section 4 is devoted to the robot motion planning and control architecture in joint and Cartesian space as well as compliance control. How virtual reality enhances the interaction capabilities of robotic systems, as well as their ease of manipulation through intuitive interfaces is introduced in section 5. Section 6 is for conclusion and discussion.

2 Related work

Robot simulation has been adopted in manufacturing as a strategic approach to improve the manufacturing cycle time and throughput (Stopper and Stuja 2004). It plays a key role in the detection of inefficiencies and opportunities in robot-assisted automation (see Neto et al. (2010)) and the prediction of the side effects of making changes (Smith et al. 1994). These approaches rely solely on a kinematic simulation of the robot manipulator. In manufacturing, task contacts and control contacts occur between the end-link and the work-piece (Kuhn et al. 2006). Then, the latter is grasped by the robot to follow a trajectory that has been generated by a kinematics controller. Here, the degree of realism would be substantially increased by modelling the work-piece and the robot end-link as physically interacting bodies with specific material properties that can accelerate under non-penetration constraints.

By strengthening a kinematic planning with a dynamic simulation and robot actuation control, the outcome of the task mentioned above closely depends on the robot guidance and on the physical interaction between the bodies. Some dynamic robot simulators are based upon generalized coordinates (i.e. joint coordinates). This approach can hardly handle arbitrary set of constraints between multi-bodies (see Baraff (1996)) in manufacturing scenarios. Further, the dynamic realization of the joint path prescribed by the kinematic planner might suffer from different effects such as frictions (see Fig. 2) that are inherent to real robots.

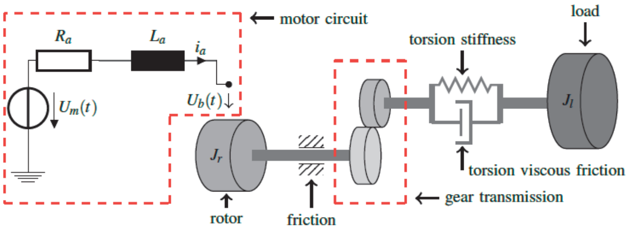

Figure 2: *The drive train model in this work that includes friction losses*

Therefore, unlike all the simulation approaches mentioned above that have neglected this aspect, it is important to extend a joint level power transmission down to actuation (see Fig. 2). Torque losses are very important, when it comes to reactively adjust the robot dynamics as reaction to external forces or torques. Such a capability is useful for teaching a robot manipulator by touch (Grunwald, et al. 2003). Advances in torque based compliance control have led to a new generation of compliant light weight robot (LWR) manipulators that cope with this issue (Ott et al. 2004).

Nevertheless, despite their unique capabilities, only a few works have addressed the simulation of compliance control (Dixon et al. 2001; Behzadpour et al. 2009). While the former work has omitted orientation control, that is, indeed, more complicated (see Nakanishi et al. (2008)), a versatile environment that supports complex interaction scenarios based upon real human motion is not provided. This is important when it comes to assess human-centered simulation processes within the manufacturing context (Zhang et al. 2008).

Some efforts have been made to integrate real human motion into 3D simulation. In particular, Microsoft's Kinect sensor that offers new capabilities for 3D image capture and human gesture recognition has been used to capture human arm motion (Al-Kaff et al. (2012)) or to avoid collisions (Petric and Zlajpah (2011)). However, a full dynamic multi-body simulation is missing in aforementioned works. An approach for human-robot interactive demonstration has been proposed in Cheng et al. (2012), but no strategy to accommodate the dynamic robot behaviour during the interaction was taken into account.

3 eRobotics and virtual reality

In this work, the goals pursued are, on the one side, to uniformly accompany the integration, understanding and analysis of traditional robots as well as new generations of compliant LWR manipulators within the manufacturing context. On the other side, the benefits that result from the synergy between virtual reality and robotics has to be maximized and exploited to overcome common issues related to robotic hardware, for instance, in terms of fast scenario analysis, component re-use, development costs and development time constraints. In addition, the capabilities of robotic systems can be extended through the integration of new functionalities, including the support of diverse user interfaces to enhance the ease of manipulation.

Reaching these goals set demanding requirements on a simulation platform that arise from the complexity of the problem at hand and the expectations when it comes to address such a multidisciplinary issue. The former aspect is related to the fact that it is indispensable to capture the key properties and specificities of the single heterogeneous and multidisciplinary sub-systems (e.g. humans, robots, etc.) involved in the simulated scenarios (see Fig. 1). The latter aspect strictly requires a faithful, holistic and versatile simulation of the overall system as a whole in order to best cope with complex scenarios and new demands.

To realize these objectives, we exploit the comprehensive, unique capabilities of eRobotics (Rossmann and Schluse 2011). The eRobotics methodology can be apprehended as an efficient extension of the well-known virtual test bed approach. It puts a great emphasis on collaborative development and distributed high computing performance to transfer know-how gained from space robotics activities to other research and application areas (see Fig. 1), including industrial automation and manufacturing (Rossmann et al. 2012). The key principles stressed by eRobotics to successfully address above mentioned issues are a realistic, holistic simulation approach that is flexible, scalable and swiftly adaptable to new demands in manufacturing, expandable to almost any other application and research field while substantially cutting down costs.

4 Motion planning and control of robot manipulators

We couple together different multi-body simulation paradigms and combine their respective strengths in order to provide a comprehensive multi-body simulation that supports the most complex multi-body constraints. The approach allows a realistic, systematic modelling, planning and control of a wide range of robot manipulators. The highly modular coupling approach is shown in Figure 3.

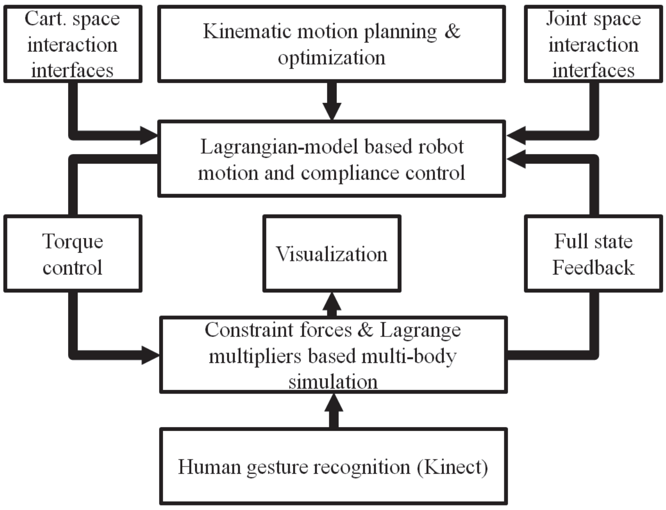

***Figure 3:** Coupled modelling, simulation, control and interaction paradigms*

We will give a short overview of the motion planning and control modules below.

4.1 Kinematics module

The kinematics block serves as motion planning and motion optimization module both in joint and Cartesian space. It supports the usual industrial robot motion types including continuous-path, point-to-point and circular path, as well as the optimization in real time of second constraints by using kinematic null-space motions that characterize redundant robot manipulators such as a LWR. One of the particularities of the kinematics module is that it allows the modelling of multi-robots that are controlled as multi-agent systems. This approach is useful for the coordination of robot manipulators as well as work-flow optimization in manufacturing (see Fig. 1) and the modelling of the human body to analyse ergonomic conditions at manual manufacturing workspaces (Schlette and Rossmann 2009).

4.2 Multi-body dynamics module

A key objective during the development of the multi-body dynamics module was to provide a uniform handling of disparate constraints (contact, impact, non-holonomic constraints, etc.) that might occur between interacting bodies and that are specific to manufacturing systems (e.g. a rotating flexible joint between two bodies). To tackle this issue, the multi-body dynamics simulation used to model the robot as well as its surrounding environment (human, work-cell, work-pieces, etc.) is based upon the Lagrange multipliers and constraint forces formalism (Jung 2011).

4.3 Robot motion control module

The dynamic robot motion control receives desired joint profiles (i.e. position, velocity and acceleration) from the kinematics module and controls the joint torques in such a way that the dynamic robot model tracks the wished joint motion without overshooting. Unlike the constraints based robot simulation introduced above, the robot control in this work relies on a Lagrangian robot model expressed in joint coordinates (Ott et al. 2004).

4.3.1 Joint space motion control

In free space, the robot motion is controlled using the computed torque method. The robot is feedback-linearized at acceleration level and a global exponential stability is given. This approach is particularly useful as it allows a highly accurate overshooting-free path tracking. In case of hard external disturbances, a passivity based feed-forward and PD-control is used for trajectory tracking. The latter turned out to be more robust in such a case as the computed torque method.

4.3.2 Cartesian space motion control

Controlling the motion of the TCP in Cartesian space is not only a natural choice, it is also an intuitive approach. According to the torque superposition principle in operational space, we decouple the control torque τ_c in two terms.

$$\tau_c = \tau_T + \tau_N \tag{1}$$

The term τ_T τ_T corresponds to joint torques related to the operational force moving the TCP dynamics in all six DoFs. A quaternion based parameterization of the TCP orientation was developed. As the robot might be redundant, the entire robot configuration cannot be described in Cartesian space. In fact, the pseudo-inertia matrix associated with the equation of motion in Cartesian space does not depend on the TCP pose anymore, but rather on the joint configuration. Therefore, the second term τ_N stabilizes the null-space motion by projecting the negative gradient of the cost function of a second constraint in addition to a joint velocity dependent damping term onto the null-space of the transposed TCP-Jacobian. The null-space is built upon the dynamically consistent pseudo-inverse of the TCP-Jacobian (Oetomo et al. 2002). A typical second constraint we support is the desired robot posture during Cartesian motion control.

4.3.3 *Compliance control*

The robot manipulator is made compliant for interaction purposes (see Fig. 4) with the environment by imposing a dynamic relationship (mass-damper-spring) between the forces and moments acting on the TCP and the time derivatives of the TCP pose error with respect to the desired pose. The desired inertia matrix is set equal to the operation space pseudo-inertia matrix. Doing so has the advantage that we do not need to measure external force acting on the TCP. The sum of TCP pose and velocity error weighted respectively with the corresponding damping and stiffness matrix is seen as the virtual force acting on the TCP. Besides the gravity compensation term, the posture is controlled with the same approach outlined in the Cartesian position control.

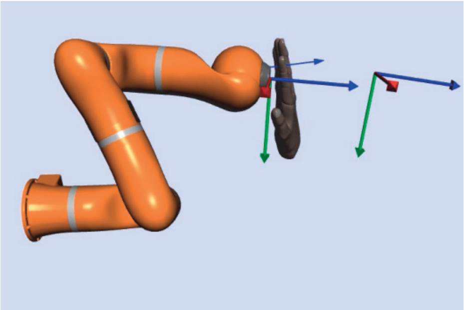

Figure 4: *Interaction with a virtual compliant LWR manipulator*

5 User-friendly robot guidance

Programming simple motion for a robot manipulator by using traditional control panels is a tedious and time-consuming task. In order to make such tasks easier even for novice users, we replace traditional control panels by intuitive interfaces. The human intention is captured over these interfaces and processed in the simulation. The latter commands joint positions that best suit to the human intention.

5.1 Microsoft Kinect based control

A first approach is to develop interaction capability between a virtual human with real life motion of a human and the simulated and compliance controlled robot manipulator. We use the Microsoft Kinect sensor as gesture recognition. It provides a kinematic skeleton of the human in real-time. In order to interact with the robot, the skeleton is endowed with rigid body capabilities and material specificities (e.g. stiffness). The dynamic motion of the virtual human is projected onto the multi-body simulation (see Fig. 5). Doing so, the human operator can easily superimpose his/her motion over the compliant robot dynamics. This interaction can be further projected onto quotidian manufacturing activities, whether to get users familiar with compliant robots within their working fields or to assess their benefits and performance.

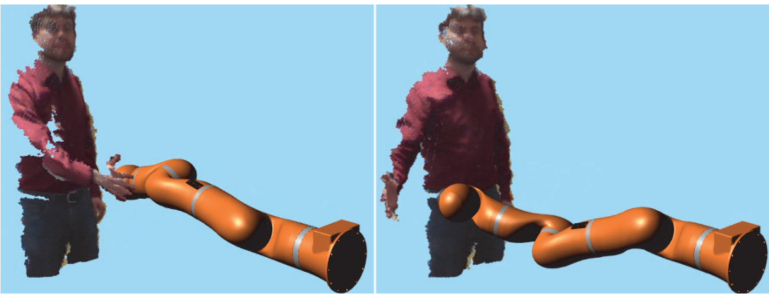

Figure 5: *Microsoft Kinect based interaction with a virtual compliant LWR manipulator*

5.2 Space-mouse based control

Certain tasks such as the guidance of a robot mounted camera require a specific TCP-centered guidance of the robot manipulator. Traditional control panels are rather unwieldy for such a task. Here, a simple space-mouse becomes an effective surrogate for complex control panels. The simulated, Cartesian or impedance controlled robot follows the TCP frame specified by using the space-mouse. Doing so allows novice operators a more natural, flexible and intuitive interaction in real-time with the tool center point of a robot in the full 6 DoF. If required, the generated joint motions are fed into the real robot control to achieve the simulated task.

6 Conclusion

Our current development efforts in providing a platform that enables a realistic simulation of robot manipulators to serve current and future needs in the manufacturing industry have been presented. We particularly used the comprehensive unique capabilities of eRobotics to couple a kinematics planning, a constraint-forces based dynamic simulation of multi-bodies and a Lagrangian-model based control of torque to command simulated robot manipulators in joint and Cartesian space as well as in compliant mode. While the former two control modes enhance the realism of simulation and therefore allow a more accurate prediction and physical tasks planning, compliance control in a simulator will foster the early and safe familiarization of novice users with future compliant robots. Moreover, it offers the possibility to assess the unique capabilities of compliant robots in a wide range of manufacturing applications. This will be possible in almost any environment, with substantially less engineering and portability effort with regard to outdated, current and future generation of robot manipulator such as LWR and at low costs. In our approach, computer simulation acts as a bridge between intuitive interfaces and real hardware, enabling the enhancement of the ease-for-manipulation of robots in manufacturing activities.

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