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Segmental Angular Momenta Analysis in Perturbed Human Walking for Stability of Lower Limb Exoskeleton

Je Hyung Jung¹, Silvia Fernández Portela², and Jan Veneman¹

¹Neurorehabilitation Area, Health Division, TECNALIA, San Sebastian, Spain. {jehyung.jung, jan.veneman}@tecnalia.com
²Tecnun, University of Navarra, San Sebastian, Spain. a902563@alumni.tecnun.es

Abstract - This paper presents preliminary results of segmental angular momenta analysis in human walking subjected to lateral pelvic perturbations. The results show that angular momenta of specific segments, right upper leg and right foot in the study, were mostly affected by the applied perturbations. This finding will be further utilized to develop a perturbation detection method for monitoring stability while lower limb exoskeleton-supported walking.

Keywords—Angular momentum; walking; perturbation

I. INTRODUCTION

Recently angular momentum has been in the spotlight as it facilitates to not only describe the logic behind human walking dynamics but also control postural balance of bipedal robots [1]. Up to date, Centroidal Angular Momentum (CAM), referring to angular momentum at the center of mass, has been mainly examined and few studies on Segmental Angular Momenta (SAM) have been presented. Moreover, few results dealing with perturbed walking have been demonstrated [2]. In this paper, we present the results of SAM analysis in human walking subjected to lateral pelvic perturbations using a statistical approach. The benefit of the use of SAM over CAM is to require less sensor sets as well as computing power in monitoring gait stability.

II. METHOD

Kinematic data of 7 body segments shown in TABLE I of a healthy subject were measured while straight walking on a customized treadmill. Total forty lateral perturbations, applied at the pelvis timed immediately after right toe off, were randomly generated while walking. Details of the experimental setup as well as recording data are found in [3]. Using the recorded data, the mean of normalized SAM for forty unperturbed gait cycles were calculated followed by the calculation of normalized SAM for forty perturbed gait cycles. Then, the root mean square errors (RMSE) of SAM were computed by

\[ RMSE_i = \sqrt{\frac{\sum_{k=1}^{N} (X_{p,k} - X'_{w,k})^2}{N}} \]  

(1)

where \(X_{p,k}\) denotes each SAM in \(j\) direction (X,Y and Z) at the \(k\)-th sampling instance under the \(i\)-th perturbation (i=1,...,40), \(X'_{w,k}\) the mean of each SAM in \(j\) direction at the \(k\)-th sampling instance in the unperturbed walking, and \(N\) total number of the samples in each gait cycle. The RMSE of the selected forty unperturbed gait cycles were also calculated for One-way ANOVA test.

III. RESULTS

TABLE I shows the results of statistical analysis. While angular momenta of most segments are significantly affected by the perturbations, the Y directional angular momenta of RLL and RF have the smallest p-values. This finding can be explained by the onset timing of the perturbations when the right leg is in swing phase, resulting in large reaction of the right leg in order to compensate the perturbations.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Axis</th>
<th>Walking (Mean±SD of RMSE)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Unperturbed</td>
<td>Perturbed</td>
</tr>
<tr>
<td>HAT (Head, trunk)</td>
<td>X</td>
<td>0.0205±0.0028</td>
<td>0.0015±0.0004</td>
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<tr>
<td></td>
<td>Y</td>
<td>0.0002±0.0001</td>
<td>0.0001±0.0000</td>
</tr>
<tr>
<td></td>
<td>Z</td>
<td>0.0000±0.0000</td>
<td>0.0000±0.0000</td>
</tr>
<tr>
<td>Right Upper Leg (RUL)</td>
<td>X</td>
<td>0.0042±0.0014</td>
<td>0.0055±0.0003</td>
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<tr>
<td></td>
<td>Y</td>
<td>0.0017±0.0005</td>
<td>0.0022±0.0006</td>
</tr>
<tr>
<td></td>
<td>Z</td>
<td>0.0021±0.0006</td>
<td>0.0028±0.0004</td>
</tr>
<tr>
<td>Left Upper Leg (LUL)</td>
<td>X</td>
<td>0.0042±0.0012</td>
<td>0.0057±0.0002</td>
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<tr>
<td></td>
<td>Y</td>
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<tr>
<td></td>
<td>Z</td>
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<td>0.0029±0.0003</td>
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<tr>
<td>Right Lower Leg (RLL)</td>
<td>X</td>
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<td>0.0001±0.0000</td>
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<tr>
<td></td>
<td>Y</td>
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</tr>
<tr>
<td></td>
<td>Z</td>
<td>0.0007±0.0001</td>
<td>0.0010±0.0001</td>
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<tr>
<td>Left Lower Leg (LLL)</td>
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<td>0.0097±0.0039</td>
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<tr>
<td></td>
<td>Z</td>
<td>0.0014±0.0001</td>
<td>0.0015±0.0001</td>
</tr>
<tr>
<td>Right Foot (RF)</td>
<td>X</td>
<td>0.0021±0.0005</td>
<td>0.0024±0.0006</td>
</tr>
<tr>
<td></td>
<td>Y</td>
<td>0.0001±0.0000</td>
<td>0.0001±0.0000</td>
</tr>
<tr>
<td></td>
<td>Z</td>
<td>0.0000±0.0000</td>
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</tr>
<tr>
<td>Left Foot (LF)</td>
<td>X</td>
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<tr>
<td></td>
<td>Z</td>
<td>0.0008±0.0001</td>
<td>0.0011±0.0001</td>
</tr>
</tbody>
</table>


IV. CONCLUSION

We presented analysis results of segmental angular momenta while perturbed walking. The results reveal that specific segments are most dominantly affected by the applied perturbations. Further study will be to incorporate this finding into online perturbation detection that is useful to monitor stability while walking supported by a lower-limb exoskeleton.

ACKNOWLEDGMENT

Authors wish to thank Mark Vlutters from University of Twente for performing the experiment and providing the recorded data.

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Collision Avoidance for Human-Robot Interaction Distinguishing between Static and Dynamic Obstacles

Angelika Zube, Christian Frese

Abstract — In this contribution, a Model Predictive Control approach for collision avoidance of (mobile) manipulators is extended to handle static and dynamic obstacles in a different way. This is necessary to allow the robot to move close to known static obstacles like tables and at the same time to maximize the distance to dynamic obstacles like humans to ensure safety. However, in both cases collision avoidance has to be guaranteed.

I. CARTESIAN NONLINEAR MODEL PREDICTIVE CONTROL FOR COLLISION AVOIDANCE

For redundant (mobile) manipulators in shared human-robot workspaces, control algorithms are necessary that allow the robot to perform a task defined in the Cartesian space and that simultaneously realize additionally desired robot behaviors like avoiding collisions with humans or other obstacles. Therefore, a Nonlinear Model Predictive Control (NMPC) approach has been developed to move the end-effector of a redundant robot along a reference trajectory by computing optimal joint velocities [1]. Joint constraints are directly considered during the optimization. Due to the underlying general kinematic robot model, the control algorithm is applicable to both fixed-base and mobile manipulators.

The Cartesian Nonlinear Model Predictive Controller is extended to avoid collisions with static or dynamic obstacles. But the required reaction to obstacles depends on the obstacle type. In the case of static obstacles (e.g., tables), the robot is allowed to move very close to the obstacle as the obstacle does not move unpredictably. In the case of dynamic obstacles (e.g., humans), the robot should maximize the distance to the obstacle as far as its task execution is not impeded in order to increase safety.

For both static and dynamic obstacles, collision avoidance is achieved by adding inequality constraints to the optimization problem of the Cartesian Nonlinear Model Predictive Controller which require that the minimum distance between the robot and the obstacles is greater than a safety distance.

Only in the case of dynamic obstacles, additionally a cost function extension is introduced that penalizes small distances between the robot and the dynamic obstacle. Due to this extension, the robot is pushed away from the dynamic obstacles while at the same time the robot end-effector follows the reference trajectory as close as possible.

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The authors are with Fraunhofer Institute of Optronics, System Technologies and Image Exploitation IOSB, Fraunhoferstr. 1, 76131 Karlsruhe, Germany, {firstname.lastname}@iosb.fraunhofer.de

II. WORKSPACE MONITORING

In [2], a 3D workspace monitoring method based on depth sensors has been developed that represents the space occupied or occluded by obstacles in an octree. As no further information on the obstacles detected by the workspace monitoring algorithm is available, these obstacles are treated as potentially dynamic obstacles to in order to guarantee safety in the worst case as well. Static obstacles which the robot may or even has to approach as, e.g., tables are known a-priori. 3D models of these static obstacles can be obtained for example by mapping. They are removed from the octree representation of potentially dynamic obstacles and are represented in a separate data structure to be handled as static obstacles by the collision avoidance algorithm.

III. RESULTS

The proposed algorithms are applied to an omnidirectional mobile manipulator with 10 degrees of freedom. For monitoring the robot environment, the robot is equipped with two laser scanners and two Kinect sensors. The figure below shows a snapshot of an experimental scenario including the obstacle representation and the mobile manipulator. The robot is able to move close to the table on its left side without any collision, as the table is known as static obstacle, while the robot is increasing the distance to the human (dynamic obstacle) behind the robot as far as possible.

REFERENCES

A framework for task allocation in collaborative industrial assembly processes

Lars Johannsmeier and Sami Haddadin

I. INTRODUCTION

We propose a framework for human-robot collaboration that comprises three different architectural levels: the team-level assembly task planner, the agent-level skill planners, and the skill execution level that is the last decisional component above the robot’s real-time control stack.

The planner at team-level performs the task allocation for the agents based on an abstract world model with the help of suitable cost metrics. To model our types of assembly processes suitably, we employ AND/OR graphs [1], as they implicitly model parallelism.

The team-level planner produces task sequences for every agent via $A^*$ graph-search, from which it derives task descriptions that are then passed down to the agent’s skill execution level. The agents in turn implement modular and parameterizable skills in order to map abstract task descriptions to subsequent real-time-level, where the concrete motion and interaction controls are performed in combination with protective reflexes [2].

II. RESULTS

We conducted a computational experiment to evaluate the performance of our planner. The planner allocates a team consisting of two robots and a human $\{r_1, r_2, h\}$ to an existing assembly plan in form of an AND/OR graph using a cost function that minimizes execution time.

As can be seen from Fig. 1, the planner produces parallelized execution schemes where possible, which leads to a short overall execution time. A disadvantage of such a parallelized assembly process is the dependency of the agents on each other. If one agent is disturbed in its task, other agents may have to wait. The most likely agent to be distracted from its work is the human co-worker. Considering this, in Fig. 1b the human workload has been considered as well, resulting in an execution scheme where the robots work in parallel and the human is only assigned to a task the robots are not capable of performing.

The experiment shows that the planner can be adapted to the requirements of a specific scenario by providing a cost function that reflects the needs of the situation. E.g. consider that an assembly is being built in large quantities by human-robot teams. When the demand is normal, a cost metric that measures the human workload could be used. The robots would do most of the work while the human co-workers could tend to other tasks as well. When the demand rises, a cost metric that focuses more on execution time could be used, resulting in a higher production output but also a higher human workload.

Lars Johannsmeier and Sami Haddadin are with Institute of Automatic Control, Faculty of Electrical Engineering, Leibniz Universität of Hannover, 30167 Hannover, Germany
johannsmeier@irt.uni-hannover.de, haddadin@irt.uni-hannover.de

![Fig. 1: Agents’ assembly sequences for $C_1$ (a), and $C_2$ (b). The solid arrows depict a precedence relation, i.e. the source of the arrows provides a needed subassembly to the sink.](image)

To show the feasibility of our approach we conducted an experiment with a real robot, see Fig. 2.

![Fig. 2: The robot assembles a part (a), a tool is handed over to the human (b), the human co-worker and the robot work in parallel (c), the human stops the robot because it would disturb the current assembly step (d).](image)

REFERENCES


A Wearable Device for Reducing Spinal Loads

Stefano Toxiri, Jesús Ortiz, and Darwin G. Caldwell

Abstract—A wearable assistive device is being designed to reduce spinal loads during heavy physical tasks. A biomechanical analysis is carried out to predict the reduction in spinal compression caused by the introduction of the assistive force.

I. INTRODUCTION

Manually handling heavy material can significantly load the lumbar spine and thus carries high risk of physical injury for workers in industrial lines. To reduce the risks, regulations often impose the use of aid devices.

The goal of this line of work is to design a wearable, powered assistive device that substantially reduces the spinal loads during handling tasks. This short paper presents an overview of the biomechanical analysis that suggests the beneficial effect of such device.

II. METHODS

Spinal loads are represented as the compression force $R_C$ on a revolute joint, in a simplified biomechanical model based on considerations from [1] (see Fig. 1).

![Fig. 1. The revolute joint represents the lumbar joint, whereas $R_C$ represents the compression force resulting from the multibody dynamics and the spinal muscular force $F_M$. $F_A$ is the assistive force introduced by the device.](image)

The model is used to predict the reduction in spinal loads between the unassisted and the assisted scenario. The prediction is based on a set of physical parameters and uses experimental motion and weight data acquired during lifting and lowering tasks.

III. RESULTS

Fig. 2 shows the results of the prediction previously described. The assistance uniformly reduces the compression forces on the spine. Particularly large reduction is observed in the center of the plot, corresponding to larger orientation angles of the torso. This analysis shows that as the external load increases, the lumbar compression also increases.

![Fig. 2. Estimated lumbar compression force $R_C$, calculated with real motion data corresponding to lowering and lifting loads. The blue area and lines refer to the unassisted scenario, while the green shows the reduction in the compression when assistance is provided. Loads with masses between 0 and 15kg were considered.](image)

IV. CONCLUSION AND FUTURE WORK

The biomechanical analysis supports the validity of the approach, suggesting that the assistive device would be effective in reducing the spinal loads.

A number of challenges remain to be addressed in the future work. A prototype has been designed with strong focus on wearability and freedom of movement, and is currently being manufactured. An additional important challenge is concerned with how the device is controlled. Several options will be considered, including direct operation via EMG-based interfaces and dynamics-based schemes such as compensation of gravity.

ACKNOWLEDGMENT

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REFERENCES

Simulation of Jaco robot arm for handicapped people

1 Salih Rashid Majeed
Institute for real time learning system, Siegen University
salih.majeed@uni-siegen.de

2 Klaus D. Kuhnert
Institute for real time learning system, Siegen University
kuhnert@fb12.uni-siegen.de

Abstract: this paper is a part of whole project “smart eating table for handicapped people“ this paper will describe the simulation of the robot arm that used for picking the food and put in the person mouth.

1. INTRODUCTION
As a result of the evolution that took place in the field of robotics and artificial intelligence and its relationship with human health and due to the large numbers of the people who suffer from terrorist attacks in my country (Iraq). We worked on developing of an artificial robotic system that used for helping the handicapped people in eating or drinking. This paper describes a smart table which consists of camera and sound recognition system and JACO robot arm. The whole environment that contains two dishes with different colors each one of the dishes referred to the food type.

2. ABOUT THE EXPERIMENTAL WORK
Modeling and simulation of robotic systems is essential for robot design and programming purposes, as well as operator training. The Jaco robot arm was been drawn in Blender program as shown in figure (1) with all the details which represented the material types and the color of the material to simulate the real materials. Then after drawing the robot arm, some of actuators have been added to the body of the arm to generate the motion of the arm joints. These actuators that have been used are number of bones which can rotate and represent the motion of the arm. Also in this simulation the inverse kinematic technique represented one of the most important techniques which used in the 3-D animation and how it has been implemented in Jaco robot arm as shown in figure (2). Advantages of Inverse Kinematics so what does all this mean to an animator? It means you can yank the bottom of the chain-the hand, for instance-and all of the bones above the hand automatically rotate into position. This paper presented the implementation of this arm in MORSE simulation program with whole environment contain the dishes and the table. MORSE: is a generic simulator for academic robotics. It focuses on realistic 3D simulation of small to large environments.

Fig (1) Simulation of jaco robot arm with bones in blender.

Fig (2) the inverse kinematic in Jaco robot arm.

References:
Collision Detection with a Hydraulically Actuated Robot Arm

Jonathan Vorndamme\textsuperscript{1}, Moritz Schappler\textsuperscript{1}, Alexander Tödtheide\textsuperscript{1}, and Sami Haddadin\textsuperscript{1}

I. INTRODUCTION

The methods of soft robotics like compliant manipulation, collision detection and reaction have proven to be a valuable tool for robots acting in unknown and unstructured environments. Applying these methods to hydraulically actuated "hard" robots poses some problems regarding the strong influence of friction which degrades the inner joint torque control loop based on hydraulic pressure measurements. We apply collision detection methods and observer-based feedforward control to the humanoid robot Atlas to achieve higher position accuracy facing model errors. Compliant behavior can be ensured by including an additional force/torque sensor into the disturbance observer algorithm. The implemented methods can be used to protect the humanoid robot against high contact forces and resulting falls in typical disaster scenarios and enable the use in scenarios nearer to the human.

II. MODELING AND CONTROL APPROACH

We use the standard rigid joint fixed base arm model

\begin{equation}
M(q)\ddot{q} + C(q, \dot{q})\dot{q} + g(q) = \tau_m - \tau_f + \tau_{\text{ext}} \tag{1}
\end{equation}

and a joint impedance controller

\begin{equation}
\tau_m = \tau_d = K(q_d - q) + D(\dot{q}_d - \dot{q}) + \dot{g}(q) + \dot{C}(q, \dot{q})\dot{q} + \dot{M}(q_d)\dot{q}_d + K_{\tau,o}\dot{\tau}_1 - K_{\tau,o}\tau_{\varepsilon} \tag{2}
\end{equation}

including stiffness $K$, damping $D$, compensations $\dot{g}$ and $\dot{C}$, inertia feedforward $M$ as well as shiftable friction feedforward $\tau_1$ and disturbance joint torque feedforward $\tau_{\varepsilon}$.

The generalized momentum based disturbance observer

\begin{equation}
\dot{\tau}_{\varepsilon} = K_{\text{O}} \left( M(q)\ddot{q} + \int_0^t [-\tau_m + \gamma(q, \dot{q}) - \dot{\tau}_1]dt \right) \tag{3}
\end{equation}

\begin{equation}
\gamma = \dot{C}(q, \dot{q})\dot{q} + \dot{g}(q) - \dot{M}(q)\dot{q} + \dot{\tau}_1 - K_{\tau,o}\tau_{\text{ext,EE}} \tag{4}
\end{equation}

from [1] is adapted to include the friction model $\dot{\tau}_1$ and joint torques $\tau_{\text{ext,EE}}$ from measured external forces.

III. EXPERIMENTAL RESULTS

With a collision detection based on a threshold of the estimated disturbance joint torque (3), we were able to reliably detect collisions at the links of the Atlas robots arm. Fig. 1 shows a collision at link 4 during a joint trajectory.

The collision starts at $t \approx 13.2$ s recognizable at the high motor torque on joint 1. The detection threshold is reached at $t \approx 13.6$ s which leads to the arm holding its position in gravity-compensation-only mode as a collision reaction.

Friction effects and model errors can be compensated with a disturbance observer feedforward using $K_{\tau,o}$ in (2). This leads to a loss of compliance which can be avoided with the measurement of external wrenches at the endeffector [2].

Fig. 2 shows the estimated disturbance joint torque of the observer (3,4) with the consideration of measured external wrenches with $K_{\text{ext,o}}$ in (4). Since the external wrenches at the endeffector do not have any effect on the observer output, end effector compliance and precision with observer feedforward can be achieved at the same time. Collisions at the links will cause a stiff reaction until the detection threshold will be exceeded.

![Fig. 1. Measured and commanded joint position $q$ and $q_d$, observed disturbance and measured motor-side joint torques $\tau_{\varepsilon}$ and $\tau_m$ during a collision with a cardboard stick.](image1)

![Fig. 2. External forces joint torque $\tau_{\text{ext,EE}}$, observed disturbance torque $\tau_{\varepsilon}$ with and without external forces compensation ($K_{\text{ext,o}}$) in the observer.](image2)

REFERENCES

Pain Reflexes For Robots To Evade Noxious Contact Events

Johannes Kuehn and Sami Haddadin

I. INTRODUCTION

In physical human-robot interaction (pHRI) the safety for both human and robot has to be ensured. With respect to human safety considerable research has been done in [1], [2]. However, rather limited efforts were undertaken to guarantee robot's own safety. In [3] various collision reflex behaviors were proposed that were developed in the framework of proprioceptive collision detection and reflex reaction.

In case of noxious contact events the robot needs to be able to detect and classify the potential damage they may cause to it, such that appropriate countermeasures can be initiated. Suitable protective reflexes would also elevate human’s safety during human-robot collision.

II. ARTIFICIAL ROBOT NERVOUS SYSTEM

In generalized coordinates the contact dynamics between any suitably controlled (via the desired torque $\tau_d$) robot arm and a colliding object with state $x_c$ and its derivative $\dot{x}_c$ are determined by the robot joint configuration $q$, the joint velocity $\dot{q}$ and the external torque vector $\tau_{ext}$ that is caused by the contact wrench $\mathcal{F}_c$ or stress $\sigma_c$ (single point contact) acting on the collision object and robot, respectively, see Fig. 1. In order to rate potentially painful collisions we propose the artificial Robot Nervous System aRNS, which architecture and basic functionality mimic the human antetype. It consists of the nervous robot-tissue, the spiking model, the interpretation layer of generated spiking signals and the motor control law, see Fig. 1. In particular, during a mechanical stimulus penetration stress, depth and its dynamics are sensed via a virtual nervous robot-tissue that causes artificial Robot Neurons (aRNs) to fire depending on the respective penetration depth $\delta$, time, and aRN density in the tissue layer. Together with the pain levels no, light, moderate and severe pain the signals are then used to activate suitable pain-reflex movements. Concretely, our proposed pain-based controller serves e.g. for online adaptation of the equilibrium position $q_d$, stiffness $K_d$, and feed-forward torque $\tau_{ff}$ of a joint level impedance controller. The overall behavior allows the robot to sensitively interact with its environment at nominal pain level, while when pain level increases potential risks are mitigated by activating human inspired reflex strategies.

III. RESULTS

Experimentally the pain-reflex movement is demonstrated using the KUKA LWR4+, while contact events and the nervous robot-tissue are simulated within the real-time core of the system, so that the robot "hallucinates" a contact. Figure 2 depicts the "hallucinated" collision between the KUKA LWR4+ equipped with the aRNS for joint 2 and 4 at varying collision object velocity $v_c$. The original task is to hold a fixed configuration. The equilibrium, stiffness and torque adaption is shown for different pain levels together with the true compressive stress $\sigma$. 

REFERENCES

Compliant Interaction with an Antagonistic Pneumatically Controlled Robot Joint

Alexander Tödtheide, Torsten Lilge, and Sami Haddadin

I. INTRODUCTION

Interaction between humans and robots, as well as their application in unknown environments is a recent field in robotics, where traditionally used position control approaches reach their limits. Impedance and force controlled robots are of special interest in nowadays robotics since these can react compliantly in case of sudden contact or unprecise world models [1], [2]. For electric drives these concepts have been implemented successfully so far. However, these are quite heavy and expensive. Pneumatic actuators, and especially their movable parts, are significantly lighter, promising more direct and more dynamic motions. Furthermore, they contain an inherent compliance due to the compressibility of air which is a useful property when providing compliant behavior.

II. APPROACH

To demonstrate the capabilities of a pneumatic compliant robot joint, an antagonistic experimental setup, consisting of two pneumatic cylinders and one rotational finger joint, was developed (see Fig. 1), where tendons link the movable pistons with the finger joint. Linear valves (not shown) control the in- and outflow of air in and out of the chambers. Resulting pressure changes within the chambers are measured by pressure sensors which enable a determination of tendon forces.

We chose a cascaded control structure (see Fig. 2) consisting of an outer impedance and an inner force controller for each pneumatic cylinder. Since pneumatic systems are highly nonlinear a model based force control approach by [3] was implemented. Consequently, the controlled system behaves as a linear mass-spring-damper system. In order to support our design process, open and closed loop system were successfully simulated before experimental application.

III. EXPERIMENTAL RESULTS

Angular tracking of sinusoidal signals of 0.125 Hz, 2 Hz, 4 Hz and 7 Hz with mean absolute angular errors of 1.2°, 2.4°, 1.6° and 7.6° could be achieved showing the suitability for fast manipulations.

Compliant interaction between the finger and a human is shown in Fig. 3. The system reacts compliantly between 0.6 and 1.4 seconds. When being released, the system responds with a low damping as adjusted in impedance control.

Collision with an obstacle during a tracking operation is demonstrated in Fig 4. The controller remains stable and proceeds with the tracking if the desired angle \( q_d \) moves out of the obstacle. The force tracking of the underlying force controllers reveal good tracking performance and a linear relation between angular error and tendon forces which is a consequence of the impedance controller.

REFERENCES


Visual Servoing with Safe Interaction

Hamid Sadeghian$^1$ and Luigi Villani$^2$

Abstract—The control of the interaction during an image based visual servoing for a robot working in dynamic cluttered environments is considered. The main concerns in this scenario are the performance of the main visual servoing task, keeping the visual feature in the field of view as well as a safe obstacle-robot distance. The idea is to control suitable image moments and to relax a certain number of robot’s degrees of freedom during the interaction phase. The relaxed redundancy of the robot is then exploited to avoid collisions.

I. BACKGROUND

Classical image-based visual servoing (IBVS) is aimed at controlling the end-effector of a robot carrying a camera in such a way that some image features, attain desired values. In the presence of moving obstacles, it is important for the robot controller to ensure suitable reaction capabilities beside main task performance. In this regard, two main operating modes are usually adopted, namely, avoiding undesired collisions, or handling the physical interaction. The latter case can be implemented by increasing the compliance of the robot and using suitable observers to estimate the external forces exerted on the robot body, [1]. Physical interaction control relies on fast control loop rate, which is usually higher than that used to accomplish visual servoing tasks.

The selection of the visual features is very important in image based visual servoing and affects directly the interaction matrix. The best choice is to associate each camera degree of freedom with only one visual feature. However, such complete decoupling cannot be easily verified and only partial decoupling can be obtained using image moments and invariants [2].

II. THE RESULTS

In this research an image-based visual servoing algorithm with collision avoidance capabilities of dynamic obstacles is proposed. An eye-in-hand camera is used to extract image features which are used to control the end-effector motion. The distance between any part of the robot with dynamic obstacle (human) is measured using depth sensor (Fig. 1). This information is used to produce a repulsive vector to modify on-line the robot trajectory.

In order to keep the visual features in the field of view (FOV) during the repulsive action, the combination $s = (x_g, y_g, \mu_{02}, \mu_{20}, P_x, P_y)^T$ is selected as the features vector. During the interaction phase, the first four features which regulate the centroid and the variance of the features in the image plane is kept and the last two complementary features are released [3]. This keep the feature points in the FOV and increases the dimension of the null-space which is exploited to handle the interaction. After removing the risk of collision, the main visual servoing task is resumed. The desired values of the centroid position and the image variances during the interaction phase are the important parameters. The centroid of the object in the image plane is controlled by the former, and the the scale factor in the image plane is affected by the latter. These desired values is set intelligently by a Mamdani-type fuzzy reactive planning algorithm.

The results of the algorithm is illustrated for a case study with 7-DOF KUKA LWR4 robot arm in Fig. 2. 

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$^1$H. Sadeghian is with Engineering Department, University of Isfahan, Isfahan, Iran, and is a Visiting Researcher at Technical University of Munich, Munich, Germany (Corresponding author email: h.sadeghian@eng.ui.ac.ir)

$^2$L. Villani is with Department of Electrical Engineering and Information Technology, University of Naples Federico II, Italy
An Energy Based Injury Index for Pre-Collision Safety Control in Human-Robot Interaction

Roberto Rossi, Matteo Parigi Polverini, Andrea Maria Zanchettin, and Paolo Rocco

A stringent requirement to enable safe physical Human-Robot Interaction (pHRI) is represented by the limitation of the risk of any severe mechanical injury, i.e., internal bleeding or fracture of a bone, for a human working at close contact with a robotic manipulator. To this extent, pre-collision control strategies based on the quantitative description of the effect of a possible impact between a human and a robot, e.g., injury severity indices, can be devised in order to minimize human injury before such collision actually occurs, see [1], [2]. The original contribution of this work to the field of human-robot interaction regards a novel injury index based on dissipated energy in a potential inelastic impact, integrated in a constrained based pre-collision control strategy, see [3].

I. ENERGY BASED INJURY INDEX

The injury severity index should describe the deformation energy that causes injury on the human in a potential impact. It corresponds to the dissipated energy in a potential blunt impact between a robotic manipulator and a human at rest. Considering the conservation of the momentum during the impact and assuming a perfectly inelastic collision, it can be demonstrated that the energy dissipated in the impact is computed as follows:

$$\Delta T = \frac{1}{2} \left( \frac{m_h}{m_n} \right) \dot{x}_n^2, \quad (1)$$

where $m_h$ and $m_n$ are the human and robot reflected masses in the point of the impact and along the direction of the contact, while $\dot{x}_n$ is the relative impact velocity. Notice that model based injury indices used in literature are linear with reflected mass and robot velocity, e.g., [2], thus they can have an infinite value in presence of singularity points of the reflected mass. With this respect, we can prove that in our approach the absolute value of $\Delta T$, in presence of singularity points, is upper limited.

The value $\Delta T$, in both clamped and unclamped collision, represents the energy dissipated in the impact and converted in fracture or deformation energy. It is worth pointing out that $\Delta T$ depends on the kinematic properties of the robot, thus it can be monitored and bounded during motion.

II. PRE-COLLISION CONTROL STRATEGY

A pre-impact control strategy for redundant manipulators can be devised based on the proposed injury index. A constraint-based and prioritized motion planning algorithm is applied following the approach in [4], where a real-time trajectory generator is combined with a constraint-based optimization algorithm that feeds a lower-level position/velocity controller.

With respect to the described control architecture, the general idea behind our approach is to limit the dissipated energy to be under a certain threshold during a prescribed path-following task, while simultaneously exploit the kinematic redundancy, thus acting only in the null space of the task in a second optimization stage, to decrease the reflected mass of several points on the robot arm along the directions of potential impacts.

To validate the proposed control strategy, the 14-DOF dual-arm redundant manipulator prototype ABB FRIDA has been exploited (see Fig. 1). Experiments demonstrate that the index $\Delta T$ correctly describes the fracture energy in an inelastic impact and the pre-impact control strategy implemented succeeds in bounding this quantity under a desired threshold. Moreover, the control strategy succeeds in minimizing the reflected mass of the end effector in the direction of a potential impact, hence allowing an increased task efficiency.

REFERENCES

Towards a safe and robust control of compliant joint manipulators

Ilias El Makrini1*, Carlos Rodriguez-Guerrero1, Dirk Lefeber1 and Bram Vanderborght1

Abstract—The control of compliant joint manipulators is challenging for two reasons. First, the elastic elements of the compliant actuators can store an important amount of energy which can be potentially dangerous and needs therefore to be controlled. Second, the compliance introduces nonlinearities and uncertainties in the system. In this paper, we propose a Variable Boundary layer Sliding Mode Control (VBSMC) based method for a safe and robust control of compliant joint manipulators.

I. INTRODUCTION

The control of compliant joint robots using different approaches has been widely studied [1]. The design of a controller able to provide both a safe behaviour and good performances is, however, still a challenging task. A commonly used safe control method for mechanical systems is the impedance control. In order to achieve a precise motion, high impedance values are used. However, the adoption of such control scheme with high impedance gains can suppress the intrinsic compliance and generate dangerous motions. The Proxy-based Sliding Mode Control (PSMC) is another safe control method [2]. This was studied for enhanced physical interaction of a planar pneumatic manipulator [3]. The PSMC achieves a responsive and accurate PID-like tracking during normal operation with a slow and safe recovery from large deviations from the target position. In practice, the system to be controlled as well as its model are always uncertain or and sometimes mostly unknown. Although the PSMC controller is based on the Sliding Mode Controller (SMC), its PID component makes it less suitable for the control of nonlinear system and decreases the robustness of the controller. Therefore, the SMC was chosen as the basis of the developed method for a safe and robust control.

The SMC is a robust nonlinear controller suitable for systems with unknown dynamics subjected to unknown external disturbances. It has been extensively used for the control of uncertain systems [4]. The pure SMC presents, however, two disadvantages. Firstly, the chattering phenomenon which causes high frequency oscillation of the output command. This can create problems such as saturation and heat in the mechanical parts of the robot manipulator or drivers. Secondly, the SMC is very sensitive to the noise when the input signal is very close to zero. The use of a boundary layer, where a saturation function is employed, has been shown to reduce chattering [5].

II. SAFE AND ROBUST CONTROL

A VBSMC based position control scheme has been implemented in the Baxter robot for a safe and robust control and is shown in Figure 1. It consists in a central SMC with variable boundary layer, a gravity compensation block and a damping term $K_D$. Thanks to the nonlinear nature of the SMC, the system does not need to be linearized. Therefore, the control method does not require the knowledge of the dynamic model of the robot. By adjusting correctly the width of the boundary layer, it is possible to achieve a good trade-off between chattering elimination and tracking performance.

It has been shown that the amount of chattering is also dependent on the angle under which the state trajectory approaches the sliding surface [5]. A large approach angle creates more chattering. The idea is to adjust the slope of the saturation function in function of the state approach angle by modifying the width of the boundary layer. The use of a variable boundary layer is also beneficial in the presence of noise on the speed measurement.

![Fig. 1: VBSMC control scheme.](image)

By varying the torque limit parameter $\tau_{lim}$ and the expanding factor $\alpha$ of the boundary layer, it is possible to achieve different safety levels in terms of interaction forces while maintaining a good overall performance.

REFERENCES

Architecture for Emotional Appraisal of Multi-timescale Nexting

Christian Maksymiw, Johannes Feldmaier, Dominik Meyer, Hao Shen and Klaus Diepold
Department of Electrical and Computer Engineering, Institute for Data Processing, Technische Universität München

Abstract—In human-machine interaction it is beneficial if artificial agents can communicate their actual internal state towards a human observer in a believable and easily acceptable way. To this end, we propose to extend the architecture of a learning robotic system by a component to determine and display emotions to reflect the internal state.

I. MOTIVATION

Human beings as well as other animals seem to use experiences from earlier situations to anticipate what is about to happen next. This process of continuously anticipating the immediate future in a local and personal sense is called nexting. Modayil et al. [1] have already shown a technical implementation of nexting on a mobile robot. This robot was able to learn how to simultaneously predict all its raw sensor signals at different timescales in real time. They achieved multi-timescale nexting by using the temporal difference learning algorithm TD(λ) with function approximation. Moreover, they also showed how to determine the performance of the multi-timescale nexting algorithm after completion of the learning process in a quantitative manner. These quantitative measures can be interpreted by experts in the field. However, non-experts are often incapable to do so.

In order to enable also non-experts to assess the performance of the multi-timescale nexting algorithm, or in other words to assess the reliability of the computed predictions in a qualitative way during the learning process (online), we take one aspect about nexting into consideration that has been ignored up to our knowledge: nexting is never an isolated process in human beings. Indeed, the contrast between the outcome and our expectations has a significant influence on our current emotional state. If our expectations are exceeded, we feel highly delighted. In contrast, if the outcome falls short of our expectation, some humans are surprised or interested, whereas others could even become disappointed or annoyed.

II. PROPOSED ARCHITECTURE

Due to the link between nexting and emotions in human beings, we make use of a concept based on current appraisal theories of emotion in order to simplify the assessment of the reliability of predictions performed by multi-timescale nexting for non-experts. Analogous to human emotions which emerge from the individual’s own evaluation of the immediate, imagined, or remembered situation, we use Scherer’s component process model (CPM) [2] to map the output signals of the multi-timescale nexting process onto a two-dimensional pleasure-arousal space. The resultant point in this space can then be mapped onto distinct emotional expressions which convey the current affective state of the agent. Subsequently, this representation can be displayed with a suitable emotion display and easily interpreted by a non-expert.

Figure 1 illustrates the general architecture which we refer to as MNEmotion. It links to the preceding multi-timescale nexting process as well as to the following representation of the current affective state of the agent in the pleasure-arousal state space.

III. CONTRIBUTION AND IMPACT

The main goal of the current study is to build an autonomous agent capable of giving direct emotional feedback according to its current internal state. For this purpose we have combined the multi-timescale nexting process with a model of emotion. With this combination we deliver one component of the agent’s system of emotion and cognition.

The results show that the agent is able to express online its current affective state during the learning process with the feelings of pleasure and arousal. These feelings are mapped to distinct emotional expressions which can be easily interpreted by non-experts in order to evaluate the prediction process.

There are at least two applications for this kind of affective evaluation of a multi-timescale nexting process. Firstly, the agent can display its current personal opinion about the accuracy of the preceding multi-timescale nexting process by using emotions. This is one of the fastest ways for communicating the current learning state of an agent in a dynamic and interactive environment to a human. Secondly, the agent could use the affective representation of the accuracy of predictions for regulating the multi-timescale process itself, i.e. adapting its learning rate parameters.

REFERENCES


Collision avoidance using multiple depth cameras

Fabrizio Flacco Emanuele Magrini Alessandro De Luca

When a human and a robot share the same workspace, possibly collaborating to accomplish a given task, safety is the most important feature. Safe pHRI can be conceived as nested layers of consistent behaviors that the robot must guarantee and accomplish:

\[
\{ \{ \text{Safety} \} \} \\
\{ \text{Coexistence} \} \\
\{ \text{Collaboration} \}
\]

In this view, collision avoidance is a critical feature for human-robot coexistence. Nowadays, visual sensing is one of the best choices for integrating sensor-based collision avoidance concepts in motion control system. Moreover, the development of new low-cost RGB-D sensors, such as the Kinect, allows meeting many requirements with a very cheap and powerful sensor system.

We have presented in [1], and then improved in [2], a method that evaluates point-to-object distances directly in the depth space, a key information for collision avoidance. In this way, a large performance improvement is achieved in terms of computational times. The method allows also a correct consideration of pixel frustum, i.e., the portion of a pyramid in the Cartesian space left after its upper part has been cut off by a (skewed) plane. However, depth information is limited to the shortest distance between camera and object along the ray of projection associated to that pixel. All points behind the observed object along the same ray of projection (i.e., with a larger depth) are unobserved. The collection of all the unobserved points by the RGB-D camera form the gray area, which may be part of the free space or not. The presence of a gray area introduces undesired collision avoidance behaviors, e.g., avoidance of the human ‘shadow’. While multiple cameras can be used to reduce this area, a direct extension of our depth-space method to multiple cameras is not straightforward, since every camera has its own depth space.

We propose here a novel approach to evaluate distances between obstacles and points of interests (e.g., placed on the robot links) using multiple depth cameras. The core of the method is the introduction of a new depth-space oriented discretization of the Cartesian space, called depth grid (Fig. 1), which can be computed off line (together with camera calibration). The depth grid allows representing the robot workspace at best from the information given by depth cameras, including occluded points.

At run time, the depth grid is used to infer whether a cell is part of an obstacle or not. Thanks to the off-line initialization of the depth grid map, and its peculiar characteristics, fusing the on-line sensing information of multiple depth cameras becomes a simple task. The search of occupied cells is very fast, since all cells in the same ray of projection are represented with the same two coordinates (the pixel position). If a cell is detected as part of an obstacle, the distance to a point of interest (on the robot) is then computed by directly inheriting the approach from [2]. Once the distance information is available, it is possible to apply any desired collision avoidance algorithm—we use our potential field method presented in [1].

The real-time performance has been tested by means of collision avoidance experiments, with two Kinects monitoring a human-robot coexistence task (Fig. 2). The robot is required to move continuously its end-effector at a nominal speed of 40 cm/s through the vertices of an hexagon in the vertical plane. A human enters the robot workspace and gets very close to the robot, possibly interfering with its Cartesian or joint trajectories. Collisions are avoided by reactive robot motions, while the end-effector task resumes as soon as it becomes feasible again.

The authors are with the Dipartimento di Ingegneria Informatica, Automatica e Gestionale, Sapienza Università di Roma, Via Ariosto 25, 00185 Rome, Italy. {fflacco,magrini,deluca}@diag.uniroma1.it. Work supported by FP7 ICT-287513 SAPHARI (www.saphari.eu).

Fig. 1. Illustration of the depth grid map

Fig. 2. Collision avoidance experiment

REFERENCES


Learned Minimal Intervention Control Synthesis based on Hidden Semi-Markov Models

Martijn Zeestraten¹, Sylvain Calinon²,¹, Darwin G. Caldwell¹

Fulfilling the prospect of robots leaving factory floors, to enter the human world and act among us, could lie decades away. However, the move of robots from the large scale factory plants as in the car manufacturing industry towards smaller manufacturers might lie around the corner. Funding agencies are pushing robotics research in manufacturing through projects such as SMART-E [1]. This, combined with the recent development of lightweight robots for industrial applications, e.g. KUKA’s LBR and ReThink Robotics’ Baxter, create an optimal climate to advance industrial robotics.

Medium and small scale manufacturing companies represent the largest number of entities in the manufacturing sector in Europe. Such companies could benefit greatly from robotic automation solutions, but they generally have different needs than large scale manufacturers.

In large scale companies most robots are programmed to do one specific task for their complete lifetime. Smaller scale companies robots are likely to perform a wide variety of tasks. To make this viable, robots need to be easily (re)programmable. Programming by Demonstration (PbD) [2] provides suitable solution to this problem. PbD allows easy (re)programming of a robot by providing a small number of demonstrations of the task to be learned.

The types of tasks that performed in industrial environments can have different temporal variance. When a robot has to synchronize with other systems, exact temporal execution might be critical. On the other hand, when interacting with a human co-worker the robot should be able to cope with high temporal variance. This temporal variability needs to be taken into account in the representation of movements.

Encoding of movements can effectively be achieved using movement primitives acting as building blocks that can be assembled in parallel and series to form complex movements. Within the literature of movement primitives encoding we can distinguish autonomous, and non-autonomous systems. The system evolution of non-autonomous systems only depends on the state of the system (e.g. [3]). Such systems form an attractor landscape with a unique global minimum, guaranteeing that the system state will converge to the final state. The fact that their system evolution only depends on the system state, makes them ideal for situations where high temporal variability can be expected. However, such systems are less suitable in situations where more importance should be given to correct movement duration. In non autonomous systems, the state evolution does not solely depend on the system state, but also on a temporal signal or phase variable. These additional signals, basically acting as an external clock, achieve a more exact temporal evolution. A common approach is to model the movement dynamics as a system of linear spring-damper systems [4] [5].

We propose a non-autonomous movement encoding based on a Hidden Semi-Markov Model (HSMM). The model encodes local movement dynamics in Gaussian kernels with full covariance matrices covering all the synergies among the dynamics and different degrees of freedom. The switching between the local-linear models is handled by the HSMM. This temporal modeling of the HSMM can be seen as the phase term used in e.g. Dynamic Movement Primitives (DMP). However, in contrast to the phase term, which is usually a deterministic heuristic, HSMM provides a way to learn and represent in a probabilistic form the temporal behavior. An adaptive compliant controller is obtained by combining HSMM with Model Predictive Control (MPC). At each timestep HSMM is used synthesize desired attractors with their allotted variability on a given time horizon. A control command is then obtained by minimizing an objective function based on the synthesized information. Effectively, this leads to a minimal intervention control strategy [6].

We successfully tested this approach in a pick&place experiment. The robot is shown a small number of demonstrations of a pick-up task. During reproduction the robot, is able to successfully reproduce the task and react to perturbations in a compliant way.

REFERENCES

COMPI: Development of a 6-DOF Compliant Robot Arm for Human-Robot Cooperation

Vinzenz Bargsten¹, and José de Gea Fernández²

Abstract—This paper presents the compliant robot arm COMPI, designed having in mind some characteristics to make it suitable for human-robot collaboration: namely, compliance and lightweight. This should allow safe human-robot collaboration and contact with the environment without requiring external sensors or the delimitation of separate workspaces for robot and humans. The compliance in COMPI is achieved via active control by using a dynamic controller based on motor currents to estimate the joint torques (remarkably, the robot is using Brushless DC motors with gears of ratio 1:100) and making use of a experimentally identified robot dynamical model. The robot arm uses a distributed joint control approach in which each single joint is equipped with on-board electronics including computing power (FPGAs), power electronics and local sensors (e.g. joint position and motor phase currents). The experimental results show a very good positioning tracking performance as well as compliance to external forces.

I. CONTROL SETUP

This section discusses the control of the robotic arm taking into account the robot dynamics to achieve a compliant behavior. A first requirement for the evaluated dynamic control schemes is a mathematical model of the robot motion dynamics. It relates the robot motion defined by joint positions $q(t) \in \mathbb{R}^n$, joint velocities $\dot{q}(t)$ and joint accelerations $\ddot{q}(t)$ with the joint actuation torques or forces $\tau(t) \in \mathbb{R}^n$ [1]. Thus, an experimental identification procedure similar to [2] has been used to obtain a rigid-body model of the form $\tau = \dot{Y}(q, \dot{q}, \ddot{q}) \ddot{q}$, with the estimated dynamic parameters $\ddot{q} \in \mathbb{R}^{12n}$. During the estimation procedure constraints have been included to ensure physical consistency of the estimated parameter values. A software library has been implemented to compute the model equations for tree-structured rigid-body systems according to the Recursive Newton-Euler Algorithm, whilst in particular the linear parameter dependence as shown above is kept.

Secondly, the robot joint actuators are required to measure and apply the actuation torque sufficiently accurate. For this purpose, experiments to determine and to verify the relation between motor current measurement $i$ and output torque have been carried out. We found that the linear relationship $\tau = k_i \dot{q}$ with the motor torque constant $k_i$ is a sufficient approximation for a wide range of operating conditions.

However, timing of the sampling phase, and filtering of the sensor signal turned out to be crucial.

On this basis, a cascaded control scheme for position, velocity and motor current has been implemented on the FPGAs controlling (locally) the robot joint actuators.

II. RESULTS

A variety of configurations and combinations of central and local, low-level controllers have then been tested – from fully local joint controllers to computed-torque control with only motor current control locally. The most promising configuration consists of centrally-computed joint torques, as required for the reference motion, feed-forwarded to a local cascaded control loop of position, velocity and motor current (Fig. 1). In addition, friction is compensated locally on each FPGA joint controller. Contrary to a change in controller gains, we found that a limitation of the feed-back from the position-velocity control loop leads to a good tracking accuracy, while the robotic arm can be easily deflected by hand at every link (see Fig. 2 and video [3]).

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¹Vinzenz Bargsten is with the Robotics Research Group, Faculty of Mathematics and Computer Science, University of Bremen, 28359 Bremen, Germany bargsten@uni-bremen.de
²José de Gea Fernández is with the Robotics Innovation Center, German Research Center for Artificial Intelligence (DFKI), 28359 Bremen, Germany

Fig. 1: Low-level, FPGA-based joint control cascade in position control mode; position and velocity controllers can be deactivated such that they act on limit violation only.

Fig. 2: Left: COMPI robot arm; Right: Tracking experiment – Robot arm tracks an 8-figure in cartesian space (A). At point (B) system reacts compliantly on contact with a human. In free space again (C), moves back to reference trajectory.
Integrating Multimodal Interaction and Kinesthetic Teaching for Flexible Human-Robot Collaboration

R. Caccavale1, A. Finzi1, D. Lee2, E. Leone1, S. Rossi1, M. Saveriano2 and M. Staffa1

Abstract—We present a human-robot interaction framework that integrates multimodal collaborative execution and kinesthetic teaching to accomplish complex and new collaborative tasks in an industrial scenario. We consider the case of a hospital scenario where a human user interacts with a robotic arm in order to collect and to arrange tools.

I. INTRODUCTION AND SYSTEM OVERVIEW

An effective cooperation between a human being and a robotic co-worker during the execution of complex tasks requires natural interaction and continuous and incremental adaptation. In this paper, we present an approach to human-robot collaboration that combines multimodal interaction and kinesthetic teaching. The aim is to allow a human operator to continuously and naturally switch from collaborative execution to teaching modality and vice versa by exploiting multimodal inputs - mainly speech and gestures - and physical interaction. The multimodal interaction system recognizes multiple human commands/ actions [1] providing an interpretation of users intentions according to the context. The interpretation process is based on a late fusion approach: the results of classifiers of the single modalities - gesture (LDCRF-based recognition) and speech (Julius recognizer) - are integrated by the fusion engine (exploiting probabilistic context-free grammars), while a dialogue manager accomplishes the semantic interpretation of the observations according to the interaction context (see [2], [3]). Kinesthetic teaching requires a low level control that guarantees a safe physical interaction and an easy guidance [4]. In this work, we use the gravity compensation control to have an ideally massless robot that the user can easily and safely guide.

Fig. 1. Hospital Scenario: kinesthetic teaching and speech-based interaction.

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1DIEI, Università degli Studi di Napoli “Federico II” via Claudio 21, 80125, Naples, Italy.
2LSR, Technische Universität München, Karlstrasse 45, 80333, Munich, Germany.

II. CASE STUDY: DLR HOSPITAL SCENARIO

The hospital domain concerns the process of quality control, preparation, and packaging in a hospital center. In this context, the operator and robot co-worker are involved in the task of sorting instruments on a tray. The task is composed of 5 steps: the human brings a tray of unsorted instruments to the robot; he/she checks the instruments and puts them within the robot workspace; the human asks the robot to help; during the interaction the robot manipulates specific objects while the human checks the instruments and orders the other objects; the task is completed when the tray contains ordered and checked instruments.

a) Set-up: As a set-up, we considered a KUKA LWR IV+ manipulator endowed with a gripper operating in a workspace monitored by two kinect cameras, one for user interaction and another used to track the objects (recognized via the qr code) on the table. The setting includes two trays and three objects: a screwdriver, a yardstick (the unknown object), a tape (see Fig. 1).

b) Execution and Teaching modes: We assume the robot already aware about the target location of some tools, while the human should instruct the robot where to place (which box) the other objects thought kinesthetic teaching. During the interactive execution the user can communicate a set of primitive intentions (Point, Take/Leave, Give, No, Find, Come, Stop, Switch). The switch can be always invoked to start a teaching session, in this case the robot goes in gravity compensation waiting for the human physical guidance. In this mode, the user intentions are suitably interpreted according to the novel interaction schema. The operator first shows the target object to the robot (kinect), then he/she moves the robot arm from the object position to the target (kinesthetic teaching). In this phase additional commands can be provided (e.g. Open/Close gripper), mainly vocally, since the human physically interacts with the robot. Before stopping the teach mode, the human can ask the robot to repeat the learned sequence to verify its execution. Tests with the proposed framework are currently in progress (see [5]).

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Inverse dynamics and feedback linearization control of elastic joint and VSA robots using a Newton-Euler algorithm

Gabriele Buondonno  
Alessandro De Luca

Recent deployment of lightweight manipulators intended for physical human-robot interaction has shown the benefits of the presence of compliance at the joints, as mechanical absorbing layer for safety. Moreover, the use of intentionally compliant joints is a way to achieve more natural, human-like, and energy efficient robot motion. Thus, there is a new interest in dynamics and control of such robotic systems.

In rigid robots, the torque needed to execute a desired joint trajectory \(q_d(t)\) (inverse dynamics problem) can be computed in a numerical way using the recursive Newton-Euler Algorithm (NEA).

\[
\tau_d = \text{NEA}(q_d, \dot{q}_d, \ddot{q}_d) = (M(q_d) + B)\ddot{q}_d + n(q_d, \dot{q}_d),
\]

which runs efficiently with asymptotic complexity \(O(N)\), being \(N\) the number of rigid joints. A feedback linearization control law can be computed using again the NEA, by simply replacing \(\ddot{q}_d\) with \(\ddot{q}_d = K_p(q_d - \dot{q}) + K_d(q_d - \dot{q})\).

When the robot has elastic joints with constant stiffness matrix \(K > 0\), dynamic modeling requires a double set of variables for the position of the driving motors (\(\theta \in \mathbb{R}^N\)) and of the driven links (\(q \in \mathbb{R}^N\)) at the joints. We have:

\[
M(q)\dot{\theta} + n(q, \dot{q}) = K(\theta - q)
\]

\[
B\dot{\theta} + K(\theta - q) = \tau.
\]

For these robots, symbolic solutions to the inverse dynamics problem have been developed [1]. Moreover, it was shown that this model can be transformed into an exact linear and decoupled system by means of nonlinear state feedback, similarly to the rigid case. However, the complexity of a Lagrangian-based inverse dynamics and feedback linearization control design, requiring the derivation and real-time evaluation of higher-order dynamic model terms in symbolic form, has barred so far their use in real applications.

In this work, we overcome these limitations by introducing, for arbitrary robots with \(N\) elastic joints and for sufficiently smooth desired link trajectories \(q_d(t)\), a generalized version of the recursive Newton-Euler algorithm (EJNEA for short) that computes numerically the inverse dynamics torque

\[
\tau_{EJ,d} = \text{EJNEA}(q_d, \dot{q}_d, \ddot{q}_d, \dddot{q}_d, \dddot{q}_d)
\]

in an exact way (i.e., without resorting to approximate differentiation of quantities), still running in \(O(N)\) only. The recursive forward and backward equations involve in this case higher-order derivatives of motion and force variables.

We also address the problem of implementing in practice the feedback linearization control law for robots with elastic joints. Nicely enough, the EJNEA can serve again to this purpose, although some extra processing is needed to first obtain from the measured state \((\theta, q, \dot{q}, \ddot{q})\) the numerical value of the linearizing coordinates \((q, \dot{q}, \ddot{q}, \dddot{q})\). One has

\[
\tau_{EJ,FBL} = \text{EJNEA}(q, \dot{q}, \ddot{q}, \dddot{q}, \sigma),
\]

where \(\sigma \in \mathbb{R}^N\) is used for the stabilization of the trajectory error on the linear side of the transformed problem. The basic algorithm is complemented by a numerical factorization of the link inertia matrix \(M(q)\), which needs to be inverted in this case. As a result, the method runs in \(O(N^3)\).

The proposed Newton-Euler method can be extended also to robots driven by Variable Stiffness Actuators (VSA) [2]. Two motors are used at each robot joint, connected through nonlinear compliant transmissions to the driven link. In this way, inspired by bio-mechanical analogues, it is possible to achieve simultaneous control of the variable joint stiffness (organized as a vector \(\sigma \in \mathbb{R}^N\)) and of the link motion \(q\).

For VSA-based robots with agonistic-antagonistic actuation at the \(N\) joints, a desired four-times differentiable link trajectory \(q_d(t)\), and a desired twice-differentiable stiffness trajectory \(\sigma_d(t)\), we can compute the nominal input torques \(\tau_{1d}(t)\) and \(\tau_{2d}(t)\) that realize exactly this combined task trajectory by using an expanded version of (3), called Variable Stiffness Actuation Newton-Euler Algorithm (VSA-NEA), as

\[
\begin{pmatrix}
\tau_{1d} \\
\tau_{2d}
\end{pmatrix} = \text{VSA-NEA}(q_d, \dot{q}_d, \ddot{q}_d, \dddot{q}_d, \dddot{q}_d, \sigma_d, \dot{\sigma}_d, \dddot{\sigma}_d, \dddot{\sigma}_d).
\]

The main difference with the constant stiffness case is that a closed-form solution to the inverse dynamics problem cannot be given here. In fact, the full version of VSA-NEA requires the solution of a (decoupled) set of \(N\) systems of 2 nonlinear equations. Each system depends on the technology of the VSA device and can be solved numerically by any root finding method. The overall complexity of the algorithm grows once again linearly with the number \(N\) of VSA joints. For the considered class of VSA-based robots, a simple variant of the algorithm allows to compute also the feedback linearization control law in real time as well.

REFERENCES


Object Tracking using Particle Filter in Joint Color-spatial Space

Shile Li¹, Seongyong Koo² and Dongheui Lee¹

I. INTRODUCTION

With point-cloud from an RGB-D camera, a robot can distinguish different unknown objects when the objects are spatially separated by clustering in the Euclidean space. As a human moves the objects and contact them with each other, the robot has difficulty to further distinguish each object. The solution is to keep tracking the objects, thus contacted objects can still be distinguished. To track the 6 DOF object pose accurately, often recursive Bayesian Filtering is used. Especially particle filter is suitable, because it can handle non-linear motions induced by human and non-Gaussian noise. In a particle filter framework, a large amount of hypotheses need to be evaluated. The hypothesis evaluation function should reveal how close the hypothesis to the observation is, such that the pose estimate can be integrated from multiple hypotheses. The hypothesis evaluation function should be also computationally efficient due to the real-time requirement. In this work, to improve the efficiency and the accuracy of the hypothesis evaluation, we propose Joint Color-Spatial Descriptor (JCSD) that represents a probability density of a measurement point in the joint color-spatial space.

II. HYPOTHESIS EVALUATION

How to represent an object from a point-cloud such that it is discriminative for false hypothesis and robust to noise? First, we select \( m \) evaluation points that are equally distributed in the interested point-cloud space, which are the intersection points of a regular grid. Each evaluation point represents local part of an object by a point density calculated from kernel density estimation. Using a limited kernel bandwidth, the point density at each evaluation point can be efficiently calculated by accumulating each point to the nearby evaluation points. To combine color information, the Smoothed Color Ranging (SCR) technique [2] is used. SCR assigns weights to each point in the 8 color ranges (red, yellow, green, cyan, blue, purple, light gray, dark gray) with the weights \( \{h_i\}_{i=1}^{8} \) and \( \sum_{i=1}^{8} h_i = 1 \). With the color weights, point density for each evaluation point will be calculated eight times for each color range individually. In total, JCSD consists of \( 8m \) point density values for \( m \) evaluation points and 8 color ranges.

For evaluation of a specific pose hypothesis, the overall hypothesis likelihood is summed up by each observation point’s likelihood. For evaluation of one observation point

\[
\mathbf{z}^* = \arg\min_{\mathbf{z}} \left( \sum_{i=1}^{m} \frac{1}{\sqrt{2\pi\sigma_i^2}} \exp\left(\frac{-1}{2\sigma_i^2} (\mathbf{z}_i - \mathbf{x}_i)^2\right) \right)
\]

with \( \mathbf{z}_i \) is the observation point, \( \mathbf{x}_i \) the position of the hypothesis, and \( \sigma_i \) the standard deviation.

With point-cloud from an RGB-D camera, a robot can distinguish different unknown objects when the objects are spatially separated by clustering in the Euclidean space. As a human moves the objects and contact them with each other, the robot has difficulty to further distinguish each object. The solution is to keep tracking the objects, thus contacted objects can still be distinguished. To track the 6 DOF object pose accurately, often recursive Bayesian Filtering is used. Especially particle filter is suitable, because it can handle non-linear motions induced by human and non-Gaussian noise. In a particle filter framework, a large amount of hypotheses need to be evaluated. The hypothesis evaluation function should reveal how close the hypothesis to the observation is, such that the pose estimate can be integrated from multiple hypotheses. The hypothesis evaluation function should be also computationally efficient due to the real-time requirement. In this work, to improve the efficiency and the accuracy of the hypothesis evaluation, we propose Joint Color-Spatial Descriptor (JCSD) that represents a probability density of a measurement point in the joint color-spatial space.

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\]

with \( \mathbf{z}_i \) is the observation point, \( \mathbf{x}_i \) the position of the hypothesis, and \( \sigma_i \) the standard deviation.

The proposed method is implemented with GPU programming and tested with real-scene data. The pose tracking accuracy is hard to evaluate, because model-free tracking was performed, therefore instead of evaluating the 6 DOF directly, we evaluated tracking accuracy with fitting distance. Fitting distance specifies the average distance between tracked object model points to the observation points. In Fig. 2 the better performance of our method compared to [1] is shown. The mean tracking time for one object using 100 particles takes ca. 4 ms, while [1] needs ca. 40 ms. For tracking 4 objects (Fig. 1) including online segmentation and model update, the computation time takes ca. 52 ms, which ensures the real-time capability.

REFERENCES


Robotic Calligraphy: Learning From Character Images

Omair Ali\textsuperscript{1}, Affan Pervez\textsuperscript{2}, Dongheui Lee\textsuperscript{2}

I. INTRODUCTION

Known as the 'art of combining strokes to form complex letters', the Chinese and Korean Calligraphy can be learned by assimilating the skill of drawing these strokes. Once this dexterity is mastered, it can be used to compose a calligraphic letter afterwards. The very notion of calligraphy is endeavored to be implemented on robots in this research. Korean calligraphy is the nucleus of this research and the image of the calligraphic character is used as an input. Unlike humans or calligraphers, the robots are unacquainted with combination of various strokes used to draw a calligraphic letter. Hence it is quite cardinal and arduous to fragment the calligraphic letter into diverse strokes used to draw it. Therefore this has been the area of interest for many researchers which led to couple of unalike approaches like in\cite{1},\cite{2} and\cite{3} but with some drawbacks. Authors in\cite{1} used geometric properties of contour of the character to extract the stroke which fails in even very simple case like shown in Figure 13 in\cite{1}. Hence a novel approach ensuing Gaussian Mixture Model (GMM) is proposed in this research to segregate the input image into assorted strokes. Once the strokes are extracted, they are combined to reproduce the same character using Gaussian Mixture Regression (GMR). The resulted learned strokes are then implemented on KUKA Light Weight Robot and further improved using RL.

II. PROCEDURE FOR STROKE EXTRACTION

A. Image Pre-processing

First, the image is pre-processed to make it compatible to be estimated by GMM. This phase comprises thinning of input image. The image is thinned to prevent the GMM from modeling the thickness of the strokes.

B. Gaussian Mixture Model

In the second phase, the GMM as mentioned in\cite{5} is learned on the data points obtained in the first phase. Its parameters are estimated using Expectation Maximization algorithm and Bayesian Information Criteria is used to determine the number of clusters required to fit the data set.

C. Extraction Algorithm and Gaussian Mixture Regression

The third phase is the core of this research. In this step, a novel stroke extraction algorithm is proposed. The algorithm combines the clusters that represent the respective stroke based on the following rules. The components represent one stroke if:

1) Distance between intersecting point of two adjacent GMM components and the end point of the under-observed Gaussian is less than a threshold.
2) Angle between intersecting axes of GMM components is less than a threshold.
3) The end point of an intersecting axis of a GMM component lies with in the Gaussian distribution of intersecting cluster.

Once the corresponding clusters are combined to represent a stroke, GMR is used to get the smooth trajectory of the stroke. The information regarding the thickness of the stroke is extracted directly from the original image of the calligraphic letter.

D. Dynamic Moment Primitives (DMP) and Reinforcement Learning (RL)

A stroke encoded using GMM has a high number of free parameters which become problematic when applying RL. Hence, to reduce the number of parameters, the trajectories extracted using GMR are re-encoded using DMPs. The resulting character is implemented on a robot i.e. KUKA LWR. Its parameters are updated by using EM based RL\cite{4} which results in iterative improvement of the learned skill. The update policy is shown by Equation 1

\[ \theta_{new} = \theta_{old} + \sum_{j=1}^{K} \gamma_j \epsilon_j \sum_{j=1}^{K} \gamma_j \]  

where \( \theta_{new} \) = learned parameters of DMP, \( \theta_{old} \) = old parameters of DMP, \( \gamma_j \) = Correlation between original image and image reproduced by robot and \( \epsilon_j \) = exploration terms.

III. RESULTS

Results are shown in form of Figure 1 explicitly. The Figure 1 shows step-wise procedure of extracting stroke from original image. The characters reproduced by robot after several iterations are shown in Figure 2. The Figure 2c shows the character reproduced by robot after 7th iteration of RL. It has the highest correlation with original image which is shown in Figure 2d. The parameter update is performed after every ten reproductions with the importance sampling factor of five. The Figure 2d shows the correlation between reproduced character and original image and it is used as reward for RL.

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Fig. 1: (a) Shows the original image of calligraphic letter, (b) Shows the GMM fitted image of calligraphic letter, (c) Shows the extracted Strokes.

Fig. 2: (a) Shows the character before reinforcement rearning, (b) Shows the character after 3 iterations, (c) Shows the character after 7 iterations (d) Reward against number of iterations. The higher the better.


I. Motivation

Series Elastic Actuators (SEA), which consist of a motor and link that are attached to each other with an elastic element, were first introduced in [5] and have since then significantly influenced the design of robotic systems. Two main advantages of these actuators are their robustness and their ability to store potential energy in their elastic elements. While robustness of SEA makes robots equipped with them well-suited for interaction with the environment, the stored elastic energy enables these robots to achieve high link velocities which in turn increase their performance [3]. High link velocities, however, can be dangerous for humans interacting with robots so that control strategies need to be found which brake SEA sufficiently fast. In this line of research, we introduce a time-optimal feedback-controller which brakes SEA with linear springs and limited torque inputs in the fastest possible way.

II. Approach

Our approach to derive the desired time-optimal feedback controller is mainly based on Optimal Control Theory and in particular Pontryagin’s Minimum Principle (PMP) [2], [4]. Applying PMP to the SEA model depicted in Fig. 1, we first show that for braking SEA in minimum time the motor torque needs to either periodically switch between its maximum and minimum value or remain constant at one of these values. Then, we make use of this property to analytically describe the set of all states at which the torques change their signs along time-optimal braking strategies, i.e. we construct the switching locus corresponding to our problem [1]. Finally, a thorough analysis of the structure of the switching locus yields the desired time-optimal control law.

III. Results

The constructed switching locus, which is illustrated in Fig. 2, turns out to be a two-dimensional connected piecewise-smooth surface consisting of countably many smooth surfaces and curves [6]. Moreover, the union of these surfaces and curves with time-optimal paths, on which constant torque input is applied, can be shown to divide the three-dimensional state space into two separate regions where the optimal torque needs to take either its maximum or minimum value depending on the region (See the time-optimal trajectory in Fig. 2). In addition, it can also be shown that for a time-optimal trajectory with switching torque inputs the corresponding path always remains on the switching locus after the second to last switching of the torque input. These geometrical properties are exploited in the design of the proposed time-optimal feedback controller, which in principle determines the state’s current position in the three-dimensional state-space with respect to the switching locus. Simulation results verify our theoretical results as well as the performance of our proposed controller.

REFERENCES

A Preliminary Study on the Learning Informativeness of Data Subsets

Simon Kaltenbacher\textsuperscript{1}, Nicholas H. Kirk\textsuperscript{2} and Dongheui Lee\textsuperscript{2}

Estimating the internal state of a robotic system is complex: this is performed from multiple heterogeneous sensor inputs and knowledge sources. Discretization of such inputs is done to capture saliences, represented as symbolic information, which often presents structure and recurrence. As these sequences are used to reason over complex scenarios [1], a more compact representation would aid exactness of technical cognitive reasoning capabilities, which are today constrained by computational complexity issues and fallback to representational heuristics or human intervention [1], [2]. Such problems need to be addressed to ensure timely and meaningful human-robot interaction.

Our work is towards understanding the variability of learning informativeness when training on subsets of a given input dataset. This is in view of reducing the training size while retaining the majority of the symbolic learning potential. We prove the concept on human-written texts, and conjecture this work will reduce training data size of sequential instructions, while preserving semantic relations, when gathering information from large remote sources [3].

\textit{Posterior Evaluation Distribution of Subsets}

We computed multiple random subsets of sentences from the UMBC Webbase Corpus (~17.13GB) via a custom implementation using the Spark distributed framework. We evaluated the learning informativeness of such sets in terms of semantic word-sense classification accuracy (with \textsc{Word2Vec} [4]), and of n-gram perplexity. Previous literature informs us that corpus size and posterior quality do not follow linear correlation for some learning tasks (e.g. semantic measures) [5]. In our semantic tests, on average 85\% of the quality can be obtained by training on a random ~4\% subset of the original corpus (e.g. as in Fig. 1, 5 random million lines yield 64.14\% instead of 75.14\%).

Our claims are that i) such evaluation posteriors are Normally distributed (Tab. I), and that ii) the variance is inversely proportional to the subset size (Tab. II).

It is therefore possible to select the best random subset for a given size, if an information criterion is known. Such metric is currently under investigation. Within the robotics domain, in order to reduce computational complexity of the training phase, cardinality reduction of human-written instructions is particularly important for non-recursive online training algorithms, such as current symbol-based probabilistic reasoning systems [1], [3], [6].

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
\textsc{Word2Vec} & 100 subsets of 1M & 100 subsets of 5M & 100 subsets of 10M \\
\hline
$\chi^2$ & 0.4221 & 0.5756 & 0.9189 \\
$\beta$ & 0.8749 & 0.7616 & 0.8710 \\
$\gamma$ & 0.2963 & 0.2435 & 0.2443 \\
\hline
\end{tabular}
\caption{Chi-square and Anderson-Darling tests showing there is no Gaussian null hypothesis rejection for \textsc{Word2Vec} and perplexity accuracy values of random subsets (10\% significance level).}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
\textsc{Word2Vec} & variance & 100 subsets of 1M & 100 subsets of 5M & 100 subsets of 10M \\
\hline
\textsc{Perplexity} & 2.6199 & 213.21 & 1.0551 & 118.87 & 0.6147 & 55.218 \\
\hline
\end{tabular}
\caption{Variance values of \textsc{Word2Vec} and perplexity accuracy posteriors of random subsets.}
\end{table}

\begin{thebibliography}{10}
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Control architecture for human-like motion with applications to soft robotics

Cosimo Della Santina¹, Matteo Bianchi², Manolo Garabini¹ and Antonio Bicchi¹,²

The unparalleled versatility of human motor control system allows human beings to perform so much effectively and safely a great variety of tasks such as: balancing, walking, running also in uneven terrains, grasping and manipulating objects, just to cite a few. Responsible for the achievement of a so high level of performance are: (i) the musculo-skeletal system allowing to exert force and torques, to adjust its dynamics (e.g. joint stiffness via co-contraction of antagonist muscles), and to perceive the external world through a multitude of receptors; (ii) the Central Nervous Systems that is able to cope with the complexity of such a body and to exploit its full-potential.

As clearly stated in [14] two are the main obstacle the CNS must overcome to solve the Motor Control Problem: (i) Unknown nonlinear dynamic: human body is a complex system, with strong nonlinearities at every level. Moreover environmental force fields can not be known a priori. (ii) Degree of freedom (hereinafter DoF) redundancy problem. Three types of redundancy are typically identified. Anatomical: Human body is characterized by a complex highly redundant structure. The number of joints is greater than the number DoFs necessary to accomplish a generic task, and the number of muscles is greater than the number of joints. Kinematic: Infinite joints trajectories can achieve the same task, or simply perform the same end effector point to point movement. Neurophysiological: The muscle consists of hundreds of motor units, and they are activated by moto-neurons that can spike with different frequency (hundreds of variables).

Understanding how CNS can overcome these problems is an open problem yet, and no univocal theory exists. For the sake of comprehension and without any claim of exhaustiveness, let us briefly summarize the fundamental approaches proposed in literature to deal with these issues (for a complete review on motor control theories, see appendix ??). The neural process ensuring this behavior is called synergy¹ [15]. In [16], [9] authors propose a control system able to explain synergistic behavior in studies of finger coordination. Finally a fundamental contribute is the so-called Equilibrium Point Hypothesis (EP-H hereinafter) that can be regarded as base paradigm for soft robotics, see appendix ?? for further details. In [13] EP-H is merged together with UCM and synergy hypothesis. Despite the variety of works in motor control field, to the author best knowledge, an architecture based on control theory able to present at the same time various CNS behavior still lacks. In this work our goal is to make a step further towards this direction: taking inspiration from motor control theories, we implemented a hierarchical control architecture exhibiting well-known characteristics of human motor control system (i.e. learning by repetition, anticipatory behavior, synergistic behavior). Such a control framework is a

![Control structure](image)

Figure 1: Control structure. $u$ is the low level control variable or afferent action, $\pi$ is the high level control variable, $\mathit{ref}$ is the reference in the task space, $q$ is the position vector, $\dot{q}$ is the speed vector, $x = [q, \dot{q}]$ is the state vector, $y$ is the output vector, $h(\cdot)$ is the output function. The control system is supposed equipped by a complete proprioception.

as memory formation, decision making, and selection among alternatives.

Optimal control have been successfully exploited to represent a wide range of behavior, e.g. synergy [24], trajectory formation [7], [25]. The Uncontrolled Manifold (UCM hereinafter) hypothesis [22] assumes that the CNS selects a sub-space (called UCM) of elemental variables corresponding to a desired value of an essential performance variable, and then impose low variability in the directions orthogonal to the UCM, and high variability into the UCM. The neural process ensuring this behavior is called synergy¹ [15].

¹Note that in motor control theory there exist different definitions of the concept of synergies, which are used to explain a high level of motor coordination at different levels, see e.g. [20], [5]
proper combination of feedback control, feedforward, Iterative Learning Control and Model Predictive Control.

A major contribution of this work is to show how well-established paradigms belonging to the control theory can be used to approach motor control problem. Finally the authors want to clearly state that is beyond the scope pf this work to infer possible neuro-physiological implications based on the presented control framework. On the other hand we consider the application of this control law to soft robotic systems [1], which are robotic systems designed to obtain human-like behavior in terms of smooth movements, shock absorption, safety and performance improvements. These robots are actuated by compliant mechanisms. Historically the first one of these actuators was the serial elastic actuator, with passive fixed impedance [19]. An important evolution was the introduction of actuators with variable impedance, stiffness (VSA) or damping. Many mechanical architectures exist, for an exhaustive review please see [26]. Among the different technological solutions qbmove [4] is a modular-servo VSA multi-unit system, which implements an agonist-antagonist mechanism, obtaining a muscle-like dynamics (as described in the appendix).

Beside the described similitudes with the human musculoskeletal system, soft robots present also problems analogous to the ones previously reported for CNS: • Unknown nonlinear dynamics: It is well-known that robots are commonly nonlinear Furthermore, systems such as soft actuators typically present complex, nonlinear, hard-to-model dynamics.
• DoF problem: Soft robots present both anatomical (they typically have more than one motor per joint) and kinematic redundancy.

For this reason to control soft robot remains a very challenging task. Indeed, the majority of existing model-based control approaches has the strong drawback of requiring an accurate model identification process, which is hard to be accomplished and time consuming. In [17] feedback linearization of VSA is faced. In [8] the problem of choosing the inputs for maximizing the velocity of a link at a given final position is addressed. In [2] a framework for simultaneous optimization of torque and stiffness, incorporating real-world constraints is proposed. On the other hand model-free algorithms are promising but still confined to specific tasks, as for example induction [12] or damping of oscillations [18].

Our belief is that a control system able to work like the CNS, such the one proposed here, can successfully manage a soft robotic system. We test here this hypothesis, among with the human-like behaviors, both in simulation and in experiments, using as testbed qbmove system.

REFERENCES
The Robotic Sixth Finger: a compensatory tool for regaining grasping capability in chronic stroke patient

Gionata Salvietti¹, Irfan Hussain¹, David Cioncoloni³, Simone Rossi³ and Domenico Prattichizzo¹,²

EXTENDED ABSTRACT

The number of patients with long-term disabilities resulting in an impairment of an upper limb due to stroke are of the order of millions. However, the majority of the robotic devices are specifically designed to increase the functional recovery of the hand/arm in the first months after stroke, when, in some cases, biological restoring and plastic reorganization of the central nervous system take place. To the best of our knowledge, few devices have been designed as tools to compensate for hand/arm function when in the paretic upper limb the motor deficit is stabilized. In this view, wearability of the robot becomes a key feature in the design process, since the compensation tools should be used by the patients also outside the rehab facilities. Pons outlined in [1] two possible categories of wearable robots: exoskeletons and prosthetic robots. The former are designed to complement the ability of the human limb and restore the handicapped function usually mapping onto the anatomy of the human limb. The latter are electromechanical devices that substitutes for lost limbs after amputation. The Robotic Sixth Finger goes beyond these definitions introducing a new paradigm where the robot is grounded on the human body but is not mechanically coupled with the human limb. Referring to the scenario in Fig. 1, the robot is worn on the user forearm and can accomplish a given task in cooperation with the hand/arm. The device cooperate with the paretic hand/arm to constrain the motion of the object. The Robotic Sixth Finger can be worn on the user’s forearm by means of an elastic band. The systems acts like a two-finger gripper, where one finger is represented by the Robotic Sixth Finger, while the other by the patient’s paretic limb. The first prototype designed for healthy subject has been presented in [2], while in [3] we presented a mapping algorithm able to transfer to the extra-finger a part or the whole motion of the human hand. A commercial dataglove was used to measure the hand configuration during a grasping task. Although this control approach guarantees a reliable tracking of the human hand configuration during a grasping task. Although this approach guarantees a reliable tracking of the human hand configuration during a grasping task, it considered the motion of the whole hand to compute the motion of the extra-finger, thus limiting the possibility of the user to make fine adjustments so to adapt the finger shape to that of the grasped object. In [4] we addressed this issue by introducing a new control strategy that enabled the finger to autonomously adapt to the shape of the grasped object.

The experience gained with healthy subjects was fundamental for the development of an extra-finger for compensating hand function in chronic stroke patients. The first prototype for chronic stroke patients was proposed in [5]. The device is a modular system actuated with servomotors. The patient can regulate the finger flexion/extension through a wearable switch embedded in a ring worn on the healthy hand. To test the usability of the proposed device for grasp compensation, we set up several experiments involving subjects in a chronic state including the Frenchay Arm Test and common bimanual tasks. The Robotic Sixth Finger resulted to be easy to use and showed great potentials in preliminary tests with patients.

REFERENCES


Variable Stiffness Control for Oscillation Damping

G. M. Gasparri†‡, M. Garabini†‡, L. Pallottino†‡, L. Malagia†‡, M. Catalano†‡, G. Grioli†‡ and A. Bicchi†‡

Soft Robotics [1] is becoming more and more popular in the research community since it has been proved that the introduction of fixed or adjustable compliant and/or damping elements substantially increases the robot performance. Indeed, at least three robot characteristics take advantages by the introduction of passive elasticity in the robot design: robustness, energy efficiency and peak performance. The robustness against unpredictable impacts can be increased as the passive compliance acts as a low-pass filter cutting the peak forces and preserving the gearboxes life [1]. The possibility to store and release energy into the springs can be exploited to increase the energy efficiency of Soft Robots in cyclic motions (see e.g. [2], [3]). Optimal control studies ([4], [5] and [6]) showed how the peak speed of a conventional motor can be more than doubled if a spring of proper stiffness is used.

Several soft actuation concept have been presented (for an updated review see e.g. [7] and [8]): from Series Elastic Actuation (SEA) [9] to Variable Stiffness Actuation (VSA) [10] to actuators in which it is possible to vary both stiffness and damping at physical level [11]. In more recent years, complex multi-joint Soft Robots have been presented such as the DLR Hand Arm System [12] and the CompActTM arm [13], or the ready to use and low cost qbmove platform based on the VSA Cube [10].

In Soft Robots, on one hand, it is desirable to have the joint damping as small as possible for i) maximising efficiency in cyclic tasks and ii) allowing highly dynamic motion. On the other hand, a low damping value poses challenges if a precise tracking in point-to-point motions is required. Hence it is desirable having a variable damping in softrobots. A solution to the problem of having variable damping is to physically add, in the robot design, the possibility to adjust the damping (see e.g. [11] , [13]) at the cost of increasing the complexity and the weight of the structure. An alternative approach is the active damping control as the one proposed in this work.

Several solutions for damping control have been implemented in the literature such as: feedback linearization [14], linear-quadratic regulators [15], learning control schemes [16], or modal state-based feedback controllers [17]. A drawback of these approaches is the requirement of a model of the robot. In case of Soft Robots this leads to the necessity of a model identification process that, given the complex dynamics of the system, is a challenging and time-consuming task. Moreover, the model representation itself is prone to imprecisions. Finally, these approaches (e.g. feedback linearization) attempt to strongly change the dynamics of the system often leading to use a high control authority in order to stabilize a linear desired dynamics. Recently, a model–free damping control approach has been presented in [18] where the kinetic energy stored into the elastic transmission is dissipated by the motor. The approach in [18] is composed of two phases: in the first one the spring is completely loaded (i.e. the link velocity is null) and the reference position is moved towards the link position to stop the link, in the second phase the link is smoothly moved toward the desired position.

In this work we present a model–free approach for damping control of VSA that takes advantage of the possibility to change the stiffness. Our approach differs from the one presented in [18] because the proposed one i) is derived from optimality conditions for a one DoF system and ii) it does not require to bring the system in the desired position after having dissipated the energy but it allows to set the reference position in the desired position itself.

The Optimal Control (OC) theory has been chosen as the fundamental tool to solve the abovementioned problem. This choice is motivated by the fact that OC is a key element in understanding planning and control methodologies for soft actuators (see e.g. [5], [4] and [19]). A careful analysis of results, obtained through either analytic or numerical techniques, allows to distillate laws summarising control policies that can be applied to different tasks.

In this work we first formalize the problem of minimizing the terminal energy for a one DoF spring–mass model in which the stiffness is assumed to be the control input. Afterwards we show through a complete analysis that, under suitable conditions, the optimal control law for the stiffness is bang–bang like and the switches occur when the product of the link

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† Centro di Ricerca E. Piaggio, Univ. of Pisa, 56126 Pisa, Italy. ‡ Italian Inst. of Technologies, Adv. Robotics, 16163 Genova, Italy. This work is supported by the EC under the grant agreements no.611832 Walk-Man and ICT-287513 “SAPHARI”.
speed and the spring deflection changes sign. The rationale of the law is that the stiffness transmission should be maximum when the link is slowing down and getting away from the desired position and minimum when the link is speeding up and going towards the desired position. Therefore, the first result is that the optimal control policy for the stiffness can be summarized in the rule: stiff slow-down and soft speed-up. The schematic of the model used for the optimal control problem and the optimal control law are showed in Fig. 1. Notice that the stiffness control law is opposite with respect to the one found in previous works [4] and [20] where the objective was to maximize the link terminal speed. Furthermore we show, through Lyapunov stability theorems, that the same policy can be profitably applied to a multi–DoF system to substantially increase the rate of convergence toward a desired configuration. Finally we validate theoretical results with simulations and experimental tests performed on the qbmoves, a VSA derived by the VSA Cube [10].

REFERENCES


Phase-based assistive controller for lower-limb powered orthosis

Andrea Parri1, Tingfang Yan1, Federica Vannetti2, Guido Pasquini2, Raffaele Molino Lova2, Nicola Vitiello1,2

Abstract — This work presents a phase-based assistive controller for lower-limb powered orthoses. The preliminary results in adaptively assisting a healthy subject during ground-level walking are here presented.

I. INTRODUCTION

The design of powered orthoses should satisfy physical requirements related to a comfortable and safe utilization, but also cognitive features ensuring their intuitiveness and acceptability [1],[2]. An efficient cognitive interface should be able to decode: (i) the intended movement of the user – for instance ground-level walking, stairs climbing – and (ii) the phase of the periodical high-level locomotion task [3]. In this work we focused on the design of a phase-based assistive controller for an Active Pelvis Orthosis (APO) [4] which can synchronize with the gait phase for providing a gait-phase dependent assistive torque in a time-continuous fashion.

II. MATERIAL AND METHODS

The phase-based assistive controller relies on the capability of Adaptive Oscillators (AOs) to continuously synchronize with the features of a quasi-periodic input signal [5]. In a previous work, an oscillator-based gait-phase estimator was coupled with the vertical ground reaction forces (vGRFs) - collected from wearable sensitive pressure sensors - to extract the phase of the periodic locomotion task [6]. The gait-phase estimator consists of three blocks: AOs for learning the phase and frequency of the monitored variables (vGRF); an event detection block for detecting the heel strike during walking and triggering the computation of the actual phase error; a learning block responsible of updating and compensating the error on top of the AOs phase. As a result, the output is an accurate estimate of the gait-phase of the wearer [6].

Grounded on the gait-phase estimation process, the phase-based assistive controller allows to generate a torque vs. gait-phase assistive profile for an APO for providing a user-tailored and time-continuous assistive action, adaptive to the main volitional changes of the walking pattern. In this work the desired assistive torque $\tau_{\text{des}}(\varphi)$ is represented by the following equation:

$$\tau_{\text{des}}(\varphi) = \sum_{i=1}^{n} A_i \cdot e^{-(\varphi-s_i)^2/\omega_i}$$

where $A_i$ is the amplitude of a torque peak; $\omega_i$ its duration over the stride cycle; $s_i$ the center of the peak on the gait-phase $\varphi$; $n$ the number of torque peaks. In this study, $n = 2$ - one positive peak at the pre-swing phase and a negative peak in early stance phase. An example of $\tau_{\text{des}}(\varphi)$ is provided in Figure 1(b). The controller has been preliminary validated with an experimental session involving one healthy volunteer at the premises of Fondazione Don Carlo Gnocchi (Florence, Italy). The volunteer was requested to walk on a treadmill for 10 minutes changing the walking speed every 2 minutes in the following order: 2.4 – 3.4 – 4.4 – 3.4 – 2.4 km/h. The parameters of the assistive torque were finely tailored on the subject in a preliminary familiarization session.

III. RESULTS AND CONCLUSIONS

Collected variables - i.e. vGRF and gait phase estimate - were segmented from the 0 to 100% of the stride cycle being the 0% associated to the right heel strike. As it can be seen in Figure 1(a), the gait-phase estimate resulted in the normalized timescale of the stride cycle in the range [0;2π] rad. The maximum error with respect to the ideal reference is only 0.13 rad (3.1 % of the gait cycle) meaning that the feature of the assistive profile are minimally scattered around the selected values. The assistive torque, designed to assist specific phases of the gait cycle, showed a maximum standard deviation of only 4% of the maximum commanded torque Figure 1(b).

Results confirm that the phase-based assistive controller is a suitable choice for assisting ground-level walking in a time-continuous fashion wearing a powered orthosis. In future works other torque vs. gait-phase shapes will be designed for assisting the user in different tasks (for instance stair climbing) and the performance of the system will be investigated when transiting between different locomotion-related tasks (for instance from ground level-walking to stairs climbing).

Figure 1. Output of the phase-based assistive controller. (a) vGRF and estimated gait phase averaged over the percentage of the gait cycle. (b) Assistive torque profile as a function of the gait-phase.


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Andrea Parri is corresponding author: phone: +39 050 883016; email: an.parri@sssup.it
REFERENCES


Experimental Test of Synergies Computed on the SCHUNK S5FH under-actuated Hand

Fanny Ficuciello, Damiano Zaccaria, Luigi Villani, Bruno Siciliano

Abstract—In this paper, a method for synergies calculation developed for an anthropomorphic 15 DOFs hand, characterized by one to one mapping between configuration space and fingertip position in the Cartesian space, has been tested on the under-actuated SCHUNK S5FH anthropomorphic hand. The grasping capabilities of the hand controlled in a three dimension synergies subspace have been tested. The results demonstrate that the data set of grasps, measured on human hands, and the mapping method of human hand synergies, based on fingertip measurements and inverse kinematics, is efficient enough to compute suitable synergies subspace where it is possible to plan and control anthropomorphic hands for grasping actions, despite on the hand kinematics and actuation system.

I. THE SCHUNK S5FH

The Schunk S5FH has anthropomorphic structure very similar to the human hand for shape, size and overall cosmetic appearance. Indeed, the Schunk hand is 1 : 1 ratio to the human hand and weights 1.3 [kg]. The control, regulator and power electronics is integrated in the wrist, this allow an easy connection with market-standard industrial and lightweight robots. The current technology, however, does not allow to arrange twenty or more motors within a robotic hand having dimensions similar to those of human and ensuring appropriate requirements of speed and strength. As the matter of fact, the S5FH has 20 joints and 9 DOFs led by as many servo motors. The number of motors is significantly lower than the number of joints, thus joint motion couplings are regulated by means of mechanical synergies defined via mechanical transmission design. The reader can find the whole technical data, hardware and software specifications in [1] and [2].

II. POSTURAL SYNERGIES

About synergies computation, a data set of grasping configurations measured on human hands have been used to apply a mapping method, available from previous works, consisting on mapping human synergies to a robotic hand. This method has been adapted to the under-actuated S5FH hand that already has its own mechanical synergies. To go into details of grasping data and mapping method the reader is referred to the works [3], [4]. The differential kinematic mapping between the mechanical synergies subspace and the Cartesian space, used in the inverse kinematic algorithm used for synergies mapping is represented by the following equation

\[ \dot{x} = J_{h_s} \dot{m}, \]

where \( J_{h_s} \) is the synergies Jacobian and is computed as

\[ J_{h_s} = J_h S_m \]

and \( x \in \mathbb{R}^{15} \) is the position vector of the five fingertips, \( J_h \) is the S5FH jacobian, \( S_m \) is the matrix of the mechanical synergies, and finally \( m \) is the vector of the motor angles. Once the synergy matrix has been computed different power and precision grasps have been reproduced using only the first three synergies in order to test the efficiency of the mapping method on an under-actuated hand kinematics. In Fig. 1 a tripod grasp executed in the synergies subspace is depicted. The experiments demonstrate the efficiency of the mapping method and the potentialities of controlling the hand in a 3 DOFs synergies subspace.

REFERENCES

Inverse Kinematics with Multiple Tasks and Multiple Task Definitions

Sang-ik An and Dongheui Lee

Abstract—We discuss inverse kinematics methods focusing on multiple tasks and multiple task definitions.

I. INTRODUCTION

A robot in the human friendly environment is required to execute tasks that are usually performed by human. A significant ability of humans is the variational dexterity, so human can assign more degrees of freedom (DOFs) of the body to the more important task, while executing multiple tasks on the same time. Also, human can easily change tasks in the middle of executions to adapt to the dynamic variation of the environments. This ability allows human to have complex and sophisticated behavior and it is demanded to build a control method for the robot that resembles humans.

II. MULTIPLE TASKS

In the robot kinematic control, a task can be defined as a tuple $T \triangleq (x, \dot{x}_d)$ where $x = J(q)\dot{q} \in \mathbb{R}^m$ is the task velocity and $\dot{x}_d(q, t) \in \mathbb{R}^m$ is the desired velocity of $x$. If there are multiple tasks $T_1, \ldots, T_k$ with $T_i \triangleq (x_i, \dot{x}_d, i)$, $x_i = J_i(q)\dot{q} \in \mathbb{R}^m$, and $\dot{x}_d, i(t) \in \mathbb{R}^m$, we can consider priority relations between tasks, so an unprioritized accumulation of tasks, $(T_1, \ldots, T_k)$, has equal priority relations between tasks and a prioritized accumulation of tasks, $[T_1, \ldots, T_k]$, has totally ordered priority relations in which $T_i$ has higher priority than $T_j$ if $i < j$. The unprioritized inverse kinematics (UIK) is to find the joint velocity $\dot{q}$ in $\mathbb{R}^n$ that minimizes the total task error: $\dot{q}^* = \arg \min_{\dot{q}} \sum_{i=1}^{k} \|\dot{x}_d, i - \dot{x}_i\|^2 = J^T_1 \dot{x}_1$ where $J \triangleq [J_1^T \cdots J_k^T]^T$, $x_d \triangleq [x_1^T \cdots x_k^T]^T$, and $J^1$ is the Moore-Penrose pseudoinverse of $J$. The prioritized inverse kinematics (PIK) is to find the joint velocity $\dot{q}$ that minimizes a task error on the condition that task errors of the higher priority tasks are not changed: $\dot{q}^* \equiv \hat{q}_i^*, \hat{q}_j^* = 0$, and $\dot{q}^*_i = \arg \min_{\dot{q}_i} \|\dot{x}_d, i - \dot{x}_i\|^2$ subject to $J_{i-1}^T \dot{q}_i = J_{i-1}^T \dot{q}_{i-1}$ where $J_{i-1} \triangleq [J_1^T \cdots J_{i-1}^T]^T$. Recently, we have reformulated PIK solutions in both recursive and closed forms by using QR decomposition (QRD) and Cholesky decomposition (CLD) in order to resolve the imperfect orthogonalization problem of conventional methods [1]:

\[
\dot{q} = \tilde{R}^{-1} \tilde{q}_k, \quad \dot{q}_k = \dot{q}_{k-1} + J_k^T C_d^1 (x_i - \dot{q}_{k-1}), \quad \dot{q}_0 = 0
\]

\[
\dot{q} = \tilde{R}^{-1} \tilde{J}^T (I_m + C_d^1 C_L) C_d^1 \tilde{x}
\]

where $W \triangleq \tilde{J}^T J + \delta^2 I_n = R^T \tilde{R}$ is the CLD, $J_{R} \triangleq J^R J$ is the QRD of $J^R$, $C_{ij} = \mathbb{R}^{m_i \times m_j}$ is the $(i, j)$-th block of $C$, $J_i \in \mathbb{R}^{m \times m_i}$ is the $i$-th block of $J$, $C_p \triangleq \text{diag}(C_{ii})$, $C_{ij}^1 \triangleq \text{diag}(C_{ij}^1)$, and $C_L \triangleq C - C_D$. $C_L \triangleq C - C_D$.

III. MULTIPLE TASK DEFINITIONS

In a complicated task scenario, the definition of tasks can be dependent to the condition of the environment and a robot needs to change tasks in the middle of task executions. We define a basic task $T \triangleq (T_1, \ldots, T_k)$ as an unprioritized task of basic subtasks $T_j$ that does not change its definition during whole operation time. Then, we can construct (induced) tasks $T^i \triangleq \{T_{1}^i, \ldots, T_k^i\}$ by accumulating a subset of basic subtasks with the priority relation between (induced) subtasks $T_j^i$. For every task $T^i$, we can always find a PIK solution $\hat{q}^i = \text{PIK}(T^i)$ by using the aforementioned PIK methods. If we introduce a null task $\emptyset$ along with $\hat{q}_0 = \text{PIK}(\emptyset) \triangleq 0$, then we can define an (induced) task set $\mathcal{T} \triangleq \{T_1^i, \ldots, T_k^i\}$ that contains all tasks considered and an inverse solution set $\mathcal{Q} \triangleq \{\hat{q}_1^i, \ldots, \hat{q}_s^i\}$ that contains all PIK solutions of $\mathcal{T}$. The mapping $\text{PIK}: \mathcal{T} \rightarrow \mathcal{Q}$ is surjective, so we can work with inverse solutions to find joint velocities that allow task transitions among $\mathcal{T}$, instead of directly working with tasks. Lately, we have proposed the task transition control (TTC) that provides smooth, arbitrary, and consecutive task transitions within $\mathcal{T}$ by using barycentric coordinates and linear dynamical systems [2]:

\[
\dot{q} = \sum_{i=1}^{l} w^i \dot{q}^i, \quad w^{s+1} = -\sum_{j=1}^{s} k_j w^j + k_0 (w_d - w)
\]

where $W \triangleq [w^1 \cdots w^l]^T \in \mathbb{R}^l$, $w^{j}(s) \triangleq \delta^j d^j w^j / dt^j$, $s \in \mathbb{N}_0$, $w_d(q, t) \in \{\tilde{e}^1, \tilde{e}^2, \ldots, \tilde{e}^l\} \subset \mathbb{R}^l$, $w(0) \in \{a \in \mathbb{R}^n: 1^T a = 1, a \geq 0\}$, $w(0)^{(l)} = 0, 1 \geq \{1, \ldots, l\} \in \mathbb{R}^l$, $\{\tilde{e}^1, \ldots, \tilde{e}^l\}$ is a set of the standard basis in $\mathbb{R}^l$, and $\{k_0, \ldots, k_h\} \subset \mathbb{R}$ are stabilizing control gains that do not generate overshoots of the $(s + 1)$-th order linear dynamical system.

IV. CONCLUSIONS

A general kinematic control framework that is capable of multiple tasks and multiple task definitions is proposed. The method is expected to be used to build a sophisticated robot behavior in the human friendly environment.

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Machine-learning based teleoperation in hybrid position/force mode of a humanoid robotic platform

Alexander Werner, Markus Nowak, Claudio Castellini, and Máximo A. Roa

Stable myoelectric control of hand prostheses is still an open problem, although recent advances have been obtained using surface electromyography (sEMG) as the human-machine interface. This approach typically allows control of a few degrees of freedom. However, the main challenge is that myoelectric signals change over time under the influence of various factors such as muscle fatigue, changes in conductivity or electrode displacement, thus deteriorating the control performance. The new interactive machine-learning system summarized here is able to predict finger forces from myoelectric signals, grouped in four predefined grasping patterns (plus one additional gesture for preshaping) employing a realistic and fast per-subject calibration method [1].

The algorithm used is an incremental variant of Ridge Regression (RR) [2], which supports computationally efficient updates of the regression model when new training samples arrive. As linear models are typically not sufficient to model the relationship between sEMG and finger forces, this work combines incremental RR with Random Fourier Features (RFFs) [3] to allow the exploitation of non-linearities. The resulting algorithm is referred to as incremental Ridge Regression with Random Fourier Features (iRFFRR), and has shown excellent generalization performance even with a relatively modest number of training samples. Predictions and model updates do not increase the required computational resources, regardless of the number of updates, thus making it apt for real-time applications.

The implementation of the system was realized in the DLR humanoid platform TORO. The TORO (TORque controlled RObot) is a full-body humanoid with 27 DoFs, excluding the hands [4]. The end effectors are two i-LIMB Revolution prosthetic hands by Touch Bionics [5]. The i-LIMB Revolution is a state-of-the-art multi-articulated hand prosthesis with five active, independently drivable fingers and one active opposable thumb. The hands were fitted with development firmware, allowing direct access to the power electronics driving the six DC motors.

Teleoperation of the robot is achieved via a hybrid position and force/torque control, with visual feedback as the only cue for the operator. A Polhemus FastTrak magnetic position tracking system, equipped with two sensors (one per hand), is used to detect in real time the positions of the subject’s wrists, which are then used to enforce a compliant behavior via Cartesian impedance-based position control of the robotic arm. At the same time, the motors of the prosthetic hands are simultaneously and proportionally controlled using two Myo armbands by Thalmic Labs [6], each of which has eight sEMG sensors onboard. The armbands are placed on the subject’s forearms. The finger forces estimated by the proposed machine-learning method were scaled and used to directly drive the finger motors.

The system is able to provide accurate and stable predictions of finger forces and grasping patterns. In particular, experiments with a single-handed version were presented in [7], where subjects demonstrated reliable grasping, carrying and placing several objects in a large daily-life setup (Fig. 1), irrespective of hand/arm movements, wrist pronation and supination, and signal changes. The main application of the system so far is as a test-bench for myocontrol of prostheses for hand amputees. Potential extensions include the usage of sEMG to control walking, standing and sitting, and as a rehabilitation aid for stroke patients.

REFERENCES

Automatic Model-Based Controller Design of Reconfigurable Manipulators for Human-Robot Cooperation

Andrea Giusti and Matthias Althoff

Abstract—We present a novel approach to overcome limitations related to the control of modular and reconfigurable robot manipulators. Most previous work has faced this problem by designing decentralized controllers without exploiting the use of the overall system dynamics. In this cases, safety and dependability of the manipulator for Human-Robot cooperation may be limited since the use of related advanced model-based methods is not yet possible. This can result in injury to humans after assembling the robot. We propose a completely different approach based on distributed data stored in each module using centralized model-based control methods. The data in the modules is collected in a central controller after assembly (or reconfiguration) of the robot to synthesize kinematics, dynamics and model-based control laws on-the-fly. This ensures global asymptotic stability, which is a prerequisite for Human-Robot cooperation using reconfigurable modular robot manipulators.

I. INTRODUCTION

Reconfigurable modular robot manipulators [1] can be re-assembled for different applications introducing a clear advantage with respect to fixed-structure robots. This is especially useful in flexible environments, e.g. service robots and robots for Human-Robot cooperation. Considering a scenario where humans and robots can closely cooperate, reconfigurable modular robots have the advantage that their structure can be adapted to meet the different needs of the users by reducing their bulkiness when possible or increasing their workspace and dexterity when required.

II. MOTIVATION AND PROPOSED METHOD

The control design of this class of robots is challenging due to the changing system dynamics resulting from possible reconfigurations. The advantage of reconfigurable robots would be greatly reduced if for every reconfiguration controller redesign or tuning procedures were required. In contrast to previously published approaches, we propose a method for automatic derivation of model-based controllers using a kinematic and dynamic model of an arbitrarily assembled manipulator, considering modules with heterogeneous kinematic and dynamic properties [2]. Our proposed kinematic modelling approach is based on an novel notation and an extension of the standard Denavit-Hartenberg convention, while for dynamics we use the recursive Newton-Euler algorithm. Our proposed approach is illustrated in Fig. 1: each module is first characterized according to our proposed notation, which is stored within the module. After the selection of the modules and the manual assembly of the robot, the automatic controller design process starts. First, information related to the kinematics, dynamics and a unique identification number are collected from all modules by the central control unit. Next, the centralized controller is automatically generated to let the robot operate with guaranteed motion control performance.

III. CONCLUSION

Our proposed method enables the automatic design of model-based control laws guaranteeing the prerequisite of global asymptotic stability for reconfigurable modular robots with heterogeneous modules with the advantage of fast commissioning after reconfiguration. Additionally, also implementation of model-based collision detection and reaction strategies [3] for reconfigurable modular robot manipulators is enabled by our proposed approach.

REFERENCES

Verifiably Safe Trajectory Planning for Human-Robot Interaction

Aaron Pereira and Matthias Althoff

Abstract—We present a framework for verifiably safe trajectory planning of robots in shared workspaces with humans. Our approach takes international safety standards as a starting point and builds an approach with a view to industrial certifiability. In contrast to previous methods, we guarantee the robot will always perform safe motions. Robot dynamics are faster and more complex than previous situations where real-time reachability analysis has been applied, e.g. autonomous driving. The novelty in our method is a time-accuracy trade-off in which nonlinear terms are computed offline so that online, computation is drastically reduced. We consider serial link manipulators under computed-torque control. Simulation results are promising with real time within reach.

I. INTRODUCTION

Ensuring safety in industrial human-robot interaction is paramount for cageless, flexible factories and closer co-working desirable in future manufacturing. Strict international standards govern working environments of robots around humans, but even these are not guaranteed free from injury, for example, safety cages pose a clamping hazard as well as protection. Similarly, reduction in power and speed in the presence of a human as required by [1] is not certain to prevent injury.

II. APPROACH

Our method calculates reachable sets of the robot and the human in real time, given an uncertain dynamic model of the robot and based on standard maximum movement speeds of the human [2]. The criterion for safety is that the robot is stationary whenever the human is able to touch any part of it. This is guaranteed at each timestep, see Fig 1, by a) planning several alternative trajectories, b) checking, at each timestep, whether the next portion of the trajectory is safe using reachability analysis and c) updating the robot path if necessary to the desired safe trajectory or, if no trajectory is safe, d) coming to a previously verified controlled stop.

Taking robot dynamics into account introduces complexity. Fast stops may induce vibration and exceed torque limits. The calculation of torque is highly nonlinear in the state of the robot \([q^T, \dot{q}^T]^T\), where \(q\) are joint positions; for calculations on a set of states (rather than a single state), these computations would bring our algorithm far beyond real time. For this reason, the state space is gridded and nonlinear terms are calculated over each subset of the state space using interval arithmetic. The intervals of nonlinear terms are then saved in a lookup table for fast access online.

The forward kinematics to calculate the occupancy is also nonlinear, therefore a novel method using interval transformation matrices and zonotope representation of robot links is developed, which calculates occupancy much faster even than sample-based, underapproximative approaches.

III. RESULTS

This approach has been tested in simulation using a PUMA 560 and a light curtain to detect the human and calculations were within 10 times real time [4]. The approach is due to be implemented on the GRAIL sandwich assembly robot from RURobots Ltd\(^1\). Although our current method only considers robots under computed torque control, future research will extend this to all control regimes and optimise code to real time. Eventually, we envisage this strategy for guaranteeing safety in robot trajectory planning being certifiable for use in industry.

REFERENCES


\(^1\)RURobots Ltd., PO Box 248, Manchester, UK
Adjustable Stiffness Gripper for Industrial Applications

S. Mahboubi, S. Davis, S. Nefti-Meziani, T. Theodoridis
School of Computing Science & Engineering, University of Salford

Abstract—we present a new design of variable stiffness one-synergy gripper for pick-and-place applications. With respect to this task, it is essential to have a variable stiffness gripper to modify the rigidity of the fingers for different objects. Although the gripper presented utilises just one synergy, the extension of this design to more degrees of freedom is possible and is our future plan.

I. DESIGN EXPLANATION

Similar to most of the variable stiffness designs we utilise two rotational actuators. A CAD model of our variable stiffness gripper can be found in Fig. 1. As shown in this figure, the model consists of two servo motors. One of the servos provides compliance of the gripper and the second one is used to produce a linear displacement along the arm of the gripper and hence open and close the gripper. We used a rack and pinion gear arrangement for this purpose. The first motor M1 is fixed on this slider and it can move by moving the slider. A tendon was attached offset by spring to the axis of M1, so that the joint angle of M1 varies compliance of the gripper.

II. MODELING OF THE STIFFNESS FUNCTION

Fig. 2 shows the gripper in both open and closed states with minimum and maximum stiffness. In this figure the red grippers correspond to the stiff gripper with infinite stiffness, and the blue ones correspond to the gripper with minimum stiffness, which is equal to the stiffness of the springs K. As shown in the figure, in both states related to the stiff gripper, the angles between the tendon and spring are perpendicular and in the blue grippers, which correspond to the minimum stiffness, the tendon lies along the spring. Fig. 3 illustrates the changes in stiffness of the gripper by changing the α. In this diagram the x axis is the displacement of the end point of the tendon because of the change of the length of the springs, and the y axis is the stiffness of the gripper. In this simulation, we assumed springs with 2 N/cm stiffness constant. The Young’s modulus, diameter and density of the tendon are assumed 20 GPa, 0.3 mm and 4 g/cm³ respectively. In this graph the dark blue line demonstrates the stiffness of the gripper when α = 0. There is a plateau in the stiffness of the gripper with the value of 2 N/cm, and is equal to the stiffness of the springs. As expected the output stiffness rises by increasing the α, where the dramatic increase in the stiffness (black curve) is related to the maximum degree of the simulation when α = 60°.

Fig. 2. Gripper in maximum (red) and minimum (blue) stiffness.

The results between shallow and steep lines increase steadily, and they are related to the angles 5, 10, 15, 20, 25, 30, 35, 40, 45, 50 and 55 respectively.

Fig. 3. Stiffness of the gripper σ₀ in different α.
Learning soft task priorities for control of redundant robots

Valerio Modugno1,4, Gerard Neumann2, Elmar Rueckert2, Giuseppe Oriolo1, Jan Peters2,3, Serena Ivaldi2,4

I. INTRODUCTION

One of the key problems in the control of redundant robots is generating suitable controls when multiple tasks and constraints need to be satisfied. In the literature, this problem is classically solved by multi-task prioritized approaches, where the relative importance of the tasks is expressed by the task priorities. The two main approaches are based on strict or soft priorities.

In approaches based on strict task priorities, a hierarchical ordering of the tasks is defined, such that the low-priority tasks are solved in the null-space of the higher priority, critical tasks [1], [2]. These approaches typically require the definition of the task hierarchy a priori. However, in many contexts, it is difficult to organize the tasks in a stack and pre-define their relative importance in forms of priorities. When priorities are strict, a higher-priority task can completely block lower-priority tasks, which can result in movements that are not satisfactory for the robot mission (i.e., its “global” task). Approaches based on soft task priorities provide an appealing alternative solution, typically given by a combination of weighted tasks priorities [3], [4]. However, the simultaneous execution of different elementary tasks with variable soft priorities can lead to incompatibilities that might generate undesired movements, or still prevent the execution of some tasks. In both cases, when the number of tasks increases, the priorities and their transitions are manually tuned by expert users.

In this work, we propose to leverage machine learning techniques to learn the temporal profiles of the task priorities, represented as parametrized weight functions: we automatically determine their parameters through a stochastic optimization procedure.

II. PROPOSED METHOD

We assume that the set of elementary tasks is known, and that each task can be executed by a given torque controller \( u_i \). The global movement can be evaluated by a fitness function \( \phi \) that can be used as a measure of the ability of the robot to fulfill its mission. Our method aims at automatically learning the task priorities \( \alpha_i \) to maximize the robot performance. The priorities \( \alpha_i \) are parametrized weight functions, with \( \pi_i \) free parameters to be optimized.

As a learning algorithm, we propose the Covariance Matrix Adaptation Evolution Strategy (CMA-ES) [5], a derivative-free stochastic optimization algorithm, in view of its good exploration properties and ease of use.

III. RESULTS

We will discuss our results obtained with both a simulated and a real Kinova Jaco arm: our method not only improves the performance of the movement in terms of fitness values (over existing task priorities that have been manually tuned), but the optimized trajectories are robust with respect to the initialization of the learning process. We also compare on a simulated Kuka LWR the performance of our method with the state-of-art GHC controller [6], where the task weights are typically hand-tuned. We show that our method is not only better in terms of performance, but also computationally 10 times faster.

REFERENCES

Individual differences and social signals during a human-robot assembly task

Serena Ivaldi¹  Sebastien Lefort²  Jan Peters³,⁴  Mohamed Chetouani⁵  Joelle Provasi²  Elisabetta Zibetti²

I. INTRODUCTION

Our aim is to improve the design of robot controllers for human-robot interaction, particularly for cooperative manipulation and assembly. We study the interaction through the analysis of the exchanged social and physical signals, such as gaze, speech, forces. The dynamics of these signals is likely to be influenced by individual and social factors, such as personality traits, as it is well documented that they critically influence how humans interact with each other.

In this work, we seek a deeper understanding of the inter-individual factors that influence the dynamics of such signals during an assembly task, where a human must physically manipulate a robot to assemble an object. We assess the influence of two factors: extroversion and negative attitude toward robots (NARS). We evaluate if the score of extroversion and NARS co-vary with the duration and frequency of gaze and speech cues. We also analyze duration of interaction, of consecutive trials, tactile and force maps. We report on the experiments with the humanoid robot iCub and N=56 adult participants. Our results provide evidence that the dynamics of social signals exchanged during assembly tasks with a robot is influenced by individual factors.

II. STUDY DESIGN

We designed an assembly task to highlight, if they exists, differences in the dynamics of the exchanged signals due to the individual factors. In particular, based on the literature in psychology and HRI, we make the hypothesis that extroversion and negative attitude towards robots influence the production of speech and gaze signals: precisely, that they correlate with the duration and frequency of utterances, gaze directed towards the robot face and the robot hands where the contact occurs.

In the experiment, the human participants had to cooperate with the humanoid robot iCub [1] to assemble an object. The participants had to grab the robot arms to demonstrate the correct action to perform the assembly and explain the actions to the robot. The robot was semi-autonomous, partially controlled by an operator, while the interaction was monitored by an experimenter. The experimental protocol received approbation from the Ethics Committee of our local University.

N=56 voluntary adults took part in this study: 37 women, 19 men, aged 19 to 65 (mean=36.95, σ=14.32). To evaluate the personality traits of the participants, we used two questionnaires: the Revised Personality Inventory (NEO-PIR) [2] and the Negative Attitude towards Robots Scale (NARS) [3].

III. SOME RESULTS

Our results [4] indicate that the more people are extrovert, the more and longer they tend to talk with the robot; and the more people have a negative attitude towards robots, the less they look at the robot face and the more they look at the robot hands where the assembly and the contacts occur. Our results also show that across three trials, the performance of the participants in the physical contact improves.

The final goal is to turn our findings into implications for the design of robot controllers that can adapt to the individual differences of the human partners.

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Modal limit Cycle Control of Compliant Joint Robots for Energy Efficient Periodic Motions

Navvab Kashiri, Emmanouil Spyarakos-Papastavridis, Darwin G. Caldwell, and Nikos G. Tsagarakis

The incorporation of intrinsic elasticity into joints decreases the output impedance, which can improve the performance of robots in terms of robustness, safety, and energy efficiency. Hence, the use of actuators possessing passive compliance in robotic systems has drawn increased attention during the past decade. Adding passive flexibility to the joints can boost the output power of the robot, as the overall power is no longer dependent only on the motor powers and it can also be amplified through the passive elasticity. Optimal control techniques have been widely used in trajectory generation of explosive motions such as ball-throwing and kicking. However, the use of such methods for multi-Degree-Of-Freedom (-DOF) systems is currently computationally expensive and restricted to off-line calculations due to the typical calculation complexity of optimal control approaches.

The control of robots performing cyclic motions have been studied in several works. Limit cycle walking is a well-known example of periodic motions which has been broadly researched for rigid-joint robots. Since the potential of Series Elastic Actuator (SEA)-based manipulators, in terms of producing periodic trajectories, is well-established, the control of such dynamic motions for compliant joint robots has been studied in several works. The aim and contribution of this work is to study and provide an understanding of the effect of the joints’ compliance, as well as the operating vibration mode, on energy efficiency of compliant joint actuated robots when performing periodic motions. This work therefore presents a novel scheme for generating modally decoupled limit cycle motions.

For a given the \( k \)-link serial manipulator, shown in Fig. 1, the dynamic equations of this nonlinear system can be described using the Euler-Lagrange method. Manipulators that are fully powered by compliant actuators possess as many passive DOFs (link positions) as active ones (motor positions). The control of such dynamical systems, SEA-based robots, using feedback linearization control (FLC) methods has been widely studied. However, the implementation of a majority FLC techniques leads to a set of fourth-order link position error equation, including jerk and snap, that complicates physical interpretation of modal responses. In this work, a FLC approach is studied, in order to linearize the dynamics of robots possessing nonlinear compliance and damping in their transmission systems, in such a way that the modal decoupling can be carried out.

Having linearized the system dynamics, the use of a modal coordinate transformation allows for a modal decoupling of the full dynamics. When considering fully actuated dynamical systems, the complete modal decoupling could be achieved; however, the afore-described system is under-actuated and direct cancellation of some coupling terms is not feasible. Since the employment of a transmission torque controller is also ineffective, as the dynamics of coupling terms in such motions is faster than the admissible bandwidth of these controllers, a cancellation torque for minimization of the coupling terms is executed.

The reference link position that excites a target modal motion, is therefore generated based on the natural dynamics response of the system. In order to exploit the natural dynamics of the system, it is necessary to set its natural frequencies to the target values by tuning its active and passive stiffness. In order to excite the target modes, their damping ratios are set to zero, while the damping ratios of the other modes are set to one, in order to critically damp any undesired oscillations. In order to evaluate the energy efficiency during periodic motions, an index \( \eta \) relying upon the energy of the system in dynamic conditions is defined as the ratio of the output mechanical energy to the input mechanical energy.

\[
\eta = \frac{E_{\text{out}}}{E_{\text{in}}} = \eta(t)
\]

Fig. 2: Time evolution of the energy efficiency index in simulation of a two-DOF planar manipulator powered by viscoelastic joint actuators, when executing a combined mode motion (mode one and two). For a target oscillatory motion, the principal component frequencies are set to 1 and 6 Hz.

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Authors are with the Department of Advanced Robotics, Istituto Italiano di Tecnologia, Via Morego 30, 16163 Genoa, Italy.
Design Methodology for the Internal Springs of a Lever-arm Based Variable Stiffness Actuator

Eamon Barrett, Matteo Fumagalli, Stefano Stramigioli and Raffaella Carloni

Abstract—This work presents a design methodology for an Ω-shaped leaf spring for a lever-arm based Variable Stiffness Actuator (VSA). Design requirements and guidelines are developed analytically and realized through finite element analysis with the aim of maximizing the VSA’s torque-deflection workspace.

I. INTRODUCTION

The torque-deflection workspace of a VSA [1] is limited by the actuator’s maximum output torque \( \tau_{\text{max}} \) and passive output deflection \( \phi_{\text{max}} \), but also by the internal spring’s energy absorption capacity, which in turn depends on its stiffness \( k \) and maximum deflection \( s_{\text{max}} \), as illustrated in Fig. 1a. For a given pivot position of a lever arm based VSA [2] the output deflection is thus limited to \( \phi_{\text{max}*} \) with the corresponding torque \( \tau_{\text{max}*} \) by the spring deflection \( s_{\text{max}} \):

\[
W_{\text{max}} = \int_{0}^{\phi_{\text{max}*}} \tau(\phi) \, d\phi \approx \frac{1}{2} \cdot \phi_{\text{max}*} \cdot \tau_{\text{max}*} = \frac{1}{2} \cdot k \cdot s_{\text{max}}^2 \tag{1}
\]

II. DESIGN METHODOLOGY

A. Design Requirements

The energy that can be stored in the spring should be maximized, while meeting practical design requirements. Firstly the spring’s dimensions are limited by the size of the actuator. Secondly, the springs of lever arm based VSAs need to achieve a certain maximum deflection \( s_{\text{max}} \) in order to limit the internal loads on the pivot point of the lever.

B. Design Guidelines

In order to maximize the energy capacity, the spring’s shape and thickness have been laid out such that it is as stiff as possible, while the stress remains below a permissible level. Distributing the stress as uniformly as possible maximizes the strain energy in the material [3].

A strong, but flexible material, with high yield strength and low Young’s modulus is needed for a VSA’s internal elastic elements. A large modulus of resilience ensures high energy storage, while a low Young’s modulus allows to achieve the required deflection \( s_{\text{max}} \).

C. Finite Elements Analysis

The design guidelines have been implemented with the aid of finite elements analysis. Two materials have been selected: spring steel, a classic spring material with very high yield strength and high Young’s modulus, and the engineering plastic Polyoxymethylene (POM), with lower yield strength but also much lower Young’s modulus. The simulated torque-deflection workspaces are shown in Figure 1b. The compliant spring material POM allows for a larger torque-deflection workspace than steel, and thus greater energy storage. A VSA with POM spring has been realized (see Fig. 2).

III. CONCLUSIONS

The presented design methodology allows for a systematic design procedure that gives insight into how the spring parameters affect the performance of a VSA and takes practical requirements into account.

REFERENCES

