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BioRob-Arm: A Quickly Deployable and Intrinsically Safe, Light-Weight Robot Arm for Service Robotics Applications.

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Abstract

Using conventional rigid industrial manipulators for service robotics applications typically demands huge efforts for safety measurements resulting in high installation and operation costs. We present how the BioRob robot arm is based on a combination of compliant actuation and lightweight mechanical design to obtain the flexibility, mobility and, most important, the inherent safety properties needed to implement effective and safe service robotics applications. We discuss the sensors and control structure used to damp the oscillations caused by the significant joint compliance of the arm and to obtain the accuracy needed for the intended applications. The concluding example of a typical pick and place application with teaching by manual guidance illustrates the benefits of the BioRob design for service robotics applications.

1 Introduction

Many small and medium enterprises (SMEs) are in need of improving their market position by increasing production and cost efficiency with robotic automation solutions. In contrast to major industrial enterprises, SMEs have to cope with frequently changing conditions of the production process more often. Automation of these applications demands service robots sharing workspaces with humans, featuring high collision safety, intuitive user interface and programming, the capability to flexibly change the surroundings and the place of deployment, as well as moderate costs for installation and operation. Common industrial robots currently available on the market are typically not flexible enough and too big or too expensive for these applications. In the last years, several efforts were made to reduce the deployment time of industrial robots. Nevertheless, the installation of robot systems is still a long and costly procedure. Particularly in small and medium enterprises this is a main hindrance for automation.

2 Service Robotics for SMEs

The following key requirements are important for successful practical establishment of service robots, especially in small and medium enterprises and applications with an unstructured and shared environment for humans and robots:

- *Safety*: Inherent safety at high speeds and human-friendly design boost efficiency and acceptance.
- *Flexibility*: Mobility and short installation and deployment times allow to quickly change the robot's location and to flexibly react to changing production conditions and current needs.
- *Usability*: Simple and intuitive programming that can be performed by untrained personnel.
- *Performance*: Task execution with speed and accuracy comparable to a human arm.

In contrast to conventional industrial applications, accuracy is in most cases less important than the listed requirements [1].

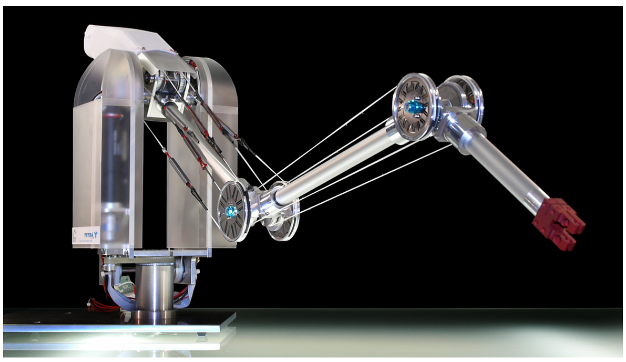

Figure 1: BioRob-X4 demonstrator

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2.1 Pre-collision safety

Collision safety can be divided in two phases, pre-collision and post-collision safety [2]. Pre-collision strategies aim at reducing the effects of an imminent impact, whereas post-collision strategies try to limit the forces the robot can apply while in collision with a person or object. Pre-collision safety can be obtained by padding the robot links, reduction of inertia and mass, as well as surveillance of the workspace around the robot by a virtual fence of non-contact sensors preventing collisions. Post-collision safety strategies include tactile sensors, active and passive compliance.

A pre-collision strategy to limit the maximum impact force that can be generated by a robot arm colliding with a static object to a preset value was proposed in [2]. A method evaluating explicit measures of danger was proposed in [3]. Recommendations for safe velocity and force limits for robots operating in the proximity of humans are states by the standard ISO 10218 [4]. It concentrates on separating the human and robot workspace as far as possible. Even in collaboration mode, a minimum distance depending on the relative velocity between human and robot is defined. A cooperation with physical contact is not covered. In collaboration mode, an tool center point (TCP) velocity limit of 250 mm/s and a dynamic power limit of 80 W or a static TCP force limit of 150 N are specified. Additionally, a special teaching and control device is needed which has to be pressed throughout the process. These demands restrict the efficient and ergonomic operation of the assistance robot system and moreover, a serious failure of the hardware or software can still result in dangerous collisions causing severe injuries.

The afore-mentioned strategies and standard guidelines aim at actively reducing the impact forces and the effective robot arm inertia. They alone are therefore not appropriate for human-robot interaction applications. Elimination of hazards through passive pre-collision strategies such as reduction of the robot arm mass and inertia by mechanical design is more effective and more fail-safe. Still, active pre-collision safety methods have the advantage to allow the definition of a quantifiable value for the maximum impact forces, thus being an important supplement to passive pre-collision safety strategies. The surveillance of the workspace is also very useful, as it can significantly reduce the probability of a collision.

2.2 Post-collision safety

Joint compliance is seen as an important strategy to increase post-collision safety. As showed in [5], it is however not suited to effectively reduce the maximum impact peak force, because the main impact phase is over before active compliance control methods relying on sensors and actuators with limited bandwidth can react. The performance of passive, mechanical joint compliance is better, due to a delay-free decoupling of motor and link.

A rigid robot manipulator can be made actively compliant by control with additional sensors. Two approaches have been proposed to achieve active compliance: force control and impedance control. Both are not designed to control or limit collision forces of robots [2]. Because of limited sensor and actuator bandwidth, the system behaves stiff in case of a collision. High safety properties can only be obtained when limiting the maximum joint velocity and operating at speeds far below the possible maximum speed. A high performance reduction is the result.

Instead of actively controlling the behavior of the robot, mechanical compliance can be build into the joints or links. The advantage is the possibility to save energy in the elastic elements. As opposed to active, controlled compliance, mechanical compliance exhibits a delay-free compliant behavior in case of a collision. As a result, the motor and link inertia are physically decoupled. This is particularly important when using high gearbox ratios. In that case, the reflected motor inertia can be of the same magnitude as the link inertia. Contrary to active compliance, passive compliance therefore reduces the impact forces to a certain degree.

An early concept with an constant elastic coupling between motor and link was the series elastic actuator [6]. When using a constant passive compliance design, a trade-off between performance and safety must be made, because the force and position bandwidth decline with increasing joint compliance, whereas compliance bandwidth increases. To overcome this limitation, variable compliance actuation is seen as a promising candidate. Several variable impedance actuation concepts were presented over the last years, such as distributed parallel actuation [7], antagonistic actuation [1], and others [8]. Almost all of the demonstrators of these concepts are still rather heavy and complex.

2.3 Flexibility

The project SMErobot presented the vision of a three-day-deployable integrated robot system and several technologies and demonstrators showing the feasibility of the concept [9].

Many SMEs, however, have to cope with frequently changing conditions of the production process. For these applications, there is a need for a mobile, cost-effective robot platform with installation, deployment and programming times of only a few minutes to be able to use the robot arm according to the current demand.

Further important requirements involve the intuitive and quick programming of the robot arm even by untrained personnel and the ability to operate it in the same workspace of humans without the need for costly and performance-reducing safety measures.

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3 BioRob Robot Arm

3.1 Mechanical design

The BioRob robot arm is based on an antagonistic, series elastic actuation concept inspired by the elastic muscle-tendon apparatus (**Figure 2**). Each joint is actuated by a DC motor coupled to the joint by four cables containing springs and other compliant elements as series elasticity. The resulting joint compliance possesses nonlinear, progressive spring characteristics. In addition to motor position sensors, also angular joint position sensors are used. The actuation design is described in detail in [10, 11].

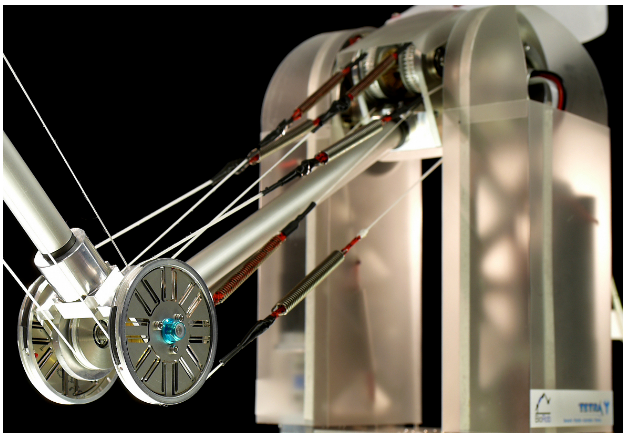

Figure 2: BioRob joint actuation

The BioRob arm used in this scenario consists of four elastically actuated joints. As can be seen in **Table 1**, the dead weight of the robot arm including power electronics is as low as 3.75 kg. Due to the antagonistic pulley actuation, most of the robot's mass can be located at the base of the robot arm. **Figure 3** illustrates the position of the motors and sensors in the robot arm. This results in low inertia and allows for installing less powerful and smaller motors and transmission elements, reducing the mass of the robot arm significantly.

Link	Mass [kg]	Length [m]
1	1.500	0.276
2	1.350	0.307
3	0.530	0.310
4	0.350	0.090
$\sum$	3.750	0.983

Table 1: Link masses and lengths (including power electronics and motors)

Because of the lightweight design, the arm is passive safe even when moving at high speeds. Compared to other light-weight robot arms, the mass and inertia are significantly reduced while preserving reaching range and speed. So even at high speeds and without use of collision detection, the BioRob robot arm is safe because of the resulting low kinetic energy. A typical pick and place operation can be performed with an overall power consumption of less than 20 W, approximately 10 times less than the energy consumption of conventional systems with comparable features and far below the 80 W power limit set by the safety standard for the operation of robot arms in the proximity of humans [4]. The robot arm can produce static forces up to 30 N, which is also far below the limit of 150 N set by the ISO standard. Reducing the maximum speed to the recommended limit of 250 mm/s is not necessary because of the low robot arm mass and inertia. The arm can handle payloads up to 2 kg, but for cooperative pick and place applications with a common workspace of humans an robots, best performance and maximum inherent safety is obtained with a maximum payload of 0.5 kg, according to the German BGIA recommendations [12].

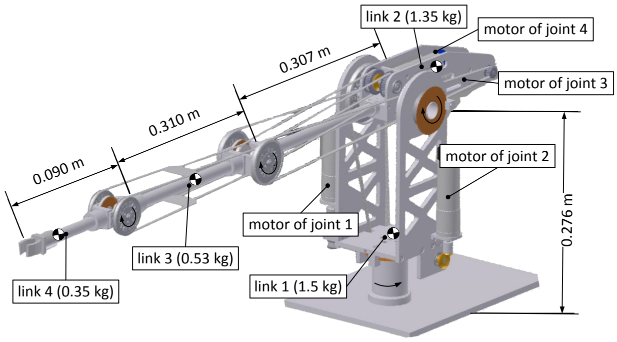

Figure 3: BioRob 4 DOF robot arm structure

The joints are elastically actuated with a joint stiffness between 15 and 30 Nm/rad. The elastic actuation results in higher control efforts for oscillation damping. As an advantage, the arm reacts compliantly in contact situations without delay. Position encoders in motors and joints ensure a cartesian accuracy below 1 mm. The position sensors also allow for measuring the elastic forces in the joints by using the joint stiffness characteristic curves, enabling force control, collision detection and reaction. The joint compliance is constant, but can be actively changed by means of control. As with all constant compliant approaches, force and position control bandwidth is indeed limited by the mechanical compliance, but due to low system inertia, the bandwidth is high enough for fast and reliably manipulation tasks.

The low overall system weight, the compliant actuation concept and very low power consumption are ideal features for use of the robot arm as a manipulator on a mobile platform and achieving long operation times.

3.2 Controller structure

Because of the high joint elasticity of the robot arm and the resulting oscillations, special control efforts are to be made for damping to achieve the cartesian accuracy needed for the targeted applications.

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Figure 4 shows the variables needed for the description of the mathematical model of an elastic joint. Important parameters are joint angle q, motor angle θ, link length l, joint elasticity k, motor inertia J, link inertia J_c and link mass m. The motor torque τ_m is the system input.

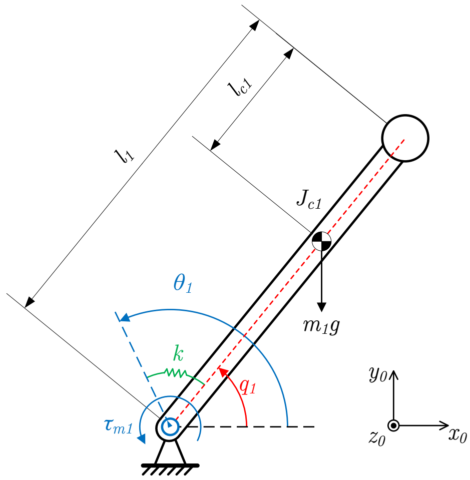

Figure 4: Model of a single compliant joint

The controller structure for the BioRob robot arm is shown in **Figure 5**. It consists of a global gravity compensation and a joint-level state space controller with integrative part, using the static desired motor positions $\boldsymbol{\theta}_d$ calculated from the given desired joint positions $\boldsymbol{q}_d$. A dynamic model based control algorithm was avoided, because it would need more control efforts and would be less robust. The controller ensures steady state accuracy, which is important for the accuracy of the pick and place positions at the start and end of the trajectory. The trajectory tracking error is of only minor importance for this application. The mechanical compliance compensates for remaining errors and inaccuracies from the imprecise teaching process by manually guiding the robot arm (**Figure 7**).

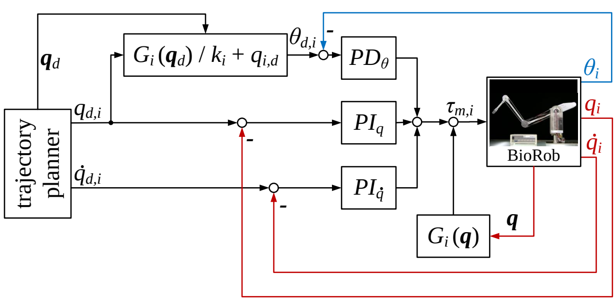

Figure 5: Controller structure of joint i

3.3 Safety properties and collision detection

Because of the compliant and light-weight mechanical design, collision detection of low force impacts is made possible using joint positions in addition to motor currents. Collision detection can be used to further reduce impact forces. In combination with pre-collision strategies such as proposed in [2] [3], the impact forces could be limited to very low values with only slight performance reduction.

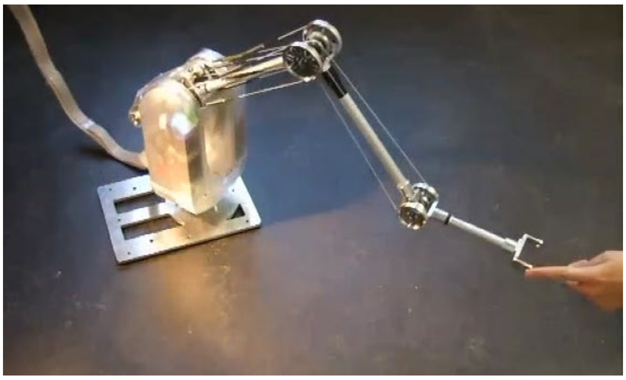

Figure 6: Collision detection (videos available on [13])

4 Pick and Place Application

Many applications in SMEs have only moderate demands regarding load and accuracy, but high demands regarding safety properties, performance and flexibility. In most cases, no automation solution for these applications exists. The features of the BioRob arm are suitable for these applications: loads up to 0.5 kg (maximal load 2 kg), trajectory start and end position accuracy below 1 mm, inherent safety even at high velocities, and quick deployment and programming.

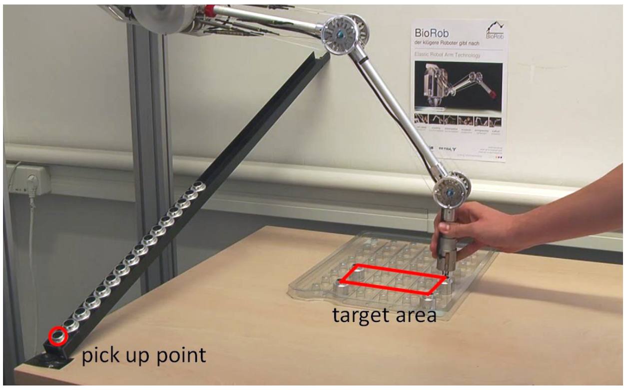

Figure 7: Teaching procedure (video available on [13])

This allows investigating many applications in SMEs, like shown here with handling of small aluminum parts. For this pick and place application, the robot is operated in a suspended position, very much like a human arm attached to the shoulder. This results in a more human-like workspace and is possible because of the low arm weight. As a benefit of the low system inertia and the high joint compliance, the robot's end effector can be moved by hand without effort, enabling fast programming of the robot by manually guiding the end-effector. The teaching process

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consists of programming five points: the pick up point and four points at the target area (**Figure 7**).
The teaching process can be performed faster and with less accuracy compared to rigid robot arms, because when executing the programmed trajectory, the joint compliance compensates for inaccuracies made in the teaching process. Therefore, there is no need for a time-consuming check and correction of the programmed trajectories and no additional safety monitoring systems are necessary. The trajectory can be tested online with the robot arm (**Figure 8**) without performing tests in simulation, even when humans are in range of the manipulator. For the pick and place operation, a cycle rate of five seconds is achieved at 20 % of the maximum motor power.

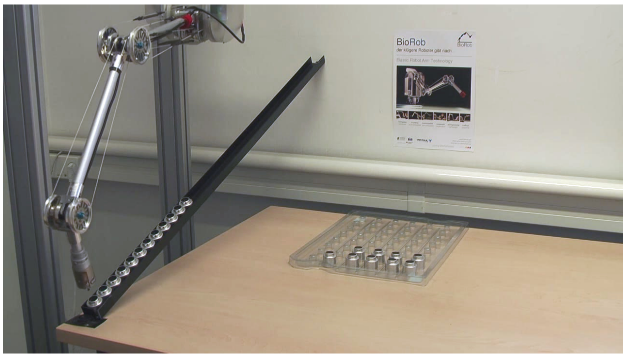

Figure 8: Pick and place procedure with a cycle rate of 5 s per part (video available on [13])

5 Conclusion

Service robotics applications with human-robot interaction pose high demands regarding safety, mobility and flexibility. It is hardly possible to meet these requirements with conventional, rigid robots. For many applications, an automation solution is therefore still missing.
The BioRob robot arm attains human-oriented features through light-weight design and antagonistic, series elastic actuation. It can be quickly adapted to changes in the production process, because a change of workplace including installation and teaching procedures is possible within a few minutes. The robot is inherently safe and can be used for cooperative applications with humans without need for safety surveillance systems. The mechanical joint compliance compensates for position inaccuracies, therefore allowing inaccurate and fast teachings by manually guidance of the end-effector, resulting in faster programming and quick adaption to new tasks and changing production conductions.
The exemplary demonstration of a pick and place task shows that, despite the high joint elasticity, the BioRob manipulator can be used to perform pick and place operations programmed by manually guided teaching. The teaching procedure takes less than 15 seconds and the accomplished cycle rates are high enough for most applications. The deployment time for a change of workplace and a complete system startup and manual guided teaching is as low as several minutes and even lower if the system is on standby.

6 Outlook

Future work will concentrate on reducing the pick and place cycle time. We expect that cycle rates comparable to the abilities of a human arm are conceivable when enhancing the controller further. Two mobile service robot demonstrators with BioRob arms as essential components are being developed and tested as survey, inspection and handling assistants coping with frequently changing production conditions in two selected SMEs. In contrast to many conventional automation solutions it is possible to integrate untrained personnel in the automation process, which is a crucial factor for its sustainable success and acceptance. Therefore, the usability of the demonstrators will also be an important concern. Demonstrators of the BioRob robot arm will be presented at AUTOMATICA 2010 fair.

7 Acknowledgments

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