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SAFE HUMAN INTERACTION WITH THE COMPLIANT ROBOT ARM BIOROB

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ABSTRACT

To open up a highly expanded functionality in direct cooperation with humans regarding mobile service and assistance robotics applications, as well as new applications in the field of automation in industries, the new biologically inspired, lightweight and elastic robot arm "BioRob" offers a new kind of human machine interaction. The functional principle of the robot arm permits the system to apply forces, to estimate the weight of payload and to detect collision and touch in a similar way as the human arm. Further this technology allows for a direct teach-in or a hand guided robot movement. In this paper, strategies for this novel, more flexible, easily reconfigurable and highly safe human robot interface are shown and discussed.

***Index Terms*—** human-robot interaction, compliant robot, collision detection, service robotics

1. INTRODUCTION

For many assembly lines industrial robots are indispensable. They are construed to execute routine processes with high speeds, endurance and precision. These conventional industrial robots are machine tools and entirely inapplicable to work in co-operation with humans. Only at the cost of additional safety measures such as mechanical security fences, electronic supervision systems or limitation of performance parameters, industrial robots can be deployed for service tasks together with humans. Still, these systems are only safe to a limited extent because of possible hardware and software failures. Flexible and fast programming, which is essential for efficient service robotics solutions, is also restricted by the hardware, as can be seen in the standard defining the safety requirements and regulating the use of industrial robots for service applications [1].

For safe and reliable human-machine interaction a new generation of robot arms is required. These robots need characteristics comparable to the human arm, as they are intended for safe interaction with humans in workspace designed for humans. The robot arm should have human-like capabilities such as handling, positioning, assembling, estimating weights, detecting collisions and guided movements. Ideally, the effort for programming these capabilities would be as small as possible, to achieve a "plug and play" behavior. The communication between robot and human should be as direct as possible, using the mechanical structure of the arm, especially in service and assistance applications.

Fig. 1. BioRob X4 Version 3

Compliant actuator design is widely seen as a key to increase safety and flexibility [2]. The BioRob robot arm aims at satisfying these requirements by combining passive and active joint compliance with an extremely light-weight construction, resulting in very low energy consumption and high fail-safe safety properties. In the following sections, we will describe the hardware design of the BioRob robot arm and discuss its passive and active (controlled) characteristics.

2. FUNCTIONAL CHARACTERISTICS OF A HUMAN ARM

The human arm is a manipulator, which is able to cover a huge range of tasks and applications. It consists primarily of a endoskeleton and a muscle-tendon apparatus with variable stiffness. The intrinsic accuracy of the human arm is rather low, but is increased by using the

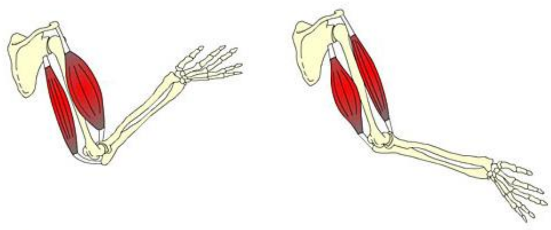

Fig. 2. Principle of movement of the human arm [3]

eyes as a visual feedback system. In addition, the biological compliance of the human arm supports grasping and contact situations, allowing for more inaccurate movements. Objects of various weights can be handled by varying the stiffness of the muscle-tendon apparatus. Collisions can be detected by the arm itself with a high level of safety. But most important for safety is the lightweight structure which results from the antagonistic arrangement of muscles and tendons as series elastic actuators which relieves the bones from bending stress when carrying a load (cf. Fig. 2). The lightweight structure also ensures a low energy consumption.

3. FUNCTIONAL PRINCIPLE AND DESIGN OF THE BIOROB X4 ROBOT ARM

The BioRob robot arm is a biologically inspired robot arm. The aluminum skeleton is the basic structure. Actuator and joint are connected by several compliant elements such as wires, linear and radial springs. These elements are coupled antagonistically. The effect of the springs in combination with DC motors is comparable to the human muscles. Springs in the transmission of robot joints provide a passive compliance, which is able to protect the motors and gearboxes from external shocks, and the users from the reflected inertia of the motors in case of a collision. Cables can transmit motions and forces similar to tendons and are much lighter than gears or chains. They allow placing the actuators away from the driven joints. In the BioRob robot arm, the actuators are located in the first and second link, reducing the system inertia and the energy consumption.

To be able to position the end effector exactly, an absolute measurement system fixed to the joints of the stiff skeleton is used (q in Figure 3). For this measurement system the elasticity is irrelevant. A second measurement system is located inside the motors of the robot (θ in Figure 3). By combining these two encoder systems, it is possible to calculate the deflection of the elastic coupled elements and estimate the joint torques.

The electronics including power amplifiers are completely integrated into the shoulder of the BioRob robot arm and can drive up to six joints. The robot is controlled by an ultra compact PC, which operates with a realtime Linux. The controller communicates with the robot via EtherCAT, a hard realtime capable bus system which allows very high control frequencies.

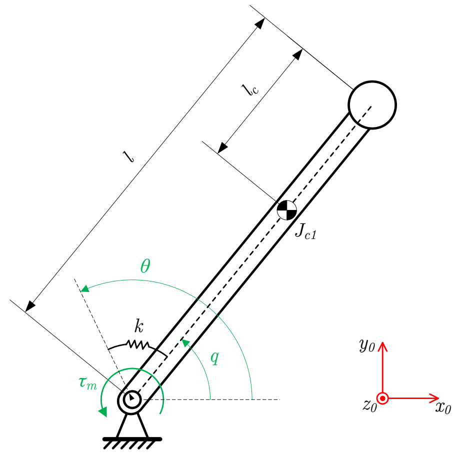

Fig. 3. Principle of a BioRob joint [4]

	BioRob X4
Compliant joints	4
Total weight (including controller PC and power electronics)	4 kg
Arm length (shoulder to flange)	666 mm
Length of first link (base to shoulder)	276 mm
Payload (maximum)	2 kg
Payload (nominal)	0.5 kg
Energy consumption (w/o load)	nominal 15 W
Mounting position	arbitrary
Power supply	12 V, max. 40 W
Controller	compact PC

Table 1. BioRob X4 parameters [8]

The load can have a weight of up to 2 kg, which is a remarkable high weight regarding to the robots weight of 4 kg (including the controller PC). The average energy consumption of the arm is about 15–20 Watts (also including the controller PC) and allows for using the robot arm on mobile platforms. Actual states of the robot system are shown by the full color column lights and presented by sounds which are played back by the integrated sound system.

Several patents were filed for the BioRob robot arm technology by Bernhard Möhl [5] and TETRA GmbH, Ilmenau [6],[7].

4. PASSIVE CHARACTERISTICS OF THE BIOROB ROBOT ARM

The reactions of the BioRob system to its environment are passive characteristics. A part of the belonging properties results from the robots mechanical structure, another part is implemented in the robots software and

Fig. 4. Manually guided teach-in [9]

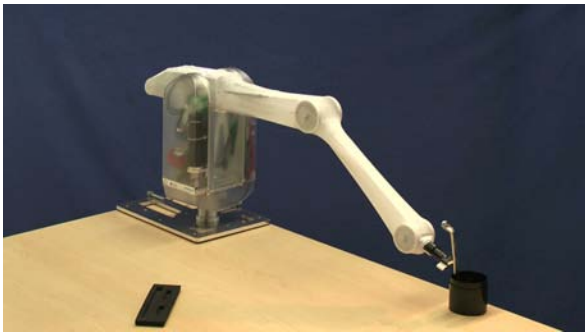

Fig. 5. Playback of the trajectory with unknown load [10]

control. Primarily passive characteristics are used for the human machine interaction between the user and the robot system.

Application based it can be complex to teach a robot a complete workflow trajectory. Using active properties, the possibility to move single or multiple axes via coordinate transformation is offered. Otherwise a much easier way is to take the robot passively "by the hand" to show it the desired trajectory. With conventional robots, this is not possible because of their weight and high gearbox ratios. The BioRob robot arm is very light-weight and in addition the motors, the heaviest part of the arm, are located at the opposite side of the joint to the next joints. Combined with a low, non self-locking motor gear ratio, a manual passive arm movement and positioning is easily possible for each user.

This property can be used for a direct hand guided teach in. The user takes the robots end effector at his hand, and moves the robot arm as needed for the particular application (Figure 4). To record the movement of the robot, several methods are feasible. For the first one, the user teaches a series of position setups step by step. Between these steps the BioRob trajectory generator plans the final trajectory. For the second one the complete movement will be scanned, saved and finally optimized. Using a special editor the trajectory can be changed, adjusted and optimized in a table of position sets in dependency of time. For another method if some kind of application profile exists the hand guided teach can be used for fast and easy calibration of this profile for trajectory generation, as described in [4] for a pick-and-place application as example. With this new process of trajectory teaching the robot is ready for an application between minutes and not days when using conventional robot systems.

The position difference between motor and joint can be used for gesture detection. As the robot structure can be moved easily because of the elasticity, it is very easy for a human to input gestures like pulling the end effector, pushing the robot or stressing it with a load to start trajectory playback or to reset the current collision state. So the robot itself plays the role of a human machine interface.

5. ACTIVE CHARACTERISTICS OF THE BIOROB ROBOT ARM

Active characteristics refer to properties of the robot, which can be realized by controlling the robot. Colliding on an object the mechanical compliance is a passive characteristic while the reaction of the controller is an active one.

Without a proper control the robot would not be usable because of the elasticity in the system. Appropriate controlling strategies are necessary to obtain good properties as a non-oscillating movement, good performance, such as high speed for pick-and-place applications, and adequate high positioning precision, depending on the application requirements.

The BioRob robot arm is a complex non-linear system. Single joint based PID-controllers, as they are often used in conventional industrial robots, are not sufficient. Necessarily non-linear model based controllers, which contain models of the drives, the elasticity and the robot structure, have to be used to obtain the desired properties. The controller considers the position sensor information from all motors and joints at the lowest level of control. Based in the models, a feed-forward control is possible, which allows to control the robot at a higher frequency and speed as the sensor information is coming for a closed control loop, increasing the performance.

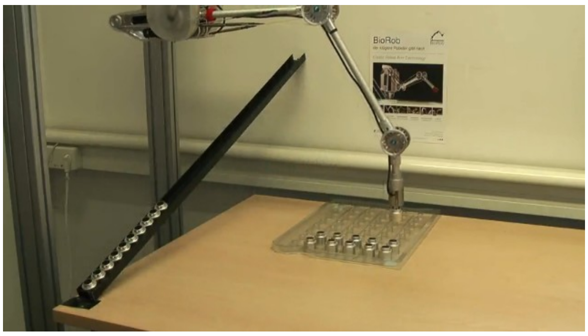

Fig. 6. Execution of a pick-and-place application [11]

An additional active safety property is realized, based on the dynamics robot model, by a collision detection and handling. The motor and joint sensor information can be used to determine the elongation of the elasticity, which can be seen in Figure 3. With this information, an estimation for the respective joint torque can be calculated. If the real joint torques differs too much from the computed joint torque, which is necessary to move the robot and the load, a collision is detected. This also allows limiting the joint torques on software side, which is realized by limiting the maximum difference between motor and joint position. If a collision is detected, the control switches to a special mode. Based on the user defaults, different collision handling strategies are possible, from stopping the trajectory, a bounce back, an active backward moving, disabling outputs or switching to a very soft mode, where the user can easily move the robot [12].

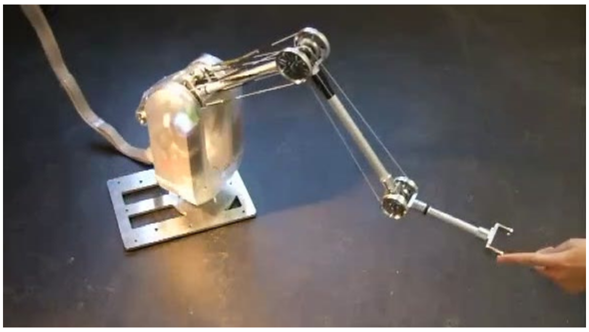

Fig. 7. Collision detection [13]

Based on the joint torque control and a zero-gravity mode, unknown loads can be measured. With the model based computed torque, it is known which static torques are necessary in every joint position and which dynamic torques are necessary to do specific movements. If a load is applied to the end effector, there is a difference between the model based computed torque and the real necessary torque at the specific positions or for the specific movements. This difference is measured as there is a higher position difference between motor and joint position sensor values. With this information an estimation can be made about the load the robot is carrying.

Other possible active strategies based on joint torque control and measurement of unknown load is a force assisted movement for a hand guided teaching or an assisted handling of objects. If a load is applied to the end effector, the robot can measure the load and take it into account in control. So if a human is doing a teaching or wants to move the robot, he does not feel that the robot has a load applied to the end effector. Or the robot can actively follow the applied movement from the human, so the human does only need to apply very low forces to move the robot arm. But if he releases the robot, the robot will stay in its position.

6. SUMMARY

For safe, flexible and reliable human-robot interaction in service robotics applications, novel types of robotic arms are needed. A lightweight structure and joint compliance, two key properties of the human arm, are essential to meet these requirements. We presented the BioRob robot arm that was designed for these applications. We discussed methods for fast reconfiguration and programming of service robotics applications.

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