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Biologically Inspired Robot Manipulator for New Applications in Automation Engineering

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Abstract

The fast growing interest in flexible, versatile and mobile robotic manipulators demands for robots with inherent high passive safety suited for direct human-robot interaction. To gain access to these new applications in the field of automation engineering where close vicinity and direct cooperating with humans are required, the “BioRob” project demonstrates the applicability of a new biologically inspired, lightweight and elastic “bionic” robot manipulator specifically designed for safe human-robot interaction. This paper presents the mechanical design and controller structure used for the new demonstrators with up to four compliant joints. The advantages of the design and potential application areas for the manipulator are discussed.

1. Introduction

Traditional industrial manipulators demonstrate outstanding specifications regarding precision and speed movement. But this performance can only be achieved by avoiding thoroughly any elasticity in the kinematic chain which would produce uncontrollable oscillations during motions. Adequate stiffness requires massive construction of the robot links, joints and gears, resulting in a poor ratio of payload to deadweight. Articulated robots of the size of the human arm weigh often more than ten times of its biological counterpart. Another drawback caused by the stiffness are rigid movements. Due to safety reasons industrial manipulators can operate efficiently only in an environment strictly separated from human interactions. Although safety restrictions exist for industrial robots, those manipulators are not primarily designed to interact directly with human users and cannot be easily applied in applications for human-robot interaction. Due to their large effective inertia, resulting in high impact loads, they have a high injury risk potential.

One way to enable human-robot interaction for small-size industrial robots is to add a compliant covering to reduce the risk in case of a collision, as done by different as safe classified commercially available robot arms. Another approach is to use additional, external sensors like cameras to monitor the environment of the robot and to slow down or stop its motions if a human comes too close, e.g., [3]. However, additional sensing equipments result in additional costs and additional space and time requirements for their installation and do yet not work reliably enough in any situation.

To overcome these safety and performance limitations, different alternative actuation approaches have been proposed in literature. The most widespread approaches are the active compliance, often used in industrial manipulators, and the approach of series elasticity. Each approach has its advantages making it suitable for special tasks but often at the expense of general applicability.

Active Compliance in Industrial Manipulators

Active compliance is achieved by active software control of a normally stiff robot. Measuring the reaction forces and moments or the position difference the motion of the manipulator can be adjusted according to the stiffness, i.e. spring rate, simulated in the controller [4], [5]. Since the compliance is achieved actively its response time is limited to the acceleration of the actuator and the bandwidth of the controller. Therefore, the manipulator may respond not fast enough to react on occurring impacts. Furthermore, the functionality is based only on the control software. A failure in the electronics, noisy sensor data or even a bug in the software can have serious consequences for the robot and its environment.

On the other hand, actively controlled compliance enables the generation of a wide range of possible force-elongation as well as an online adaptation of the compliance according to changing situations similar to the variability of the human muscle. To overcome these limitations, the use of passive elastic elements, e.g. springs, could be an answer.

Series Elastic Actuation

In recent years several examples of robot actuators with passive compliance have been propagated in the literature. The setup is basically a spring in series with a stiff actuator (Fig. 1). A similar setup is often used to model the joint elasticity of stiff robots. Many control approaches exists to handle unintentional elasticity in the joints caused for example by deformation in the gearing [6], [7], [8]. Due to the fact that only small joint deformations are assumed, these methods cannot be transferred directly to the class of series elastic actuators, where larger perturbations are common. Though starting from these approaches, an extended control approach can be developed to fit with the requirements of series elastic actuators.

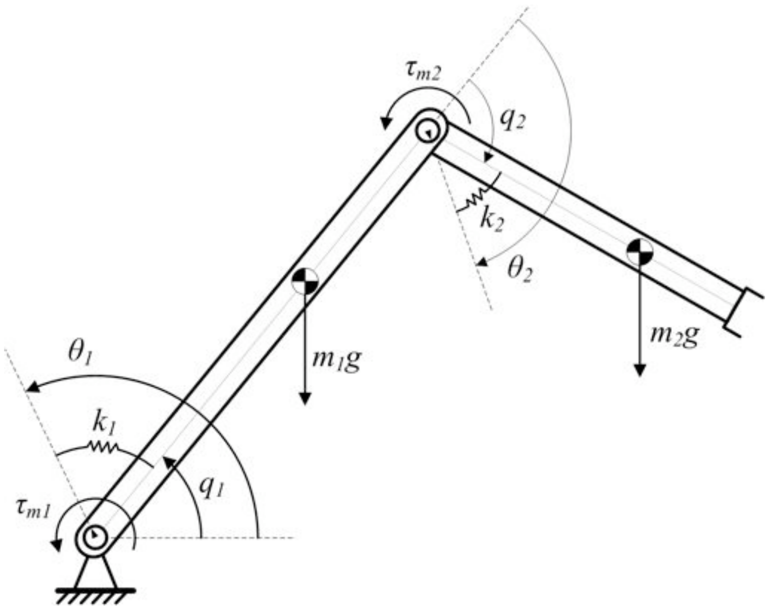

Fig. 1: 2 DOF rotational manipulator with series elastic actuation. The elongation of the elastic elements is defined by the difference between link position q and motor position θ.

One of the first suggestions of series elastic actuators is that of Pratt and Williamson [9], [10] who propose a linear actuator system with spiral springs as series elastic element. Their suggestion applies primarily to walking robots in which series elasticity (or 'low impedance' actuation) shows remarkable advantages for efficient control. A similar concept was also adopted for the arms of the humanoid robot 'Cog' [11]. To treat different or varying loads or force/moment situations at the end-effector by series elastic actuators requires means for adapting or controlling the spring coefficients. Van Ham et al. [12] proposed an interesting idea for mechanical adjustment of the elasticity coefficient of a spiral spring. The series elasticity in this case works in a triangular geometry causing a non-linear relationship between the elongation of the spring and the momentum of torsion it exerts on the limb. Although most proposals about series elastic actuators handle occurring oscillations with standard control approaches, they often suffer general applicability due to their special mechanical design or limiting constraints.

Pneumatic Actuators

Another approach comprising series elasticity is the use of ‘pneumatic’, ‘artificial’ or ‘fluidic’ muscles, which exists in various realizations [13]. Among them the braided type like the McKibben actuator is most often used for robotic applications [14], [15]. Although satisfying performance can be demonstrated, two drawbacks can be observed. First, the controllability suffers from the turbulent flow of the compressed air and reduces the accuracy of the robot motion. Further, the good ratio of load weight to dead weight of this kind of actuators does not consider the weight and size of the inevitably needed compressors or compressed air bottles, which severely limit applications on a mobile platform. In addition, the acoustic noise generated during operation, make this kind of actuator inexpedient for many possible service robot applications in a human environment.

3. Bionic Manipulator Design

To realize safe human-robot interaction with high passive safety in case of collisions, robotic manipulators have to be build with immanent low impedance resulting from a lightweight structure and a passive compliant design. The bionic manipulator (Fig. 2) fulfills the requirements of a cooperative human-machine interaction with its function, construction and control principle.

The construction principle (Fig. 3) of the bionic drive [1] is inspired by the functional principles realized in the elastic and antagonistic muscle and tendon apparatus of the human arm. Unlike other existing biologically inspired designs, our principle is based exclusively on the application of the series elasticity in the drive in combination with an adequate position sensor system. The design therefore only relies on the innovative combination of standard mechanical and electrical components. Based on a close-to-reality multibody dynamics simulation model the general applicability of the bionic manipulator has been demonstrated by the authors also for industrial robot applications [2]. Even with an elementary, decentralized control structure the manipulator driven by series elastic actuators performed well compared with conventional small sized manipulators.

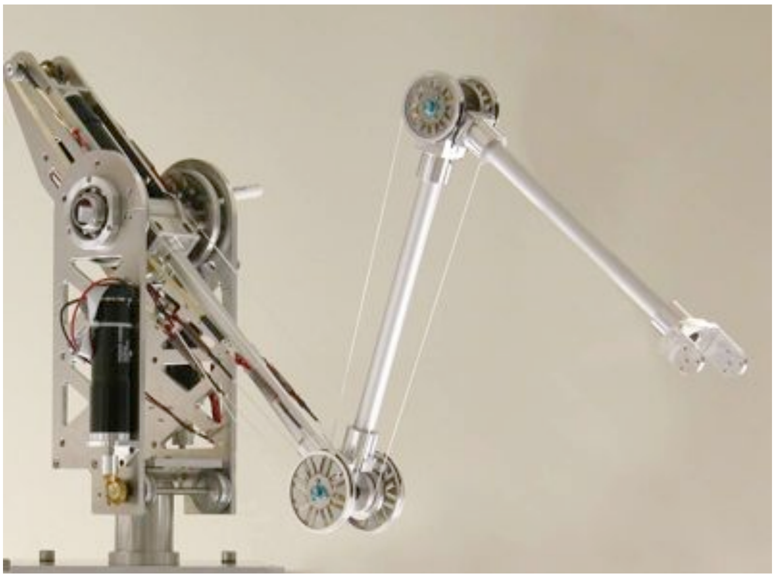

Fig. 2: Mechanical setup of the new 4 DOF demonstrator with a range of 1 m.

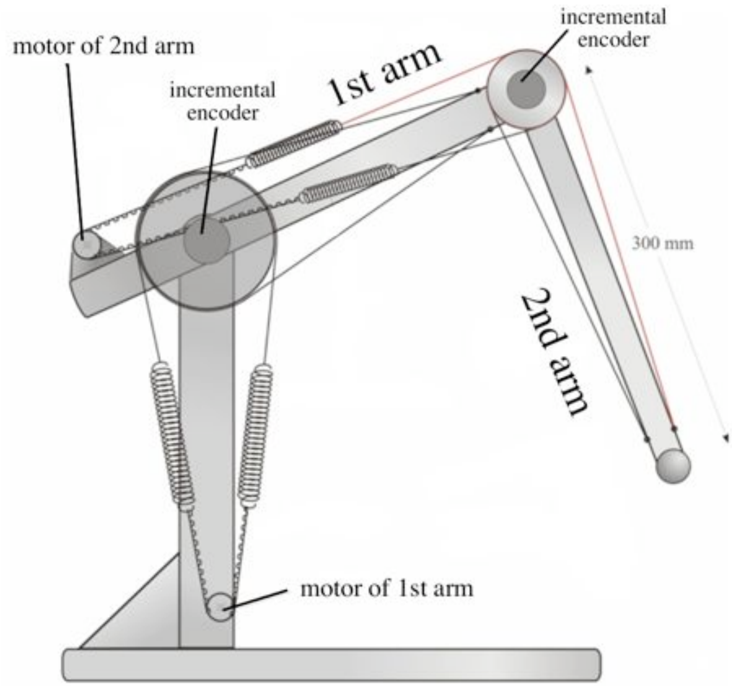

Fig. 3: Design principle of the bionic manipulator (2 DOF).

Each of the main three to four joints of the manipulator is actuated by a conventional, rotational DC-drive, which is not located at the actuated rotational joint but attached at the other end of the corresponding link. This conventional rotary electric actuator is elastically coupled to the actuated joint by means of a pair of cables and springs. The cables are attached antagonistically to the end of the actuated link, thus relieving the arm from bending stress and enabling a more lightweight design of the link. An additional weight and inertia reduction is achieved by placing the motors near the base of the robot. The weight of the motors is used to balance the system (e.g. 2nd motor in Fig. 3). The angular positions of the motors and the actuated joints are measured by high resolution optical encoders.

Compared to the experimentally validated, current demonstration model with two elastically actuated joints (Fig. 6), the weight of the new BioRob manipulator currently under construction (Fig. 2) will be reduced to an estimated total dead weight of 2.5 kg for an estimated maximum payload weight of 0.5-1 kg. Future versions of the bionic manipulator will have higher payload capabilities, resulting in an even better payload to dead weight ratio.

From the construction principles, substantial differences to conventional robotic manipulators result. Through the biologically inspired, series elastic actuation and lightweight construction, a high passive safety in the direct environment of humans can be achieved without the use of costly, additional sensors like visual monitoring systems or joint torque sensors.

Difficulties: Oscillations caused by the elasticity in the actuation require additional control efforts. With high resolution incremental encoders on both sides of the elastic elements, however, a special state space controller can effectively damp these oscillations. Further, the range of possible payloads is limited by the characteristics of the elastic elements.

Advantages: With the passive, mechanical compliance without time delay and the low mass of the links, the manipulator is intrinsically safe. Furthermore, the lengthening of the elastic elements measured by the incremental encoders can be used to calculate forces acting on the system, eliminating the need for additional, heavy and expensive torque sensors. This also offers new options for a more efficient control. As mentioned before, the use of standard components provides the potential of a cost-effective manufacturing and maintenance at sufficiently high manufacturing quantities. Compared to industrial robots no additional costs arise for safety sensors when employing the robot in the direct environment of humans.

4. Control Structure

The lightweight manipulator design with high joint elasticity poses a challenge towards the control structure. Compared to robots with gearbox elasticity, the maximum deflection between actuator and link position is significantly higher. Even for conventional robots operating at high velocities, where only small joint deformations are assumed, the nonlinearities are not negligible. As a result, in case of high joint elasticity a special control structure is required taking nonlinearities resulting from the elastic structure into account.

The nonlinear state space controller used for the bionic manipulator takes advantage of the high-resolution position sensors installed on both sides of the elastic elements, that is, in the DC-drives as well as in the elastically coupled joints.

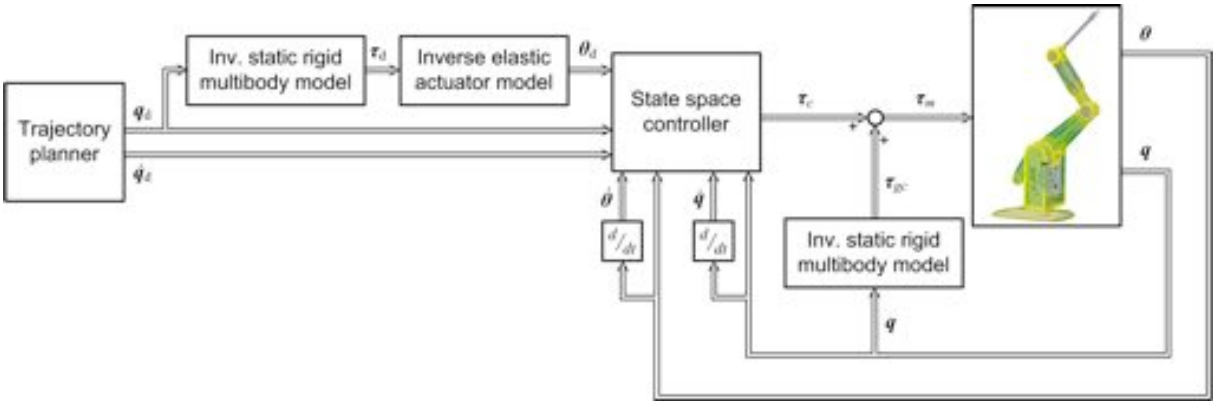

Fig. 4: Control structure of the BioRob manipulator.

The controller algorithm shown in Figure 4 makes use of the inverse static rigid multibody model to approximately linearize the nonlinear elastic manipulator with gravitational compensation forces $\boldsymbol{\tau}_{\mathrm{gc}}$. The model is also used to compute the required motor positions $\boldsymbol{\theta}_{\mathrm{d}}$ that results in the desired link positions $\boldsymbol{q}_{\mathrm{d}}$ in stationary state. These computed values and the measured link positions $\boldsymbol{q}$, link velocities, motor positions $\boldsymbol{\theta}$ and motor velocities are then used by a state space controller to damp the oscillations of the elastically coupled links. A controller solely based on motor position sensor data is not able to sufficiently damp the oscillations, as shown in Figure 5 on the left side. The plot on the right side shows the damping effect caused by the additional link sensors. The current setup operates faster than 2 s per cycle of a typical pick and place trajectory. Future versions of the manipulator will be designed to operate at a frequency as low as 1 s per cycle.

As an advantage of the control structure, the manipulator model used in the controller algorithm can be obtained by static calibration. This process can also cope with variable loads, providing a manipulator that can be flexibly used in a host of different applications.

A force-based interaction with the environment is possible, even though no torque sensors are installed. Because of the relatively high elasticity, the angle deflection between link and joint is high enough to estimate the joint torque by evaluating the difference between the motor angle und the joint angle, measured by the high-resolution rotational position sensors. Calculating forces allows an intelligent handling of collisions, additional to the intrinsic elastic behavior.

Despite the elastic elements, the 2 DOF laboratory model featured remarkable repeatability characteristics. An experimental setup (Fig. 6) with the repeated threading in the eye of a needle showed that the manipulator is able to maintain its repeatability, even when interrupted by a collision forcing the manipulator to draw back.

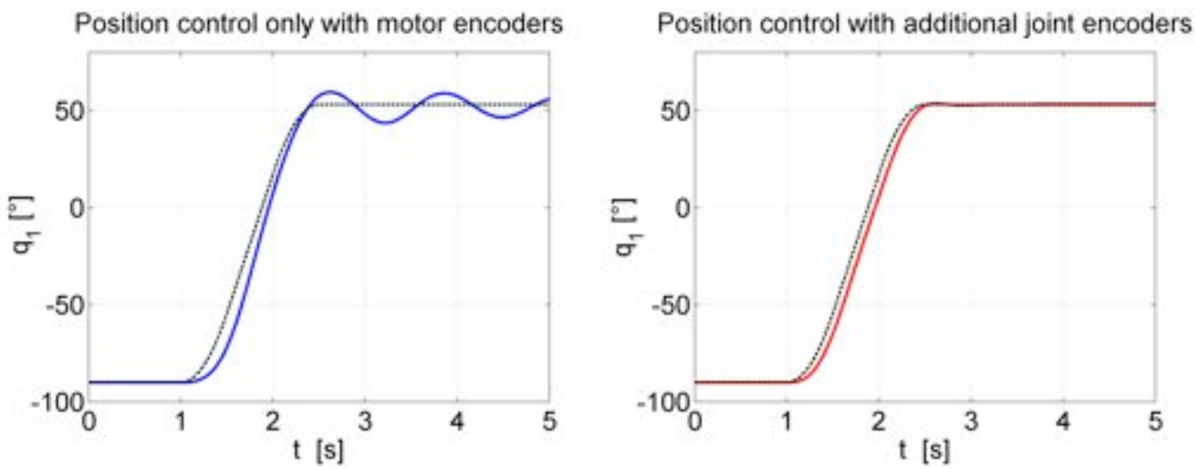

Fig. 5: Position control of the first link of the 3 DOF elastically actuated manipulator (obtained in simulation).

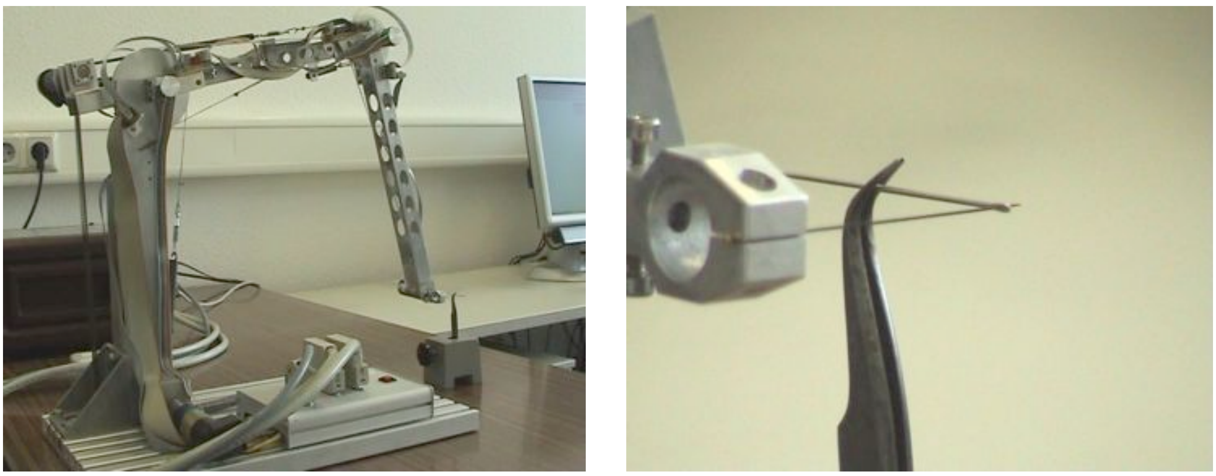

Fig. 6: Experimental setup demonstrating the repeatability characteristics of the manipulator.

5. Conclusions

The elastic actuation of mechanical manipulators offers new and challenging opportunities. Through the low weight and compliant mechanical structure, the novel manipulator design is more energy efficient and provides higher occupational health and safety characteristics than conventional rigid manipulators. The main drawbacks of series elasticity, oscillations caused by the elastic mechanical elements, can be handled by modern control algorithms taking advantage of the precision with which the geometry and kinematics of the system can be monitored.

6. Outlook

Currently, new demonstrators with 3 and 4 bionically driven joints (Figure 2) are being designed and constructed in cooperation with TETRA GmbH, Ilmenau. These demonstrators will be presented at AUTOMATICA 2008. Furthermore, the manipulator is being integrated and tested exemplarily in several new prototypic applications in small and medium enterprises are being investigated, for which conventional industrial robots are suitable to only a limited extent, for example automated planting of cuttings and handling of small, lightweight objects with the range and frequency of a human arm. These new applications will include close interaction between humans and robots. Therefore, safety issues will play a major role. Regarding safety aspects, no robot will be able to rely solely on active electrical systems. Passive safety systems as inherent in the proposed biologically inspired series elastic robot design are more fail-safe, react without delay, and become increasingly important.

Current research focuses on the inverse dynamics model of the elastic manipulator used for planning trajectories that take the elasticity of the system into account. Also being investigated are biologically inspired control strategies to improve the system for better performance such as shown by man and higher animals. Feed forward components within the feedback control possibly play an important role as used by nature to steer ballistic movements with muscle power.

Acknowledgements

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