Design and Control Mechanisms for a 3 DOF Bionic Manipulator

Sebastian Klug[1], Oskar von Stryk[1] and Bernhard Möhl[2]

[1] *Fachgebiet Simulation und Systemoptimierung, Technische Universität Darmstadt, Hochschulstr. 10, D-64289 Darmstadt, Germany*
[2] *Fakultät 7.2 Experimentalphysik (Bionik Labor), Universität des Saarlandes, Universitätscampus, D-66041 Saarbrücken, Germany*

klug@sim.tu-darmstadt.de, stryk@sim.tu-darmstadt.de, moehl@mx.uni-saarland.de

Project Web Page: http://www.biorob.de

***Abstract* – Functionality and design of a bionic robot arm consisting of three joints driven by elastic and compliant actuators derived from biologically inspired principles are presented. In the first design standard springs with linear characteristics are utilized in combination with electrical drives. Different control approaches for the bionic robot arm are presented, discussed and evaluation in numerical simulations and experiments with regards to the long-term goal of a nature-like control performance**

***Index Terms* – bionic, wire driven, serial elastic actuator, ballistic movements, joint control, trajectory optimization**

I. Introduction

Industrial manipulators are usually designed to carry loads a high speed and with high positioning accuracy. In order to fulfill these requirements elasticity and backlash in the actuators and gears as well as the deformations in the links, which occur under load, must be eliminated. This results in a heavy, solid arm construction and an unyielding motion, far from the smooth, compliant and accurate motion of a biological arm. For industrial applications usually the manipulator control consists of a trajectory planning phase following by an online setpoint trajectory following control on the joint level. It's overall aim usually is to to drive the robot in such a way that it reaches the destination in the fastest or the most energy-efficient way [1]. The disadvantage of a conventional rigid manipulator is, beside from its small ratio of load weight to dead weight, the stiffness and unyielding motion of the robot. Thus industrial manipulators can be operated efficiently and safely only in an environment strictly separated from human interaction.

Although biological manipulators are also made up of rigid links (the bones) each joint is usually driven by several, redundant and highly elastic and compliant actuators (muscles and tendons). Compared with current industrial manipulators biological arms have a yet unmatched ratio of load weight to dead weight. The compliant design, which relieves the links from bending stress and which enables fast ballistic motions in combination with a natural intelligent control, makes the main difference. For example, for fast, ballistic point-to-point motions of a biological end effector the motion has a relatively low position accuracy in its first part enabling a motion of the end effector, which is possibly faster than internal sensing capabilities and thus not feedback but feed-forward controlled, into the proximity of the final destination. Near the goal the end effector may then be smoothly guided to it under visual feedback. Various investigations [2]-[4] have shown [, that the elastic characteristics of the biological actuators in combination with adequate control principles, are responsible for fast and accurate ballistic movements.

II. Design Principle and Motivation

The construction principle (Fig. 1) of the bionic drive as suggested by Möhl [5], [6] is inspired by the biological example of the elastic and antagonistic muscle and tendon apparatus.

A. Laboratory Prototype

For the laboratory model of the bionic arm a spring with linear characteristics was used in the first design to bring

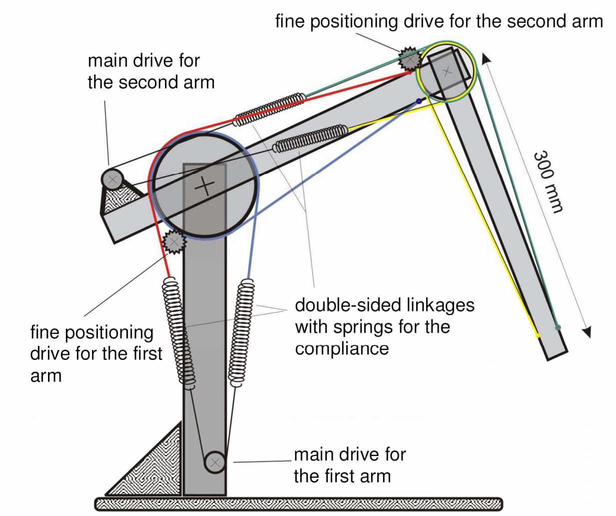

Fig. 1: Basic construction principle of the bionic manipulator. Through the double-sided linkages the arm is relieved from bending stress. By the linear springs a compliant motion is achieved.

the compliance into the system. The actuator is elastically coupled by means of the spring to the joint. The double-sided linkages are arranged in a way that they are relieving the bending stress in the links. In addition to the main drive the system can be extended by a second (however slow and weak) drive for fine positioning if needed. Both drives can be coupled by a magnetic clutch which allows the positioning drive to correct the position within the elastic range of the main drive. This provides optimal conditions for the fine positioning drive to adjust the position with a resolution of about ten micrometers at the end of the arm. From this construction principles, substantial differences to conventional robot systems results.

Potential difficulties: An elastically driven system of two links in series behaves highly oscillating and needs adequate control efforts for damping. For the damping control an additional position sensor at the actuated joint is needed in order to determine the actual position and velocity of the actuated joint. Further, by using a spring with linear characteristics, the range of loads, the arm can handle, is limited by the stiffness of the spring.

Potential advantages: Although the elasticity brings some problems with it, there are some advantages. Because of the system immanent compliancy a substantial danger reduction can be achieved. The arm can also be programmed to react on occurring contact forces to avoid collisions in order to not harm anyone or damage the robot itself. Although there is no explicit force sensor, the occurring forces can be measured. The sensor is implemented in the actuator system. Since the position of the motor and the joint are known the lengthening of the spring can be calculated. Thus, by knowing the characteristics of the spring and the geometry of the robot arm, the occurring moments can be calculated, independent of the contact point of the collision. With this measurement principle also a separation of force control and positioning control can be obtained. Furthermore the double-sided linkage construction releases the bending stress in the links of the robot arm, similar to the bones and the muscle-tendon apparatus in the human arm. This allows light-weight construction of the whole arm, which enables a faster working speed and saves considerable energy.

B. *Feasibility Study*

For a feasibility study supported by the German ministry of education and research (BMBF), a detailed and parameterized multi-body dynamics (MBS) simulation model on the basis of the existing laboratory model of the bionic arm was developed. The model consists of three "bionically" driven main axes and a conventional 3DOF wrist, so it has altogether 6DOF for the free choice of the position and orientation. With the help of this model different applications (Fig. 2) were examined. The simulation made it possible to systematically design and optimize the geometrical, kinematic and kinetic parameters of the robot. Besides the general applicability of the bionic robot arm, the presumed advantages of the bionic robot arm have been shown [7]. Based on a close-to-reality simulation model of the appearing forces and moments the performance of the bionic robot arm in different industrial application scenarios was analyzed. The comparison focused especially on smaller sized industrial robots. With an arm rang of approx. 650 mm and a max. payload of about 4 kg an operating speed of approx. 130°/s could be achieved with the bionic robot without overloading the motors. In direct comparison the bionic arm is slower than industrial robots. But considering that for the simulation parameters of off-the-shelf DC-motors were used which were not developed particularly for a certain type of robot, the results were satisfying.

For applications with three elastically driven joints, each with linear characteristic, it turns out that the classical control concept is sufficient. In the simulation a positioning accuracy of the endpoint was reached close to 0.1 mm, which matches well the known performance of the laboratory model. Due to the elasticity in the drive the positioning accuracy of the robot during the "flight phase" of a movement varies considerably. During high accelerations the actual position deviates by several millimeters from the desired position, so that an exact tracking control of a predefined path with high speeds is not possible. Higher accuracy can be achieved, when the system is running long enough to control the exact position or if overshooting is permitted within certain limits, which in turn causes a decrease of the operating speed. On the other hand a higher accuracy is attainable also by using the

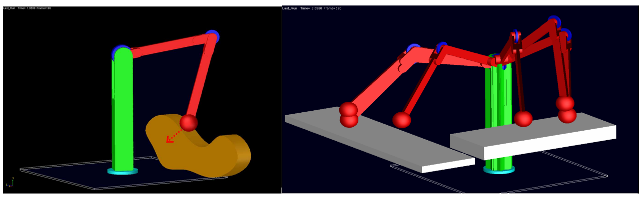

Fig. 2: Different Applications: measuring of contact forces (left), Pick & Place (right)

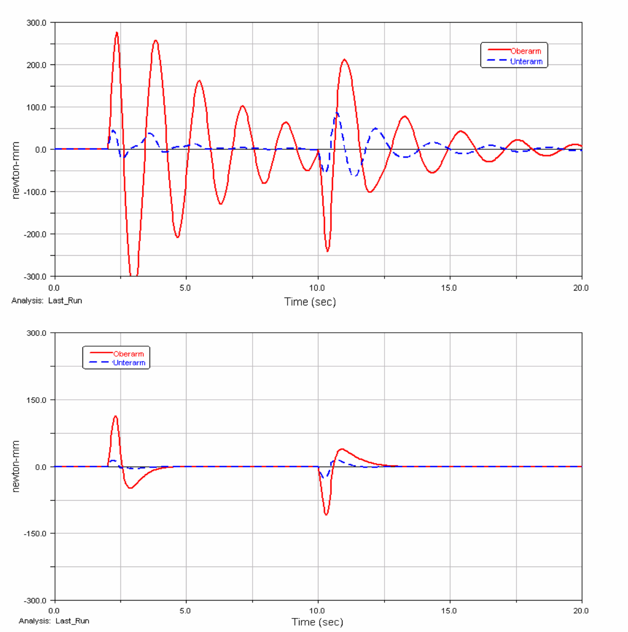

Fig. 3: Torque reduction effect of the oscillation damping on the stress of the main drive of the 2nd (solid line) and the 3rd (dotted line) joint: without (top) and with compensation (bottom)

fine-positioning motor, which can correct the position in the micrometer range. However the speed of this correction movement is significant smaller than the desirable operation speed.

In fast movements the occurring torque affecting the engine could be reduced over 40% (Fig. 3) when compared to movements without oscillation damping, since the entire movement is more softly by the absorption reducing the force peaks. This effect is based alone on the control principle described above. It is conceivable that by a systematic utilization of the occurring oscillations the torques could be still reduced further.

As mentioned above due to the bending load throw-off by the double-sided linkages the bending moments appearing in the links are transformed to pressure forces, acting in the lengthwise direction of the arm. Based on the forces and moments which appeared in the simulation the expected stresses in the arm and its stability were calculated. Compared with industrial robots about 50% oft the dead weight can be saved at the same load-carrying capacity, even if not all possible cases of failure of the material (e.g. buckling) have been considered. The theoretically energy consumption of the bionic robot arm for different tasks was estimated on the basis of the loads calculated in simulation. It appeared that the robot would have a 60% lower energy consumption due to its significant smaller dead weight and the favorable placement of the motors far from the axis, whereby the amount of the saving depends on the applied motor type.

TABLE 1
COMPARISON OF DIFFERENT LOAD WEIGT AND DEAD WEIGHT CONDITIONS

manipulator	max load weight	dead weight	ratio
Kuka KR3	3 kg	53 kg	0.06
Mitsubishi PA-10	10 kg	38 kg	0.26
DLR arm II (2000)	7 kg	18 kg	0.39
DLR arm III	14 kg	14 kg	1
bionic robot arm (conservative estimation based on our investigation)	4 kg	17 kg	0.24
human arm (very variable!)	>5 kg	<5 kg	>1

The fact that off-the-shelf components can be used for the realization of the bionic robot arm, instead of customized ones, is a big advantage. Thus the cost for construction, manufacturing and maintenance is low and supply with replacement parts is facilitated enormously. The forces computed in the dynamic robot simulation allow a specific selection of the robot size and suitable motors for a particular scenario.

C. Market Potential

According to the current UNECE study “World Robotics 2004” the number of installations of robots will rise in the next years around 7% per year. For new fields of applications including human-robot interaction and service robots, the growth rate is expected to exceed 10% by far. Right for new applications where the use of conventional industrial robots is not possible or not economical, different promising applications for the bionic robot arm arise. Requirements exist for small, economical and flexible applicable manipulators cooperating with humans in smaller and middle sized enterprises. Often the acquisition of a conventional robot, designed for industrial tasks, is not profitable for small factories and workshops where it must operated in the same environment with humans.

Mobile manipulators which should be used in the human environment are one example among the new field of applications specified above. Some applications in the near future will go even further, where robots and humans should work “hand in hand”. Because the prevention and detection of collision with humans is an essentially task, today's prototypes are equipped with complex sensor technologies and control mechanisms. Nevertheless it is requires enormous efforts to realize such a technology in a failsafe manner. Due to the natural compliance of the bionic robot arm a substantial risk reduction can be achieved for these tasks (besides a substantial reduction in energy consumption).

The ratio of load-weight to dead-weight and the energy consumption are substantial criteria for the applicability on mobile platforms. Further benefits are increased loading and operation cycles of the batteries as well as on better tilling stability because of the lower center of mass of the whole system. Although the bionic arm with its carefully estimated design has a slightly worse ratio than some conventional light-weight industrial robots (Table 1), we are convinced that for a design tailored to a special, defined application this property can be improved further. Furthermore with the bionic drive principle we can realize the same characteristics of reduced dead-weight and compliancy less expensive and also possibly more robust.

III. BACKGROUND

Over recent years the biological muscle was the archetype for many different new approaches by the development of new actuators for robotics and their control. Both muscle anatomy, as basis for the understanding of the biomechanical characteristics, and the control mechanisms of the biomechanical movement of muscles, are examined in biology and medicine in detail [8], [3] and offer a broad spectrum for bionic transfer. The main difference between muscles and industrial actuators is the elasticity. Accordingly, there are different construction principles of artificial flexible actuators. A far common approach are pneumatic muscles which were developed and investigated in different forms [9]. But also different approaches based on a combination of electric motors and elastic elements through which the motor is connected to the joint [10]-[12]. Many of them are using antagonistic drives. [13] to have an easier control of the stiffness.

Without hardware-based elasticity, the compliance is often achieved “virtually” by accordingly complex force and moment control mechanisms and special sensory equipment, like it is the case of the DLR lightweight arm and similar manipulators [14], [15]. This “simulated” compliance, however, requires high efforts and cost for sensors, actuators and model-based controllers and must be maintained actively. There are intrinsic limitations to what can be achieved by simulated compliance, because also the fastest regulation has a certain minimum reaction time and not all mechanical characteristics of the arm, gears and motors can be represented satisfactory precisely in the controller.

Since several years different methods exists for industrial robots to deal with elasticity [15]-[18], however it is usually a matter of unintentional elasticity which appear by deformation under load. Nevertheless the principles for position control and oscillation damping can also be used for our setup. Besides these conventional approaches, there are several theories about the underlying physiological and neurological structures of reaching motions in vertebrates [2]-[4]. The adaptation of these mechanisms to robotics enables new applications for autonomous manipulators and increases the quality of its movements.

For a future implementation in the bionic robot arm a short survey of different approaches to deal with elasticity will be discussed in the next paragraph.

IV. Control Mechanisms

A. Conventional Controllers

Control of industrial manipulators typically is hierarchical with a trajectory planning phase resulting in set-point trajectories for the individual joints followed by an independent PID joint control. The control approach for stiff robots with elastic deformations in the joints can also be assigned to the bionic robot with its elastically coupled drive. If for specific applications the path of the manipulator is given or prescribed in advance it is possible to calculate an optimized trajectory which is time optimal and which compensates the oscillations within the feed-forward term [17].

Model-based dynamic trajectory optimization may provide set-point trajectories which are much better suited to the individual robot dynamics than obtained by other path planning approaches resulting in fast and accurate motions [1]. However, a kinetic model of the robot is needed. Following the Lagrangian approach, the dynamic model on a robot with N elastic joints consists of $2N$ second-order differential equations

$$M(q)\ddot{q} + S\ddot{\theta} + c(q,\dot{q}) + g(q) + K(q-\theta) = 0 \qquad (1)$$

$$S^T\ddot{q} + J\ddot{\theta} + K(q-\theta) = \tau \qquad (2)$$

with the real position of the joints $q \in \mathbb{R}^N$ and the motor position $\theta \in \mathbb{R}^N$. The inertia matrix $M(q)$, the Coriolis and centrifugal terms $c(q,\dot{q})$ and the gravity term $g(q)$ are related to the real angular position of the joints. The diagonal matrix $K > 0$ is the diagonal matrix of the joint stiffness, the diagonal matrix $J > 0$ contains the effective motor inertias and S accounts for the inertial couplings between motor and joint. $\tau \in \mathbb{R}^N$ in eq. (2) represents the torques supplied by the motors.

For a specific application the desired joint-angular trajectory $q = q_d(t)$ is given by calculating the inverse kinematics of a Cartesian trajectory. By setting $f(q,\dot{q},\ddot{q}) = M(q)\ddot{q} + c(q,\dot{q}) + g(q) + Kq$ eq. (1) can be rewritten as

$$f(q,\dot{q},\ddot{q}) + S\ddot{\theta} - K\theta = 0\,. \qquad (4)$$

Since the motor which drives a joint is placed on the foregoing link, the matrix S is strictly upper triangular [18]. Thus the desired motor trajectory $\theta_d(t)$ can be calculated by starting from the last scalar equation in (4) going upwards to

$$f_1(q,\dot{q},\ddot{q}) - \sum_{j=2}^{N} s_{1,j}\ddot{\theta}_j - k_1\theta_1 = 0\,. \qquad (5)$$

that gives

$$\theta_{1,d} = \frac{1}{k_1}\left[f_1(q_d,\dot{q}_d,\ddot{q}_d) - \sum_{j=2}^{N} s_{1,j}\ddot{\theta}_{j,d}(q_d,\ddot{q}_d,\cdots,q_d^{[2N]}) \right]. \qquad (6)$$

After piecewise calculating the motor trajectory for the desired Cartesian trajectory the needed input torque can be calculated by combining eqs. (1) and (2) to

$$\tau_d = (J+S)\ddot{\theta}_d + (M(q_d)+S^T)\ddot{q}_d + c(q_d,\dot{q}_d) + g(q_d)\,. \qquad (7)$$

On the basis of this dynamic model of the robot arm the trajectory can also be optimized and adjusted for a time and energy-optimal motion [1].

The optimized feed-forward trajectory can then be combined with a conventional joint control strategy, as it is already used in the laboratory model. For the bionic robot the position sensors at the joint provides the actual angle of the links and also the (calculated) velocity, thus these values can be used for a PD controller with feed-forward compensation, written as

$$\tau = \tau_d + K_P(q_d - q) + K_D(\dot{q}_d - \dot{q})\,. \qquad (8)$$

The deciding point will be to use the controller (8) on the optimized trajectory with the calculated torque $\tau_d(t)$, angle $q_d(t)$ and angel-velocity $\dot{q}_d(t)$ for the desired motion of the robot.

In the final paper we will present an evaluation of the performance of the bionic manipulator with manually prescribed and optimized trajectories using a dynamic model.

B. Biologically inspired Reaching Motions

In contrast to the precisely executed point-to-point trajectories of industrial robots, reaching movements in biological systems are generated in a different way, as the short overview will show.

A normal reaching motion is a quiet simple action, nevertheless performed by redundant, antagonistic actuators it involves different complex motor control strategies involving visual feedback and information form nearly all available proprioceptors. Although for fast ballistic motions, that lasts a few hundred milliseconds, it is known that a control, based on visual feedback (over 100ms) or proproceptior information (about 50ms), is turned out to be too slow. So a feed-forward based approach is assumable.

Many control schemes have been developed including a dynamic model of the arm, as described above, to achieve a fast motion with an approximately straight path of the end effector and a bell-shaped velocity profile which are typical features for ballistic motions. The disadvantage is that beside the computational costs of the non-linear dynamic model of the arm, also for fast motion a whole motor trajectory must be calculated, optimized and of course executed.

A different approach suggests that the performance of a ballistic motion is a result of the special dynamic characteristics of the arm and not of the optimization of the motor trajectory [2]. In order to achieve a typical reaching motion, simple rectangular pulses adjusted by a feed-forward control and a learning mechanism similar to the reafference principle [19] were used to activate the muscles.

V. Conclusions

In the feasibility study the general applicability of the bionic robot arm for a number of different industrial applications has been demonstrated. It has been shown that the bionic driven principle compares well with conventional manipulators especially in a small to medium size, range and payload. There is even more room for improvements if a bionic arm is tailored to a specific application. It turned out, that for application where the payload does not change or varies only in small ranges a normal spring with a defined stiffness and linear characteristics performs well. Accordingly, conventional feedback control methods are efficient enough, in order to ensure a sufficient performance also of systems with many DOF. In the next development phase a combined feed-forward, feedback control mechanism, as described in section IV A, is being implemented and tested.

In a later phase of the project a possible simplification of the motion control methods by utilizing effects of different nonlinear elastic characteristics should be investigated as well as the different learning algorithms for high performance feed-forward controlled reaching motions.

Acknowledgment

The research presented in this paper has been supported in part by the German Federal Ministry for Education and Research (BMBF) under grant FKZ 0311983.

References

[1] A. Heim, O. von Stryk, "Trajectory optimization of industrial robots with application to computer-aided robotics and robot controllers", *Optimization*, vol. 47, pp. 407-420, 2000

[2] A. Karniel, G. F. Inbar, "A model for learning human reaching movements" *Biological Cybernetics*, vol. 77, pp. 173-183, 1997

[3] S. F. Giszter, F. A. Mussa-Ivaldi, E. Bizzi, "Convergent Force Field Organized in the Frog's Spinal Cord", *The Journal of Neuroscience*, vol. 13, no. 2, pp. 467-491, Feb. 1993

[4] R. M. Sunderland, R. I. Damper and R. M. Crowder, "A Framework for Biologically-Inspired Control of Reaching Motions", *Proc. of 3rd Int. Symp. of Adaptive Motion in Animals and Machines*, Sept. 2005

[5] B. Möhl, "A Two Jointed Robot Arm with Elastic Drives and Active Oscillation Damping", *Workshop: Bio-Mechatronic Systems, IEEE-RSJ Int. Conf. on Intelligent Robots and Systems,* 1997

[6] B. Möhl, "A Composite Drive with Separate Control of Force and Position", *Proc. of the 11th Int. Conf. on Advanced Robotics*, pp. 1606-1610, Jun. 2003

[7] S. Klug, B. Möhl, O. von Stryk, O. Barth, "Design and Application of a 3 DOF Bionic Robot Arm", *Proc. of the 3rd Int. Symp. on Adaptive Motion in Animals and Machines*, Sept. 2005

[8] R. L. Lieber, "Skeletal Muscle is a Biological Example of a Linear Electro-Active Actuator", *Proc. of SPIE's 6th Annual Int. Symp.on Smart Structures and Materials*, Paper-No. 3669-03, Mar. 1999

[9] F. Daerden, D. Lefeber, "Pneumatic Artificial Muscles: actuators for robotics and automation", *European Journal of Mechanical and Environmental Engineering*, vol. 47, no. 1, pp. 10-21, 2002

[10] Y. Ogahara, Y. Kawato, K. Takemura, T. Maeno, "A Wire-Driven Miniature Five Finger Robot Hand using Elastic Elements as Joints", *Proc. of the 2003 IEEE-RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 2672-2677, Oct. 2003

[11] I. Mizuuchi, R. Tajima, T. Yoshikai, D. Sato, K. Nagashima, M. Inaba, Y. Kuniyoshi, H. Inoue, "The Design and Control of the Flexible Spine of a Fully Tendon-Driven Humanoid 'Kenta' ", *Proc. of the 2002 IEEE/RSJ Int. Cenf. on Intelligent Robots and Systems*, pp. 2527-2532, Oct. 2002

[12] S. C. Jacobsen, H. Ko, E. K. Iversen, C. C.: Davis, "Control Strategies for Tendon-Driven Manipulators", *IEEE Control Systems Magazine*, vol. 10, no. 2, pp. 23-28, Feb. 1990

[13] A. Bicchi, G. Tonietti, "Design, Realization and Control of Soft Robot Arms for Intrinsically Safe Interaction with Humans", *Proc. IARP/RAS Workshop on Technical Challenges for Dependable Robots in Human Environments*, pp. 79-87, Oct. 2002

[14] M. Zinn, B. Roth, O. Khatib, J. K. Salisbury, "A New Actuation Approach for Human Friendly Robot Design", *The Int. Journal of Robotics Research*, vol. 23. no. 4-5, pp. 379-398, Apr. / May 2004

[15] A. Albu-Schäffer, G. Hirzinger, "State feedback controller for flexible joint robots: A globally stable approach implemented on DLR's light-weight robots", *Proc. of the 2000 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, 2000

[16] S. D. Eppinger, W. P. Seering, "Three Dynamic Problems in Robot Force Control", *IEEE Transactions on Robotics and Automation*, vol. 8, no. 6, pp. 751-758, Dec. 1992

[17] A. DeLuca, "Feedforward/Feedback Laws for the Control of Flexible Robots", *Proc. of the 2000 IEEE Int. Conf. on Robotics and Automation*, vol. 1, pp. 233-240, Apr. 2000

[18] P. Tomei, "A Simple PD Controller for Robots with Elastic Joints", *IEEE Transactions on Automatic Control*, vol. 36, no. 10, pp. 1208-1213, Oct. 1991

[19] E. von Holst, H. Mittelstaedt, "Das Reafferenzprinzip", *Die Naturwissenschaften*, vol. 37, pp. 464-476, 1950 (in German)