Preprint of the paper which appeared in Proc. AMAM 2005, Illmenau, Germany, September 25-30, 2005

Design and Application of a 3 DOF Bionic Robot Arm

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***Abstract*— Regarding to concrete industrial applications, we examined the functionality and the systematic design of a bionic robot arm developed and driven by biologically inspired principles. Based on a laboratory model a scalable multi-body-dynamics-simulation model has bin developed. Although it is driven by elastically coupled linkages which require additional control efforts for oscillation damping, we can show possible advantages of a lighter and bending relieved structure and a significant reduction of danger in case of collisions.**

***Index Terms*— bionic, wire driven, compliant, manipulator, simulation**

I. Introduction

Industrial manipulators usually consist of a rigid kinematic chain built up of several rigid links which are connected by direct driven linear or rotational joints. In order to move high payloads with high speed and high position accuracy the slackness in the gears as well as the deformations in the links, which occurs under load, must be eliminated. This can only be reached using rigid joint actuators and rigid links resulting in heavy, solid arm constructions (Fig. 1). Thus the ratio from load weight to dead weight for industrial robots is inferior than in animals or humans. In addition, because of their unyielding stiffness, robots can be operated efficiently 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 actuators.

Compared with technical constructions biological arms have yet unmatched ratio of load weight to dead weight and a high quality of movement through "intelligent" control.

II. Design Principle of the Bionic Robot Arm

The principle of the bionic drive as suggested by Möhl [1] is inspired by the characteristics of the muscle and tendon

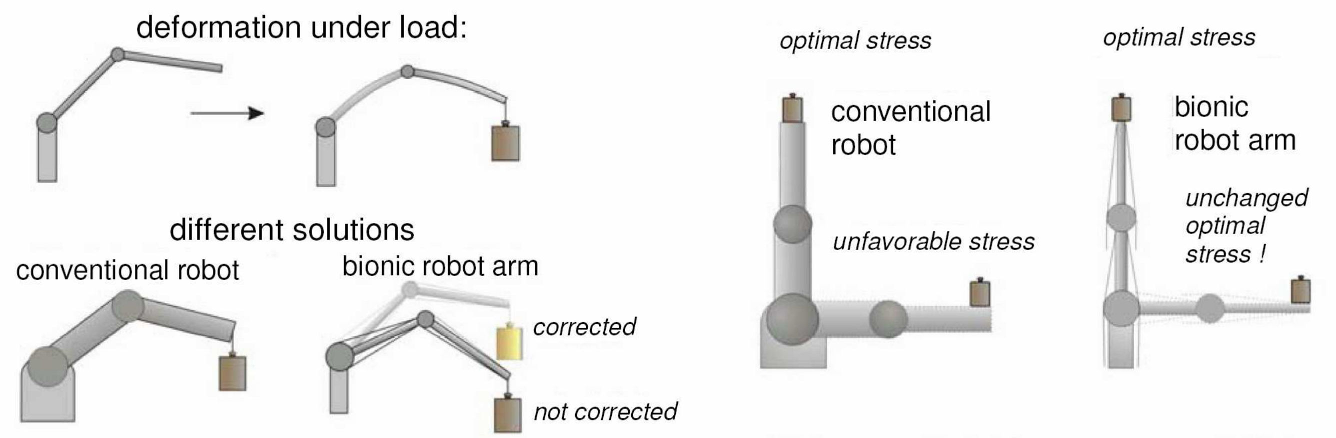

Fig. 1. Left: To minimize the deformation caused by load conventional robots are built with heavy, solid arm constructions. Through the double-sided linkages construction of the bionic robot arm deformations arise only in the elastic part of the drive where it can be measured and corrected. Right: In addition because of the linkages a constant, optimal stress distribution in the bionic arm is obtained, in different positions.

apparatus. It consists of an elastically coupled drive which relieves the arm from bending forces (Fig. 2). The arrangement can be extend to a "composite drive" by adding a precise (however slow and weak) fine-positioning drive to the strong and fast (however flexible, thus inaccurate) main drive. Both drives can be connected to - or separated from each other by an electromagnetic clutch. With this "composite drive" the position of the arm can be corrected also if the main drive is not operated (Fig. 3). From this construction principles substantial differences to conventional robot systems results.

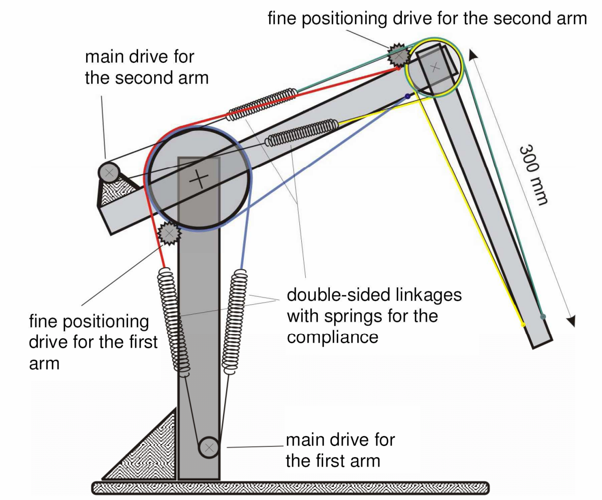

Fig. 2. Basic construction principle of the bionic robot arm. Through the double-sided linkages bending stress in the arm is relieved and with the springs a natural compliance is achieved.

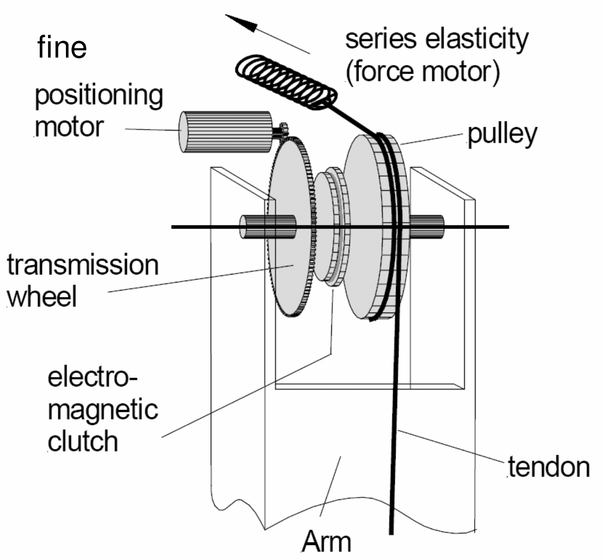

Fig. 3. Principle of the "composite drive". Because the force motor is elastically coupled to the joint, the fine-positioning motor can make small corrections even if the force motor is not operated.

A. *Potential difficulties:*

The oscillations caused by the elasticity in the drive can only be controlled by additional control efforts for damping (see also IV A). The damping control requires an additional joint position sensor in order to be able to determine the actual position an velocity of the actuated joint. Additionally, the range of operation of the robot is limited by the constant elastic spring elements to a relatively close range of loads.

B. *Potential advantages:*

The robot arm is released from bending stress through the double-sided linkage construction, similar to the human bones and the muscle tendon apparatus. Thus, deformations under load occur only in the elastic part of the drive where one can measure it and not in the arm link itself. Because of the reduced bending stress the bionic arm can be constructed lighter without changing the load capacity. The weight reduction enables a high working speed and saves considerable energy. In addition, a substantial danger reduction at the time of collisions can be obtained by the smaller weight and the natural compliance of the drive. This is a substantial advantage in applications with direct human interaction, whereas in conventional robots such usage affords extremely high safety measures. Further on, position and force control can be separated, so that applications which require a constant contact force are facilitated.

III. Background

The biological muscle is the starting point for many new approaches by the development of new actuators for robotics. Both muscle anatomy, as basis for the understanding of the biomechanical characteristic [2], and the control mechanisms of the biomechanical movement of muscles [3], [4], are examined in biology and medicine in detail and offer a broad spectrum for bionic transfer. Beside the direct simulation of biological systems [5], [6] there are different approaches to mimic biological operational principles in technical systems. At the neural control mechanisms the approaches range from the development of the CPG [7] over the use of control loops based on reflex circuits for stable, rhythmic walking in four-legged robots [8], [9] or force controlled grasping movements in humanoid robots [10] up to the construction of artificial muscle spindle (sensors for the strength and position regulation) [11], [12].

A substantial 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 [13]. Pneumatic muscles show ratios of length to produced force and dead weight to load weight, which are very similar to those of biological muscles [14], [15]. Therefore, they are often investigated for humanoid robots. Nevertheless, because of the necessary antagonistic control and the nonlinear flexible characteristics classic control approaches were proved as not optimal [16], [17] and artificial neural networks were often used, instead [18], [19]. Further drawbacks are the need for additional devices and the reaction times and positioning accuracy.

Without pneumatic muscles, elasticity is often achieved "virtually" by accordingly complex control mechanisms (see below). Drive systems which are based on a combination of electric motors and unbend cables are rather rare also with biologically inspired actuators. Beside constructions with a rigid drive and an elastic element only in the joints [20]-[22], there are several proposals related to the principle presented here. Most of them are using antagonistic drives [23] or an additional clamping device [24]-[26] to vary the rigidity of the spring actively.

Since several years different methods exists for industrial robots to deal with elasticity [27], [28], however, it is usually a matter of unintentional elasticity in the arm links themselves [29] or in the joint [30], [31] which appear by deformation under load and therefore must be compensated. Nevertheless, the principles for position control and oscillation damping can also be used for our setup.

With an appropriate control mechanism and sensor equipment also a stiff driven robot can be equipped with simulated compliance like it is the case by the DLR lightweight arm [32]. Simulated compliance, however, requires high efforts and cost for appropriate sensors, actuators and model-based controllers and must be maintained actively. Beyond that, it has the disadvantage that also the fastest regulation has a certain minimum reaction time.

Passive compliance is a substantial safety factor, if robots interact with humans in the same environment or directly with them together. Consideration of the appearing forces and current speeds as well as an intelligent task planning and simple operability of the robot are necessary for a safe man-machine co-operation [33], [34].

IV. Results

We developed a detailed and parameterized multi-body dynamics (MBS) simulation model on the basis of an existing laboratory model of the bionic robot arm. The model was extended by a third joint. The three "bionically" driven main axes were also complemented by a conventional 3 DOF wrist, so that the robot has altogether 6 DOF for the free choice of the position and orientation. In the applications considered the movements of the wrist have only small influence on the dynamic characteristics of the whole system, therefore the wrist was assumed to have a fixed unmovable load at the end of the robot arm. With the help of this model different applications (Fig. 4) can be examined. The simulation enabled us, to systematically design and optimize the geometrical, kinematic and kinetic parameters of the robot. The engine and gear models which were used in the simulation are idealized,

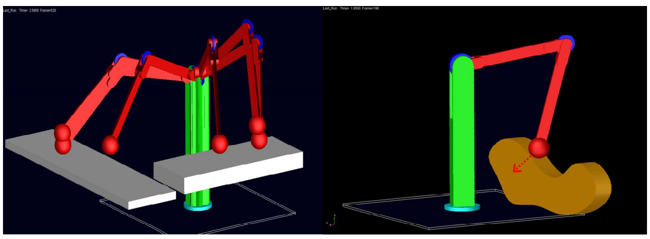

Fig. 4. Different Applications: Pick & Place (left), measuring of contact forces (right)

because at this time we were concerned only with the arising strains, working forces and moments, which are necessary in order to determine suitable engine-gear combinations for a real robot. The necessary engine parameters can be determined on the basis of the forces and moments arising in the simulation.

A. Oscillation damping

A control concept is suggested, which compensates the elastic oscillations by means of a velocity feedback. This represents a D-element in the context of a position regulation, whereas the flexible spring can be formally understood as a P-element with a relatively weak feedback (soft spring). This is sufficient, to stabilize the system. Since the laboratory model is only operated with a direct teach-in procedure the stationary position error is already considered, so that with constant payloads no further position correction is necessary and no I-element is needed. But this would be required if a given offline generated set point trajectory must be followed or if the payload conditions change during an application. Since in the simulation no direct teach-in procedure was included the control of the bionic arm was realized with a complete PID-controller in the MBS Simulation.

B. Different realizations

Based on a close-to-reality simulation model of the appearing forces and moments the application of the bionic robot arm was analyzed with different industrial scenarios considering a wide spectrum of geometrical and kinematic design. A possible application of the bionic robot arm ranges from simple pick-and-place to surface measurements and even new challenges in the area of mobile manipulation and service-robotics. To compare the performance of the bionic robot arm with industrial robot arms the model is tested in two different sizes.

The first model corresponded in size to the laboratory model and was used for validation of the simulation model. To compare pick & place applications, first the "flex-picker", well-known for particularly high operating speed, was considered as counterpart. However, it appeared soon that the special construction, i.e. parallel manipulator, and the low capacity for additional load were not directly comparable with a bionic arm. Therefore, a typical folding robot arm with a similar working area was used for comparison (KUKA KR-3). With an arm range of approx. 650 mm and a max. payload of about 4 kg an operating speed of approx. 130°/s could be achieved with this bionic robot without overloading the motors (see IV A). At a payload of only 3 kg (max. load of KUKA KR-3) an operating speed was reached of approx. 170°/s. Thus, in direct comparison the bionic arm made from off-the-shelf-components is slower than industrial robots. But considering that standard DC-motors were used, which were not developed particularly for a certain type of robot, the results are satisfying.

For the second model a range of approx. 2 m was selected, and dynamic and static characteristics comparable with those of industrial robots of the same size were chosen. A comparable performance to industrial robots can be reached in the simulation, with a corresponding dimension of motors and gears and a defined range of payloads. However, due to the long arm links and the enormous forces arising thereby when fully stretched, no reliable statement can be made for the real strain and deformation in the arm links as the MBS simulation does not consider structural properties like deformation of robot links under stress. Moreover, it must be considered that the payload varies at a significant larger degree than with the smaller version described above. A range from 0 kg – 50 kg was investigated.

C. Torque reduction

For fast point to point movements, as they occur e.g. in pick and place tasks, the torque affecting the engine could be reduced over 40% (Fig. 5) when compared to movements without oscillation damping, since the entire movement is more softly by the absorption reducing the force peaks. It could be shown in the simulation that the torques could have been reduced even further. However, the motor speeds needed in these cases were so high that they could not be achieved with any of the considered off-the-shelf DC-motor-gear combinations. 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 further reduced.

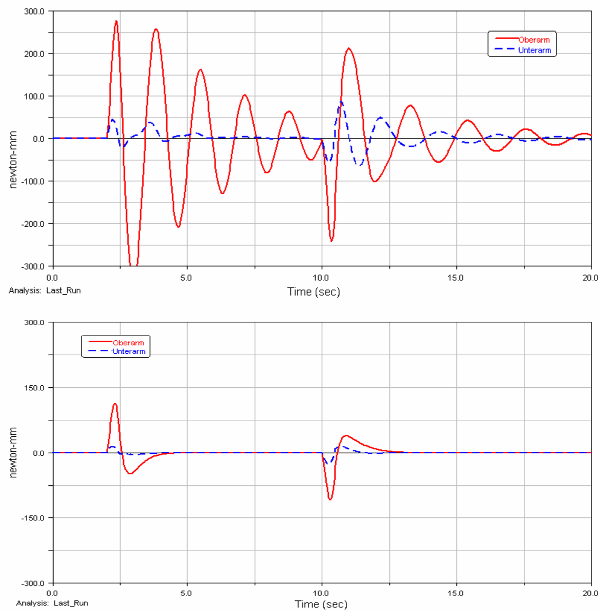

Fig. 5. Torque reduction effect of the oscillation damping on the stress of the main drive of the 2nd (solid line) and the 3rd (dotted line) joint: without (top) and with compensation (bottom)

D. Performance of positioning

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 of a predefined path with high speeds is not possible. The position accuracy at the end points of a movement depends on several factors: the applied motor-gear combinations, the stiffness of the elastic elements, the parameters of the control and - depending upon the scenario - the difference of the payloads. At the end points of a movement the iteration accuracies can be achieved in the range of industrial robots at a typical operating speed (approx. 180°/s). In simulation a higher accuracy is attainable, if the system is running long enough to control the exact position or if overshooting of the system is permitted within certain limits, which in turn causes a decrease of the operating speed. On the other hand a higher accuracy can be achieved also by connecting an additional fine-positioning motor (Fig. 3). The attainable accuracy is in the micrometer range, as can be shown by experiments with the laboratory model. However the operating speed is significant smaller than in the normal operation.

E. Computation of the structure relieving and energy consumption

Due to the bending load throw-off by double-sided linkages with springs the bending moments appearing at the robot links over the linkages are transformed to pressure forces, which act lengthwise in the arm direction. The stability calculation is based on the results of the simulation, in which the robot was exposed to the normal loads and forces due to its size. It turned out that a bend-relieved bionic arm can carry a significant higher weight with the same construction than a not bend-relieved construction with the same dead weight. In case of the prototype a six fold increase of the load results. For a larger load, however, stronger and consequently heavier motors are needed, but this affects the result only to a small extent. Compared with conventional industrial robots about 50 % of 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. Here, the motors account for the largest part of the weight. The theoretical energy consumption of the bionic robot arm for the above described 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.

The fact that off-the-shelf components can be used for

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

realization of the bionic arm, instead of customized ones, is a big advantage. Thus the cost for construction, manufacturing and maintenance is low and the supply with replacement parts is facilitated enormously. This aspect has especially been considered in our investigation. It is ensured that the applied parameters can be implemented without large expense with standard mechanical components. The forces computed in the dynamic robot simulation allow a specific selection of the robot size and suitable motors for a particular scenario. The requirements for the described scenarios can be achieved with existing standard motor-gear combinations.

V. Market Potential

The most recent UNECE study "World Robotics 2004" [35] forecasts for robot installations a yearly growth rate of 7% on the average during the next 3 years. For new fields of application including human-robot interaction and service robots, the growth rate is expected to exceed 10% by far. Concerning the features of the bionic robot arm – as described above – several promising application scenarios arise, which for conventional industrial robots are less suitable or not cost-efficient. Here appear good chances for the bionic robot arm in the following two areas: stationary small robots for various applications and mobile manipulators as personal assistant robots.

A. Stationary small robots

Requirements exist for small, economical manipulators co-operating 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 be operated in a environment with humans.

Planting robot: Together with a agricultural company the application of a bionic robot arm for the automated planting of young shoots was discussed. For this size conventional robots are too "insensitive" and cannot deal with the heavily varying requirements necessary for the handling of biological objects. In this case the bionic robot arm could offer substantial advantages with its natural compliance and manlike dynamics. The very monotonous task of setting young plants is still done manually up to now, since at the time no suitable systems are available for automation in this field. The successful establishment of a flexibly applicable planting robot would have a substantial economic influence, both for the agrarian and for the food industry.

B. Mobile manipulators

Mobile manipulators which should be used in the human environment are one example among the new field of applications specified above. In various robotics companies efforts are being made to develop mobile, flexibly applicable manipulators for different, changing applications at different locations in the production. Thus, the safety guarantee in case of robot- human interactions is a major aspect. So far the working areas of robots and humans are strictly separated from each other. One tries to achieve the necessary safety criteria by complex sensor-based safety mechanisms, however, this provides substantial difficulties for an acceptable realization.

Fig. 6. Prototype of a mobile service robot from GPS GmbH [34]

Some prototype scenarios are going yet one more step forward where robots and humans should work "hand in hand". Also here the collision of the rigid robot with humans must be essentially prevented by complex sensor technology and control mechanisms, which requires enormous efforts to realize 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 Mitsubishi robot arm applied to the mobile platform of rob@work of (Fig. 6) has one of the best ratios of load weight to dead weight within conventional robots, as shown in Table 1. These specifications and the energy consumption are substantial criteria for its application mounted on a mobile platform. Further benefits care increased loading and operating cycles of the batteries as well as on better tilting stability because of the lower center of mass of the whole system. At the moment for example the DLR lightweight arm is handled as an ideal manipulator for mobile platforms, because of its small dead weight and its ability of active compliance which is realized, however, by a complex torque control mechanism. At present the DLR lightweight arm obtains the best ratio from load weight to dead weight of a manipulator through a high technology drive and sensor systems.

Although the bionic robot arm with the carefully estimated design is yet slightly worse than the robot arm of Mitsubishi, as for the relation from load weight to dead weight, we are convinced that for a design tailored to a defined task for these property can be improved further. Furthermore with the bionic drive principle we can realize the same characteristics of reduced dead weight and compliance less expensive and also possibly more robust.

VI. Conclusions

The design and application of a manipulator whose three main positioning degrees of freedom are actuated by a bionic drive has been investigated in this paper. It has been shown that the bionic drive principle compares well conventional manipulators especially in a small to medium size, range and payload. Beyond that, the passive compliance of the robot facilitates operation in a human environment and in interaction with human workers. There is even more room for improvements if a bionic arm is tailored to a specific application.

There are still several open questions. For instance, the influence of the wrist movements was not yet studied, which can be different depending on the size and the speed of the handled object. Furthermore, there is a need for a final mechanical design of a bionic robot arm suitable as an industrial operational prototype for a specific application.

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