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Full paper

Antagonism for a Highly Anthropomorphic Hand–Arm System

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Abstract

A novel approach to antagonism in robotic systems is introduced and investigated as the basis for an unequalled, highly anthropomorphic hand–arm system currently being developed. This hand–arm system, consisting of a 19-d.o.f. hand and a 7-d.o.f. flexible arm, will be based on antagonistic principles in order to study and mimic the human musculoskeletal system, as well as to advance safety in robotics.

Keywords

Hand, antagonism, anthropomorphic, muscle, arm

1. Introduction

Biological musculoskeletal systems are antagonistic. Each joint is activated by a group of muscles, pulling the bones *via* tendons. Apparently for reasons of linearization of the dynamics [1], this architecture is rather complex, e.g., for planar motion of the elbow and shoulder only, the human arm uses a total of 19 muscles (Fig. 1), forming a complex of agonist, antagonist, monoarticulate and biarticulate muscles.

From a biological point of view, there are many reasons to use antagonistic drive principles for generating motion. Of course, a strong one is the fact that muscles, responsible for vertebrate motion, can only pull and not push. However, apart from that restriction, the antagonistic approach leads to two important advantages: the system is energy-optimal for various tasks [2] and the joints are intrinsically flexible.

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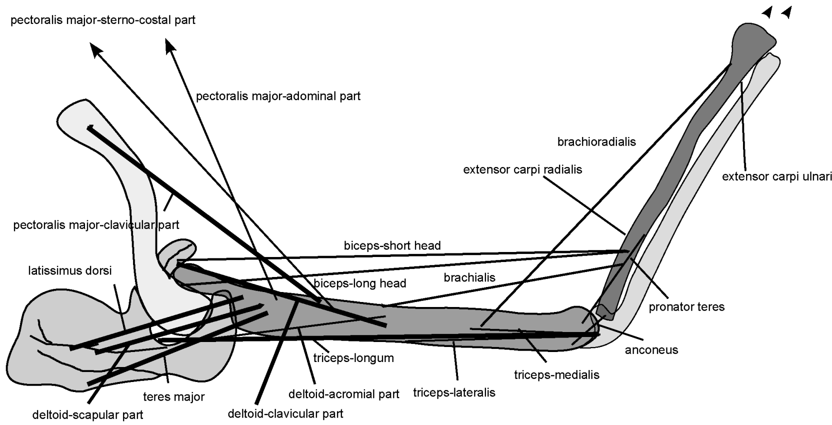

Figure 1. Simplified, planar model of the human arm [5] using 19 muscles or muscle groups in total. In this model, only the muscles that are responsible for motion of the elbow or shoulder in the plane are accounted for.

Flexibility is a key characteristic for physically interacting with an environment. When humans and robots physically cooperate, the first issue that has to be resolved is ensuring safety for the human as well as for the robot. In Ref. [3], a promising collision detection and reaction approach, applicable to flexible-joint robots, is presented, but antagonistic actuation offers fundamentally new concepts. Apart from precluding prohibitively high stiffness during physical contact, antagonism allows predefining the real physical behavior of the manipulator by adjusting the joint stiffness as a function of, for example, joint velocity or output inertia of the robot. A possible heuristic of adjusting the joint stiffness during a rest-to-rest motion is described in Ref. [4].

In order to obtain dynamic properties very similar to musculoskeletal systems, we therefore consider antagonistic drive principles of key importance for future robotics. Using this principle, we are constructing a revolutionary hand–arm system which mimics the kinematic and dynamic properties of the human hand–arm complex as closely as possible. Using biological drive and joint concepts, this new hand–arm system will consist of a hand with 19 active d.o.f. attached to a robot arm with 7 active d.o.f., all with weight, size and strength properties equal or close to that of humans.

2. Approaches to Antagonism in Robotics

Antagonistic drive principles have two major important characteristics: an antagonistic system is energy-optimal for various tasks [2] and antagonistically driven joints are intrinsically flexible. This latter property leads to completely new possibilities with respect to safe human–robot interaction, but also with respect to the control of such drive principles.

The development of antagonistic robot joints is a multi-disciplinary challenge rather than a mechanical problem. Therefore, a large antagonistic system requires a complete system design, including control strategies for the most important control modes. Due to the elastic elements, every motor action in an antagonistic system will induce vibration.

Flexibility at the joint level requires the inclusion of a nonlinear spring between the actuator and the joint. Two different principles can be distinguished in the literature: those based on linear springs and those based on nonlinear (typically rubber-based) elements.

2.1. Rubber

A classical approach towards including a rubber-based nonlinear spring is by using McKibben-like actuators. Such artificial muscle systems have been propagated since the early 1990s, focusing on muscle-like contracting actuators. In an antagonistic set-up, these actuators can be used to control a joint (Fig. 2). The McKibben muscle [6, 7] is a well-known example, consisting of a rubber tube which contracts when inflated. In spite of its muscle-like properties, its low force-to-weight and low force-to-size ratio, hysteresis and temperature dependency [8] make the muscle inappropriate for application in a human-size highly dextrous arm–hand system. Also, the system is very slow and requires large supporting structures (e.g., a compressor).

The contraction force T_j exerted by a McKibben actuator $j \in \{1, 2\}$ for each joint is given by:

$$T_j = \rho_j D_j^2 (a(1 - \varpi_j)^2 - b), \tag{1}$$

where ρ_j is the supply pressure, a and b are constants depending on the particular tube, $0 \leqslant \varpi_j < 0.2$ is the contraction ratio which is directly (approximately linearly) related to the rubbertuator length l_j, and D_j is the effective diameter of the tube before displacement. The total force ΔT that the combined rubbertuators exert on the joint then equals:

$$\Delta T = \rho_1 (a(1 - \varpi_1)^2 - b) D_1^2 - \rho_2 (a(1 - \varpi_2)^2 - b) D_2^2. \tag{2}$$

If we assume that $D = D_1 = D_2$, i.e., the rubbertuators are in their 'middle' position, then:

$$\Delta T = [\rho_1 (1 - \varpi_1)^2 - \rho_2 (1 - \varpi_2)^2] a D^2 + (\rho_2 - \rho_1) b D^2. \tag{3}$$

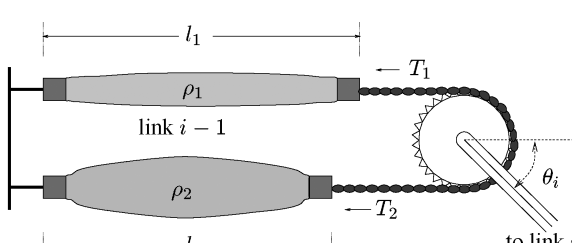

Figure 2. Two-muscle McKibben robotic joint.

Defining $\Delta\rho = \rho_1 - \rho_2$ (the 'difference pressure') and $\rho_0 = \rho_1 + \rho_2$ (the 'base pressure' or stiffness), and grouping we find:

$$\Delta T = \mu_1 \rho_0 \theta + \mu_2 \Delta\rho \theta^2 + \mu_3 \Delta\rho. \tag{4}$$

The hysteretic behavior, caused by the rubber material, of a McKibben-driven joint can be modeled by substituting different values for D. If we assume that muscle 1 has a diameter $D_1 = D + \Delta D$ before displacement and that muscle 2 has a diameter $D_2 = D - \Delta D$ before displacement, then (1) can be written as:

$$\begin{aligned}\Delta T = {} & P_1(a(1-\varpi_1)^2 - b)(D + \Delta D)^2 \\ & + P_2(a(1-\varpi_2)^2 - b)(D - \Delta D)^2.\end{aligned}$$

By splitting this equation in three parts for D, ΔD and $D\Delta D$ we can apply (4) by substituting first D and then ΔD in (3), such that:

$$\begin{aligned}\Delta T = {} & (\mu_1 + \mu_1')\rho_0\theta + (\mu_2 + \mu_2')\Delta\rho\theta^2 + (\mu_3 + \mu_3')\Delta\rho \\ & + \mu_1''\Delta\rho\theta + \mu_2''\rho_0\theta^2 + \mu_3''\rho_0,\end{aligned} \tag{5}$$

where the parameters μ_i' and μ_i'' are:

$$\mu_i' = \mu_i \frac{\Delta D^2}{D^2}, \quad \mu_i'' = \mu_i \frac{\Delta D}{D}.$$

Solving $\Delta\rho = 0$ for $\Delta D > 0$ and $\Delta D < 0$, different signs for the parameters μ_i'' are obtained and the hysteretic behavior is explained (Fig. 3).

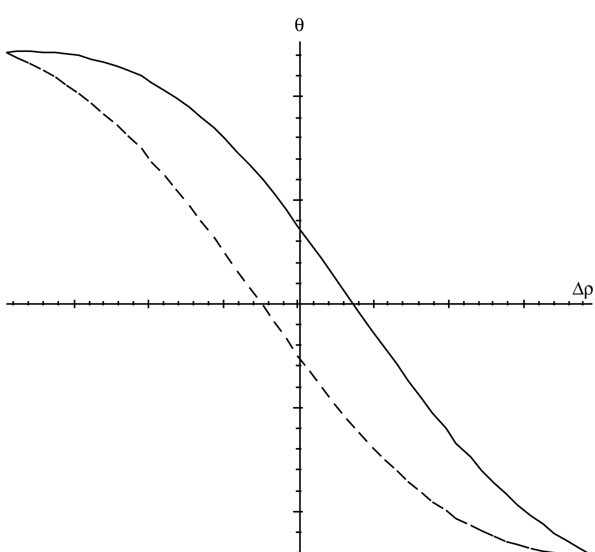

Figure 3. Equilibrium lines of (5). In this case we have taken $\mu_i + \mu_i' > 0$, while we used $\mu_1'' > 0$, $\mu_2'' < 0$ and $\mu_3'' > 0$ for the dashed line, and $\mu_1'' > 0$, $\mu_2'' > 0$ and $\mu_3'' > 0$ for the solid line.

We have investigated a different approach to obtain nonlinear spring characteristics. In this set-up, two DC motors control a joint through nonlinear elastic elements. These elastic elements consisted of a cylindrical pot containing up to six rubber balls with a diameter between 6 and 9 mm. A downside tendon leads through this pot and presses a plate located above the balls against the bottom of the pot. Owing to their highly non-linear properties rubber balls are used. These characteristics derive from the behavior of the elastomer as well as their spherical geometry.

The characteristics of the rubber balls can be approximated by an exponential function. A problem with this approach, however, appeared to be the hysteresis of the rubber balls. Although this hysteresis can be reduced by sufficient lubrication, it cannot be prevented. Furthermore, the flexibility obtained through this approach is rather limited, while the pots are comparatively large. We, therefore, abandoned this line of research.

2.2. Linear Springs

Due to their compact size and high force-to-weight ratio, DC motors are a more likely candidate for actuation in anthropomorphic systems. Most approaches consist of two motors working against (to increase stiffness) or with (to change position) each other and are connected over gear boxes *via* elastic elements. In most cases, these elastic elements consist of springs [9–11]. Since springs are linear, however, these alone do not suffice — increasing the force of a linear spring does not increase its stiffness. Therefore, such solutions have to include a mechanism changing the linear properties of the spring into a non-linear behavior.

There have been different approaches towards obtaining non-linear springs in the literature. Morita and Sugano [12] used a spring leaf with varying length in order to induce nonlinearities on the spring. The construction, however, was difficult and error-prone, and led to a complex nonlinear transfer function. Migliore *et al.* [11] used a special spring device inducing a force–length relationship which can be determined by the curvature of a bar extending two springs. The construction is relatively large and may suffer from non-linear friction and wear-and-tear. Tonietti *et al.* [13] introduced a variable stiffness actuator, a rather complex and large structure actuating three springs with tendons over rollers. English and Russell [14] construct an antagonistic elbow joint using similar approaches as presented in this paper. However, in our approach the elbow actuators cannot be placed in the lower arm, since that space is needed for the hand actuators. Also, they assume that arm stiffness is independent of joint position, but that would lead to linear springs and remove the requirement of robustness against collisions, since the stiffness near the joint limit would not increase, as it does in our case.

Our concept follows the approach in Ref. [13], but in a significantly simplified form. In our set-up, each motor is equipped with a non-linear spring element (see Fig. 4). Each element consists of a linear spring which pushes the tendon, forming it into a triangle. The height h of this triangle relative to half base l determines the stiffness of the construction (Fig. 5). Two motors, each of which is equipped

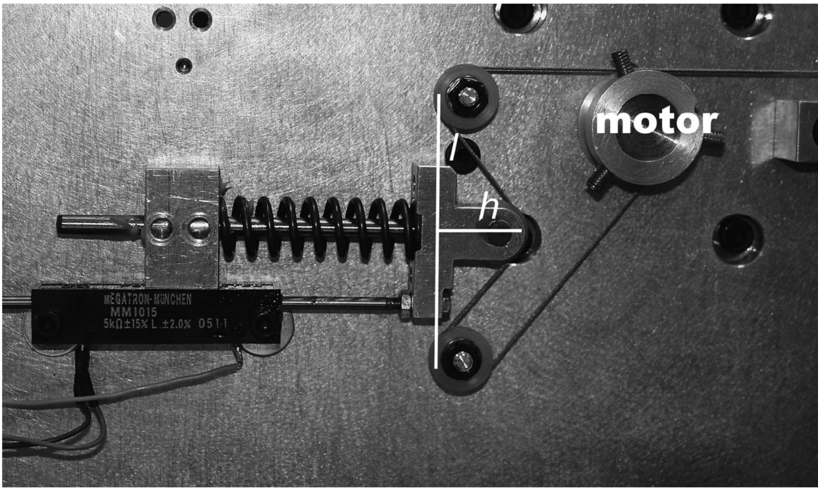

Figure 4. Set-up for a non-linear spring. Height h of the triangle relative to $l/2$ determines the stiffness constant.

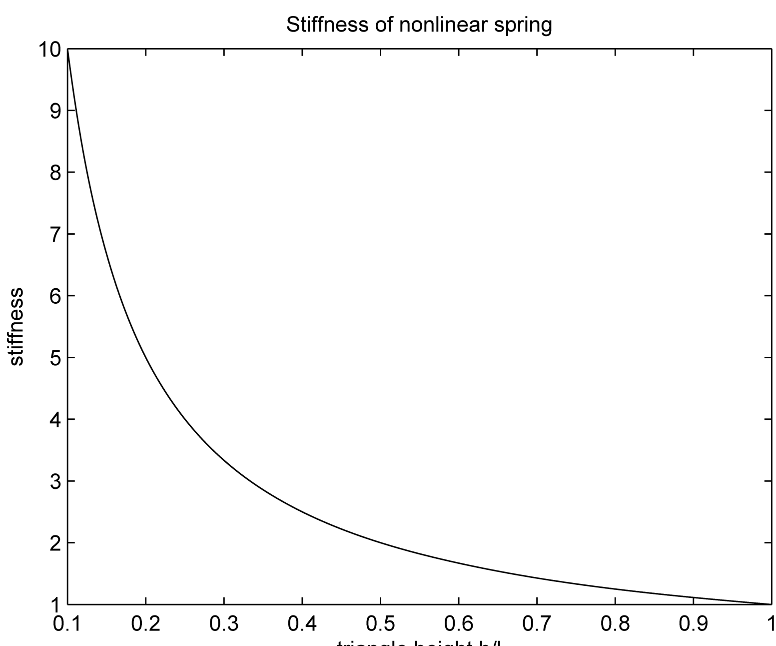

Figure 5. Stiffness of the joint relative to the height of the l/h triangle.

with a non-linear spring element, then can be used to increase the total stiffness (up to infinite stiffness) by pulling in counter directions, since their tendons are stiffly connected to each other *via* the joint that they are controlling.

3. Control

The structure and behavior of antagonistic joints is radically different from standard robot joints. Since the (passive) elasticity of the control path should be used as a feature of the joint, it is not possible to use joint-side position control, because a (theoretical) ideal controller would make the joint stiff. The passive elasticity of the joint would therefore be an unused feature. As a consequence, vibration damping of the system has to be realized without the use of position control.

Furthermore, the control path is quite different from 'standard joints', as the stiffnesses within the control path are changing during operation and are non-linear, which makes most of the standard linearization methods unsuitable. Currently, our control approaches do not take the non-linearity into account.

The whole system can be divided into a system with high bandwidth consisting of motors gears and motor position controller, and a second one with low (and varying!) bandwidth, including the elastic elements, the output and the vibration damping controller.

Both systems can be investigated separately to find a suitable solution.

3.1. Vibration Damping

As mentioned above, vibration damping using output position is not suitable, but several other inputs could be used for vibration damping:

(i) Motor force/torque. Oscillation of the output will of course cause additional force/torque on the motors and could be measured *via* the motor current. Since future joints have to use gears (with yet unknown efficiency) the quality of these signals will not be suitable for vibration damping control.

(ii) Motor position. Since an ideal motor position controller will reduce position errors to zero, motor position cannot be used for vibration damping.

(iii) Motor-side force on elastic element. Owing to the severe weight and space restrictions, we decided not to equip the system with motor-side force sensors.

(iv) Output force/torque. Joint-side force–torque measurement would provide a suitable signal for vibration damping. However, weight and space restrictions lead us to leaving out such sensors.

(v) Output position/velocity. As already mentioned, using output position for vibration damping is not a good idea. However, if the signals are good enough, the time derivative of the output position can be computed and the resulting velocity can be used for vibration damping. First tests showed good performance and stability.

In the antagonistic test bed, vibration damping has been realized using output velocity and a simple proportional controller with good results (see Fig. 7). Of course further improvements have to be made including stability analysis and nonlinear control. A promising alternative is using model-based control.

3.2. Force Control

Since the spatial limits in the anthropomorphic arm are quite strict, the number of sensors needed has to be kept low. We, therefore, opted for using system state knowledge for additional data acquisition.

As adjustable stiffness is a design goal of the system, the stiffness is a given parameter. Using the inverse stiffness, a position difference Δq equivalent to the desired force F_{desired} can be calculated. Since the position of the output q is the average of the input positions q_1 and q_2 if the external forces $F_{\text{extern}} = 0$, the 'force controller' just has to keep $\Delta q - \Delta q_{\text{desired}} = 0$. This controller (Fig. 6) has been implemented on the test bed with good results.

Here, a model-based approach might also help to minimize friction and hysteresis effects.

Figure 7 shows the step response of the controller for the antagonistic joint test bed. Results depending on the damping parameter of the system are shown.

4. Design of an Anthropomorphic Hand

In the year 2000 we presented the DLR Hand II, being a second step towards multi-fingered, dextrous hands. As well as DLR's Hand I, in order to ensure applicability on a large range of different robots Hand II has all of the actuators and electronics integrated within the fingers and the palm. The use of external actuators, as propagated in several other hands, strongly limits the applicability of such systems.

On the downside, the integration of actuators and electronics leads to an increase in finger and hand size of about 50%. In order to use the hand for grasping objects designed for humans and in order to compensate for the size of the hand, the fifth finger of Hand II has been omitted; also, it has been shown that the little finger is only mandatory for 5% of all grasping tasks.

The fingers of Hand II have 4 d.o.f. each; 2 d.o.f. are located in the base (metacarpal) joint and 1 d.o.f. is located in each interphalangeal joint. The in-

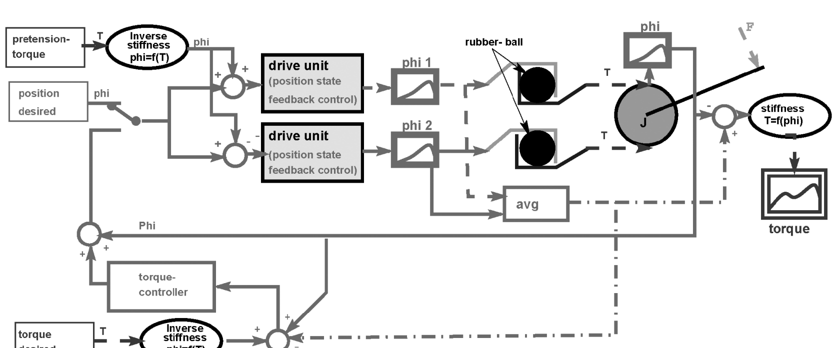

Figure 6. Force control structure.

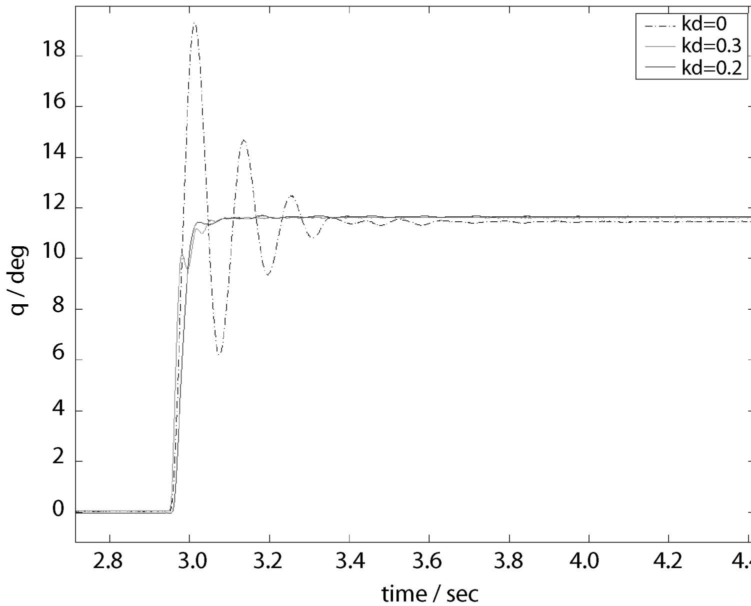

Figure 7. Controller step response of the antagonistic joint using different vibration damping parameters.

terphalangeal joints are coupled to reduce the number of actuators needed and subsequently the size of the fingers.

4.1. Anatomy of the Human Hand

In our design of an anthropomorphic hand our goal is to closely copy the properties of the hand rather than its intrinsic structure. The solutions found in biology must be transferred to technical components and evaluated before they can actually be used.

4.1.1. Skeleton

The human hand consists of a palm with metacarpal bones and finger bones (three per finger: the proximalis, medialis and distalis phalanxes). The index, middle and ring finger are similar in their structure and configuration, whereas the thumb and little finger differ considerably; the latter has a bone structure similar to the middle fingers, but its tendons, ligaments and muscles resemble those of the thumb.

4.1.2. Joints

Understanding hand joints is imperative to realize an anthropomorphic hand, since joints found in biology are radically different from technical joints. The human hand uses mainly three kinds of joints, which can be divided into 1- and 2-d.o.f. joints (contradicting Kapandji [15], Benninghoff [16] also mention 3-d.o.f. joints in the thumb; for reasons explained below we ignore this third d.o.f.).

The 1-d.o.f. joints in the hand all are hinge joints (Fig. 8); 2-d.o.f. joints can be divided into two types. The metacarpal joint of the thumb is a saddle joint, but

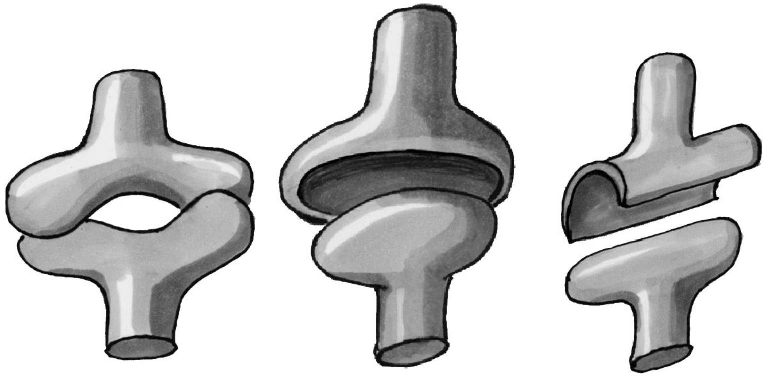

Figure 8. (Left) Saddle joint. (Middle) Condyloid joint. (Right) Hinge joint. From [17].

with non-orthonormal axes, and can be described by the saddle of a scoliotic horse [18]. In contrast, the metacarpal joints of the fingers are condyloid. The main difference between saddle and condyloid joints is that condyloid joints have (roughly) intersecting axes which saddle joints do not have. For the thumb, the axes of the metacarpal are non-orthogonal screw.

The most accurate 'technical' approximation of the human 2-d.o.f. joints are cardan joints for the condyloid type and hyperboloid joints for the saddle joint type. Both approximations are, however, inaccurate. Rotational movement of a condyloid joint intrinsically produces translational movement since an ellipsoid cannot be described by a rotation around two axis. The hyperboloid joint is a precise approximation of a saddle joint with an orthogonal screw axis, but not for a non-orthogonal axis such as found in the thumb.

Finger joints. As mentioned above, the metacarpal joints of the human fingers are condyloid joints with 2 d.o.f. The axes of these joints are roughly orthonormal and intersecting. The range of motion in flexion increases from 90° for the index finger progressively with the other fingers, whereas the range of motion in extension is about 30–40° for all fingers [15].

All interphalangeal joints of the human hand only have 1 d.o.f. and are hinge joints.

The range of motion of the proximal interphalangeal joints is increasing from the index towards the little finger to 135° [15], whereas the range of motion of the distal interphalangeal joints is less than 90° in flexion and about 0° in extension (passive extension is possible up to 30°).

Thumb joints. The thumb can be assumed to be the most important part of the human hand. This is most obvious in hand surgery: a lost finger can be coped with, but a lost thumb is generally solved by policization of, for example, the index finger [19].

The metacarpal joint (anatomically correct: trapezo-metacarpal joint). Since the coupling of the bones in the human hand is not stiff, compliant motion in almost every direction is possible. Subsequently, there are several opinions of how many d.o.f. the metacarpal and thus the first interphalangeal joint of the thumb has. Kapandji [15] hypothesizes 2 d.o.f. in the metacarpal and 2 d.o.f. in the first interphalangeal joint, while Ref. [16] suggests 3 d.o.f. in the metacarpal and 1 d.o.f. in the first interphalangeal joint.

Following Kapandji [15], we consider the metacarpal of the thumb to be a 2-d.o.f. saddle joint. In contrast to 'standard' saddle joints, the contact surfaces are not formed by a common generatrix rotating about two orthogonal axes (e.g., hyperboloids). Rather, Kuczynski [18] showed that the surface of the saddle on the proximal side of the joint is bent around a third axis. This deformation of the saddle surface introduces a coupled additional rotation around the longitudinal axis of the thumb which is necessary to enable opposition of the thumb, required for most manipulation tasks (during this rotation the inner surface of the thumb changes its orientation by 90–120° towards the inner side of the palm).

The interphalangeal joints (anatomically correct: metacarpo-phalangeal joint and distal interphalangeal joint) of the thumb are similar to those of the fingers. Kapandji proposes that the fifth d.o.f. of the thumb is located in the proximal interphalangeal joint as a limited-range d.o.f. along the longitudinal axis of the medial phalanx. One hint to prove this is that the proximal interphalangeal joint of the thumb is not a hinge joint, but a condyloid joint. Based on the experiences from policization, this d.o.f. can be assumed less important; after all, near-perfect hand functionality can be regained by replanting the index finger as a thumb. The range of motion of the proximal interphalangeal joint is 60–70° in flexion and 0° in extension, whereas the the distal interphalangeal joints motion range is about 75–80° in flexion and 5–10° in extension.

4.2. Getting it Together: the Joints of the DLR Anthropomorphic Finger

As already mentioned, the most difficult point in the design of an anthropomorphic hand is to understand the human hand and copy its properties rather than copying the biological structure hand itself. There are several key differences between biological and technical systems which have to be taken into account in order to end up with a optimal technical system. An example is the lack of renewable materials in technical systems. Also, there is a need to keep the system as simple as possible from a control point of view, since we are still not able to build capable enough biologically inspired control methods for complete integrated systems. Therefore, several simplifications have to be realized.

4.2.1. Actuation

One of the major problems of most current robotic hands (e.g., the UB Hand [20], Robonaut Hand [21], Karlsruhe Hand [22], DLR Hand) is robustness against impact. The maximum force that can be exerted by these hands is sufficient for performing manipulation tasks and their agility is good enough to catch balls, but they are limited in use due to their sensitivity regarding impacts. For instance, the weight of the ball that is caught by Hand II has to be limited to prevent major damage to the hand; the maximum speed of service robots opening doors has to be strongly limited to prevent major damage in the case of contact with stiff objects in the environment. The reason for this sensitivity is the lack of mechanical elasticity of the fingers, resulting in an inability to store energy short-term. Flexibility obtained through active control, such as is obtained with Hand II that is impedance-controlled using a control frequency of 1 kHz, can be used to react to slow impacts and contact with stiff objects, but in the case of fast impact ('ball throwing'), a large amount of energy is transferred within the first microseconds, to which no active controller can react.

To make systems more robust against impacts from balls, doors, walls, etc., the mechanical structure of the system has to be intrinsically elastic and should be able to store a reasonable amount of energy. It is important, however, that the compliance of the system can be varied, since it has to act compliant for contacts but stiff for precision manipulation. Therefore, future robotic systems have to be of the variable stiffness type.

However, there is another argument. Tendon-driven hands, especially where tendons are led over several joints and are very stiff (e.g., steel cables), in due time always suffer from tendon slack and tendon superextension, since eccentricity in joints and other mechanical tolerances leads to varying tendon lengths. In systems which are driven by only one actuator, this problem can only be addressed using additional (not variable) elasticities within the tendons, thus decreasing system performance.

A solution which solves both problems mentioned above is the use of antagonistic drives. By having two actuators controlling a single joint *via* spring elements with nonlinear stiffness, impact can be stored in these springs, while varying tendon lengths, causing small changes in the stiffness of the joint, can be easily addressed by calibration. After all, the drives enable control of the passive stiffness of the joint.

Therefore, the fingers of DLR's anthropomorphic hand will be actuated by antagonistic actuators.

4.2.2. Joints

The condyloid joints of the human fingers imply an additional movement of the finger in the longitudinal direction, since the ellipsoidal contact surfaces cannot be generated using a 2-d.o.f. motion and a common geriatrix. First, this leads to complications calculating the inverse kinematics of the finger. Furthermore, extended wear is to be expected at the contact surfaces. Contact surfaces of technical joints and human joints are completely different since the contact areas in the human hand are flexible. Flexible joint surfaces in technical systems would fail due to excessive wear. Wear in biological systems is compensated for by renewable materials. For these reasons, hyperboloid joints are more applicable. Simulations showed that the use of non-intersecting axes of hyperboloid joints reduces the functionality of the hand only marginally if the main axis of the finger (flexion/extension) is distal to the secondary axis of the finger (adduction/abduction).

4.2.3. Realization

The structure of the finger is designed as an endoskeleton with bionic joints. The metacarpal joint is designed as a hyperbolically shaped saddle joint, whereas the interphalangeal finger joints are designed as hinge joints (Fig. 9). The proximal interphalangeal joint of the thumb is, contrasting biology, also designed as a hinge joint. This circumvents the negative side-effects of technical condyloid joints, while leaving out the thumb's fifth d.o.f. is not problematic.

The kinematics of the new hand is closely adapted to human hands. Thus, every finger differs in 'bone' length, size and kinematics, e.g. the fifth finger PIP joint has to have an inclination of about 15° to enable opposition to the thumb, while the index and middle finger only have minimal inclination.

All joints enable dislocation of the 'bones' without damage in the case of overload using the elasticity in the drive train. The routing of the finger tendons is quite similar to the human hand, but in a more technical manner with respect to more easy control of the hand and to consider the fact that human joints can compensate wear by tendons, ligaments and cartilage growing again, while technical parts cannot compensate for any wear at all. Using Hand II in dozens of applications we experienced that the assumption, that the friction torque in finger joints is negligible

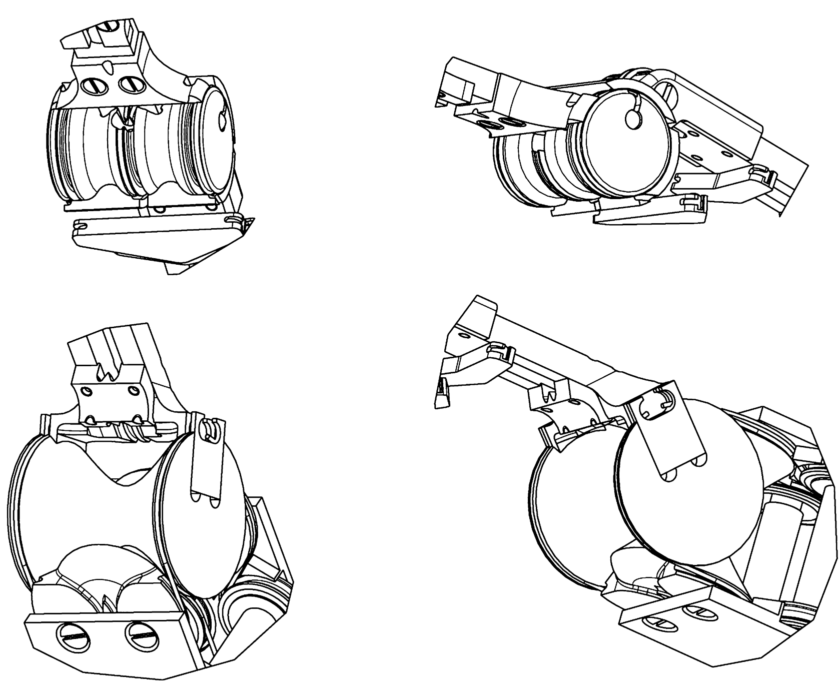

Figure 9. Joints of antagonistic finger (patent pending).

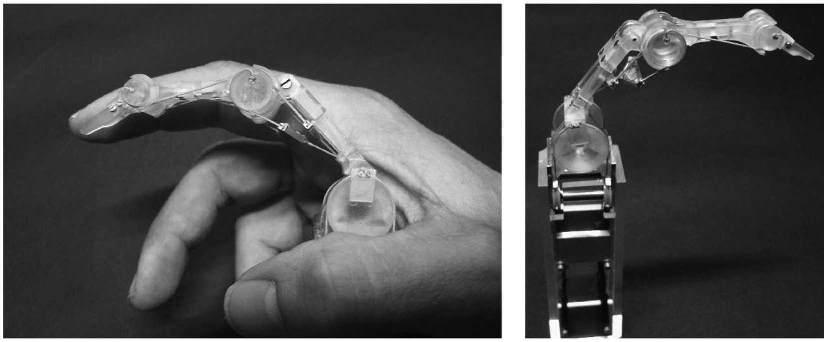

Figure 10. Finger prototype.

Figure 11. Realization of the first antagonistic finger of the DLR hand–arm system in a test bed. The drives and flexible elements of the test bed can be clearly seen in the background.

even if sliding contact bearings are used, proved to be true since the friction contact is in a very small distance regarding the axis of revolution. Nevertheless, all sliding surfaces are hard-anodized to reduce friction. It turned out that enlacement friction is much more prominent and has to be further investigated.

A first prototype of the index finger has been built in stereolithography to verify the functionality of the joints and the tendon routing (Fig. 10).

In a test bed, a fully functional version of the finger, using alloy structure and steel cables, is attached to an antagonistic drive unit (eight motors) to enable the development of control strategies and to test mechanical parameters of the system, e.g., maximum forces, friction in joints and tendon guides, accuracy and wear. This prototype is shown in Fig. 11.

5. Results and Summary

The design of an anthropomorphic hand–arm system is a multidisciplinary challenge and enters new ground in many fields. Thus, it is imperative to perform several tests before designing the whole system. In particular, due to the enormous difference with respect to existing robotic approaches, the control strategies of the arm have to be investigated carefully.

We have demonstrated the advantages of an antagonistic approach with respect to safety *via* simulation, showing that both impact force and the transferred kinetic energy were significantly lowered by decreasing the joint stiffness.

Preliminary tests with the antagonistic test bed have shown that the control of antagonistic joints can be done with relatively simple controllers, since the system can be treated as two (nearly) independent systems of different bandwidth. The performance of vibration damping is more than sufficient and the controller can be shown to be stable. Force control without using force measurement has been implemented which enables us to reduce the required number of sensors and associated electronics.

First prototypes of the robot joints (antagonistic and variable stiffness) have been designed and built, and will be tested on the new multi-purpose test bed in order to evaluate the best approach. This will be followed by a prototype of the wrist.

5.1. Future Work

Based on our current results we will follow this line of research with respect to the design and control of novel robotic joints. One of the key issues, i.e., the development of the required software and electronics architecture for the hand–arm system, will be based on the results of the medical robot 'Kinemedic' recently developed at DLR's Institute of Robotics and Mechatronics.

Mechanics: the prototypes for the wrist, elbow and shoulder joint have to be tested. Based on the results of these tests the decisions whether to use antagonism or variable stiffness has to be made for every joint and the final versions of the joints have to be built.

Control: the controllers developed on the antagonistic test bed have to be improved. The stability of the controllers has to be proven over the whole range of stiffness, and the parameters of the force controller and the vibration damping have to be tuned. Thus, it is essential to extend the actual models to nonlinear ones. To deal with the nonlinearity of the system, model-based approaches might be viable; furthermore, adaptive control must be investigated as a solution to enhance the performance of the controllers.

Since output-side position control is not possible due to the antagonistic principle as well as the damping and thus the hysteresis of the elastic elements is quite high, strategies to compensate friction and hysteresis have to be developed to reduce position errors at the output, etc. Investigation to this point is currently underway.

Finally, a simulation environment, up to the dynamical properties, of the hand–arm system is under development.

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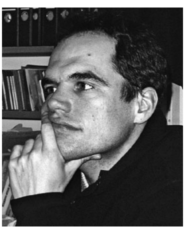
About the Authors



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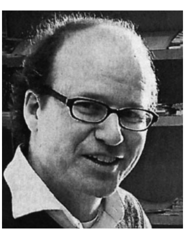

Patrick van der Smagt received his PhD on Neural Systems for Robotics from the University of Amsterdam in 1995. He then moved to Germany, joining the Institute of Robotics and Mechatronics at the DLR. First focusing on learning systems and cerebellar models, he built-up and is head of the Bionics Group which focuses on biologically inspired technical systems, from sensing to motion. He is and was Editor and Book Editor for *Neural Networks*, conference chair and board member, EU project leader, has published numerous papers and holds several patents.