Nonlinear Model-Based Control Architecture for Antagonistic Pairs of Fluidic Muscles in Manipulator Motion Control

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Abstract

In this paper a control structure and joint trajectory planning algorithm are presented for a type of kinematically redundant manipulator actuated by joints with pairwise antagonistic pneumatic muscles. The used muscles and the resulting behavior of a single manipulator joint featuring antagonistic muscles in a symmetric configuration are characterized.

The joint limits resulting from the limited deflection of the pneumatic muscles can present a problem for the planning of the reference joint trajectories. An algorithm is presented to ensure the joint limit avoidance in the redundancy resolution of the presented manipulator.

Beside the distinct limits, the pneumatic joint actuation also results in a hysteretic behavior, it is shown that in this case the hysteresis can be described by a Preisach hysteresis model. The resulting hysteresis model allows the construction of a model-reference following controller, with a model control loop, designed for good tracking performance and a disturbance rejection loop optimized for suppression of disturbances. Experiments confirm the improvement in tracking control as compared to the system solely controlled by a feedback regulator.

KEYWORDS: PAM, pneumatic muscle actuation, hysteresis model, modular robot

1. Introduction

Pneumatic muscles have matured to become reliable, highly durable low cost actuators. Due to favorable characteristics like high power-to-weight ratio and their inherent compliance, they are well-suited to be applied to construct light-weight versatile robots /1/, /2/.

1.1. Muscle characteristics

Most of the pneumatic muscles in use today are based on the McKibben muscle, consisting of an air proof so-called rubber bladder which is surrounded by a sheath of inextensible fibers and closed at both ends by caps /3/. When pressurized, the bladder increases in vo-

lume, resulting in an expansion in radius and an axial contraction due to the unextensible sheath. When attached to an appropriate bearing the pressurized muscle is able to exert a pulling force. When pressure is released, only the relaxation of the deformed muscle slowly relaxes the muscle, allowing it to passively return to its original shape. Therefore, like their natural counterparts, pneumatic muscles can only exert pulling forces and have to be used in an antagonistic setup. One of the main challenges in the application of pneumatic actuators is their difficult controllability, as the available muscles exhibit a wide range of nonlinear effects. Apart from omnipresent creep, their deflection, which can reach values of up to 25% of the muscle length in the unloaded case, is dependent upon the applied air pressure, the force, as well as the velocity of change. Due to frictional effects in the air path and the muscle material, the deflection exhibits an asymmetrically hysteretic behavior, see filled areas in Figure 1, which prohibits the precise open loop control of single muscles. The manufacturer guarantees a contraction hysteresis of at most 3% of the nominal length. The deflection error of the muscle due to the hysteresis can thus reach values of over 10% of the possible stroke.

The gray contours in **Figure 1** depict the load force and contraction loops measured at different air pressures at a frequency of 0.1 Hz, acquired for a pneumatic muscle of type FES-TO DMSP-10-150N. To derive a description for the mean relation between contraction and load force for a given air pressure, the mean force for a certain length is calculated from the flanks of the loops and displayed as a colored line. The resulting mapping is given in **Figure 2**.









An abundance of approaches has been suggested to model the resulting mapping /4/. Boblan et al. compare several possible approaches to describe the static relation between contraction, pressure and muscle force /5/. He concludes that the static relation of a single muscle can be described with best accuracy by a sine model, consisting of a superposition of linear and sinusoid components. Therefore, a sine model approach was chosen in our investigations and parameterized using the measured data displayed in Figure 2. Consequently, this model was inverted to provide the necessary air pressure for an admissible combination of muscle contraction and muscle force.

1.2. Manipulator setup

Figure 3 (left) depicts the used manipulator structure as introduced by Schmitt et al. in /1/. A single stage consists of a pair of antagonistic pneumatic muscles of the type DMSP-10-150N, possessing a working length of 150 mm and a muscle diameter of 10 mm. From the module design depicted in Figure 3 (right) the relation between the joint angle and the corresponding effective actuator lengths L_A and L_B can be derived:

$$L_{A} = \begin{vmatrix} r_{u} \\ I_{u} \end{vmatrix} + \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{vmatrix} \begin{pmatrix} -r_{o} \\ I_{o} \end{vmatrix} \text{, and } L_{B} = \begin{vmatrix} -r_{u} \\ I_{u} \end{vmatrix} + \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} r_{o} \\ I_{o} \end{vmatrix}$$
(1.1)

From the kinematics of a single segment in (1 .1) and the static mapping relating the air pressure and the applied force to the resulting mean contraction in Figure 2 derived from the measurements described in Section 1.1, the inverse mapping can be calculated which provides the necessary air pressures in each muscle for a combination of desired joint angle and individual muscle forces. The resulting feedforward control structure is displayed in **Figure 4**. The described feedforward structure compensates the static nonlinear relations between the mean values of the contraction force and displacement to the pressure.







Depending on the combination of the muscle forces, drive torques as well as antagonistic torques will be produced. The antagonistic torques do not result in a motion as they merely cause a prestress in both actuators, that can be used to vary the joint's stiffness /6/. In the following, the external force input is only used to generate a prestress in the system.

In the antagonistic setup the same effects causing hysteretic behavior in a single muscle will result in hysteresis between the desired and the measured joint angle. Due to the symmetric setup of the joint actuators the resulting hysteretic behavior will consequently be symmetric.

2. Redundancy resolution scheme for muscle-actuated manipulator

The manipulator segments are combined in a serial fashion to form the manipulator. As soon as the number of segments exceeds the number of degrees of freedom necessary for a specific task, the structure possesses redundant degrees of freedom. For a serial manipulator the direct kinematic problem, connecting the joint positions to the pose of the end-effector $\mathbf{x} = \mathbf{g}(\mathbf{q})$, has a unique solution. For kinematically redundant manipulators however, the inverse mapping is not unique as an infinite set of possible joint configurations q can be found, that result in the same pose of the end-effector $\mathbf{q} = \mathbf{h}(\mathbf{x})$, an example is shown in **Figure 5**.



Figure 5: Different configurations of the kinematically redundant manipulator leading to the same pose of the end-effector.

As no closed-form solution exists, the inverse kinematic problem can be only be solved numerically, in order to choose one of the infinite number of possible solutions some addition tasks or performance criteria have to be defined. As the redundant manipulator is actuated by pneumatic muscles, their finite range of deflection has to be taken into account. With the maximal contraction length of 25% of its length and the geometric properties of the structure, this leads to a controllable angle range of $-30^{\circ} \le q_i \le +30^{\circ}$. One important issue when calculating the joint angles from the set of solutions of the inverse kinematic problem is therefore to keep the desired joint angles as small as possible, e.g. by looking within for the solution that minimizes the function $J = \mathbf{q}^T \mathbf{q}$.

A simple optimization for small joint angles over the whole structure may still lead to solutions in which single angles exceed the admissible joint limits. In **Figure 7** (solid lines) the solution of the inverse kinematic problem for a given path of the end-effector is shown. The path for the end-effector is defined in 5 DOF in Cartesian space. A manipulator with 6 joints consequently possesses one redundant DOF. The minimization of the joint angles for a given pose leads to solutions in which the cost function $J = \mathbf{q}^T \mathbf{q}$ is minimal and most of the joint angles are quite small at the expense of the angle shown in red, to an extend that the desired angle becomes larger than the largest possible angle.

Therefore, the joint limits mentioned above have also to be taken into account in the redundancy resolution scheme. A cost function which allows to minimize the joint angle, while regarding the joint limits is the following function:

$$f(\mathbf{q}) = \sum_{i} 4q_{i}^{2} - \ln\left(1 - \left(\frac{q_{i}}{q_{i_{max}}}\right)^{2}\right)$$
(2.1)

The weight grows towards infinity as the angle approaches the joint limits. Therefore, joint angles growing towards the joint limits will be severely punished. The value of the weight function is shown in **Figure 6**.



Figure 6: Weighting function over the range $\begin{bmatrix} -1 & \text{rad} \\ +1 & \text{rad} \end{bmatrix}$.

The search for an optimal joint vector **q** that minimizes the cost function (2 .1) under the constraint $\mathbf{x} = \mathbf{g}(\mathbf{q})$ is conducted via convex optimization. This task is a type of constraint minimization problem that can be solved by using Lagrange multipliers λ . To combine both constraints into one equation, the following Lagrangian function can be used:

$$\Lambda(\mathbf{q},\lambda) = \mathbf{f}(\mathbf{q}) + \lambda^{\mathsf{T}}(\mathbf{g}(\mathbf{q}) - \mathbf{x})$$
(2.2)

with the unknown row vector λ^{T} , which defines a linear combination of the constraints. A local extremum of the Lagrangian function can be found using a gradient descent approach

$$\nabla \Lambda(\mathbf{q},\lambda) = \mathbf{0}. \tag{2.3}$$

An efficient method to solve the resulting nonlinear system of equation is the Newton-Raphson-method; the zeros **X** of the system F(X) = 0 are calculated through the following linear iteration formula:

$$J_{\mathbf{F}}(\mathbf{X}^{p})\Delta\mathbf{X}^{p} + \mathbf{F}(\mathbf{X}^{p}) = 0, \qquad (2.4)$$

$$\mathbf{X}^{p+1} = \mathbf{X}^p + \Delta \mathbf{X}^p. \tag{2.5}$$

Starting from vector \mathbf{X}^0 the vectors \mathbf{X}^{p+1} are iterated until the absolute value of the change of the solution vector is smaller than the stopping criteria ϵ . The system of equations in (2.3) can be split into two parts, one for the vector \mathbf{q} , the other for λ :

$$\mathbf{X} = \begin{bmatrix} \mathbf{q} \\ \lambda \end{bmatrix}$$
(2.6)

$$\mathbf{F} = \begin{bmatrix} \mathbf{F}_{1} \\ \mathbf{F}_{2} \end{bmatrix} = \begin{bmatrix} \frac{\partial}{\partial \mathbf{q}} \Lambda(\mathbf{q}, \lambda) \\ \frac{\partial}{\partial \lambda} \Lambda(\mathbf{q}, \lambda) \end{bmatrix} = \begin{bmatrix} \nabla f(\mathbf{q}) + J_{g}^{\mathsf{T}}(\mathbf{q}) \lambda \\ g(\mathbf{q}) - \mathbf{x} \end{bmatrix}$$
(2.7)

The first part is responsible for the optimization and the second for the constraints. Both parts can be solved using the Newton-Raphson-technique. The only difficulty is to calculate the Jacobian; the equation (2.8) represents the linear system that has to be solved. J_1 and J_2 are the Jacobian of the F_1 und F_2

$$\begin{bmatrix} \mathbf{J}_{1}(\mathbf{q},\lambda) \\ \mathbf{J}_{2}(\mathbf{q}) \end{bmatrix} \begin{bmatrix} \Delta \mathbf{q} \\ \Delta \lambda \end{bmatrix} = -\begin{bmatrix} \mathbf{F}_{1}(\mathbf{q},\lambda) \\ \mathbf{F}_{2}(\mathbf{q}) \end{bmatrix}$$
(2.8)

To calculate the Jacobian matrix \mathbf{J}_1 , it is written as two separate matrices:

$$\mathbf{J}_{1} = [\mathbf{J}_{1,1}, \mathbf{J}_{1,2}] = \left[\frac{\partial}{\partial \mathbf{q}} \mathbf{F}_{1}, \frac{\partial}{\partial \lambda} \mathbf{F}_{2}\right]$$
(2.9)

Both submatrices are derived through inspection of equation (2.7)

$$\mathbf{J}_{1,1} = \frac{\partial}{\partial \mathbf{q}_{j}} \frac{\partial}{\partial \mathbf{q}_{i}} \left(\mathbf{f}(\mathbf{q}) + \lambda^{\mathsf{T}} \mathbf{g}(\mathbf{q}) \right)$$
(2.10)

The same approach for J_2 results in

$$\mathbf{J}_{2} = \begin{bmatrix} \mathbf{J}_{g}(\mathbf{q}), \mathbf{0} \end{bmatrix}.$$
 (2.11)

With these submatrices the iteration formulation is at hand

$$\begin{bmatrix} \mathbf{q}^{p+1} \\ \lambda^{p+1} \end{bmatrix} = \begin{bmatrix} \mathbf{q}^{p} \\ \lambda^{p} \end{bmatrix} - \begin{bmatrix} \mathbf{J}_{1,1}^{p} & \mathbf{J}_{g}^{p^{\mathsf{T}}} \\ \mathbf{J}_{g}^{p} & \mathbf{0} \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{F}_{1}^{p} \\ \mathbf{F}_{2}^{p} \end{bmatrix}$$
(2.12)

Figure 7 shows two inverse kinematics solutions for a movement of the end-effector of a six DOF manipulator along a path defined in 5 DOF in Cartesian space. The kinematic redundancy is to find consistent joint trajectories that minimize specific cost functions. Shown in solid lines are the manipulator joint angles resulting from an unweighted minimization of the joint angles (solid lines). The simple minimization still allows a violation of the joint limits, happening for the angle shown in red. The minimization of the angles weighted with (2 .1) is shown in dashed lines. As can be seen, the use of the weight function ensures the compliance of the planned trajectories with the joint limits.



Figure 7: Planned trajectories for the manipulator joint angles resulting from an unweighted minimization of the joint angles (solid lines) and a minimization of the weighted angles (dashed).

3. Preisach hysteresis model of the antagonistically actuated segment

A variety of hysteresis models have been applied in an attempt to model the inherent hysteretic behavior of pneumatic muscle actuators. Minh et al. successfully demonstrated the application of a Maxwell-slip-model for the description of the contraction length to force behavior for a single muscle /7/, as well as for the torque hysteresis for the movement in a joint driven by an antagonistic muscle pair /8/. While the described modeling results provide a good reproduction of the behavior of single muscles, no control approach is presented that can be extended to incorporate the control of a joint driven by an antagonistic muscle pair. Attempts have been made to apply classic hysteresis modeling approaches, like Preisach models, to the modeling and control of pneumatic muscles and pairs of pneumatic muscles /9/, /10/. The results obtained in these works provided only limited modeling success, as an important necessary precondition as given by Mayergoyz /11/ to ensure the applicability of a Preisach-approach, the congruency condition, is not fulfilled by the asymmetric hysteretic behavior of a single pneumatic muscle. Therefore, the models derived in the mentioned works were only able to reproduce major loops similar to ones used in the identification process of the model. The main potential of a Preisach model, the ability to model the minor loop behavior and the model inversion for an approximate compensation of the hysteresis could therefore not be exploited.

Mayergoyz recognized that a hysteresis nonlinearity can only be represented by a Preisach model if it fulfills the wiping-out property and minor-loop congruence property conditions /11/. It is shown in /12/ that the use of the presented symmetrical antagonistic setup featuring a pneumatic muscle pair with a compensation of the static mean nonlinear force-contraction-pressure characteristics results in a symmetrical hysteresis behavior, which fulfills all necessary conditions to allow modeling by a Preisach model.

3.1. Preisach model of hysteresis

The Preisach hysteresis model was first developed by Preisach in 1935 in an attempt to model the physical mechanisms of magnetization /13/. Although it was first regarded to be a physical model of hysteresis, the Preisach model turned out to be a phenomenological model that has mathematical generality and is applicable to phenomena from many disciplines. A rigid mathematical generalization has been presented by Mayergoyz, who also determined the necessary conditions for the applicability of such a model /11/.

The simplest type of hysteresis operator $\hat{\gamma}_{\alpha\beta}$ can be represented as rectangular loops in the in-/output-plane, as shown in **Figure 8** (left). Its output switches between +1 and -1 depending on the initial output and the history of past inputs, representing a local memory. In addition to the set of operators $\hat{\gamma}_{\alpha\beta}$, with α and β corresponding to the "up" and "down" switching values of the input u(t), a weighting function $\mu(\alpha,\beta)$ has to be considered, which is called the Preisach function and can be identified for a given system. The resulting Preisach model with the system output f(t) is then given by

$$f(t) = \iint_{\alpha \ge \beta} \mu(\alpha, \beta) \hat{\gamma}_{\alpha\beta} (u(t)) d\alpha d\beta.$$

$$(3.1)$$

Figure 8: An elementary hysteresis operator $\hat{\gamma}$ (left) and Preisach plane (right).

The switching values are subject to the relation $u_{max} \ge \alpha \ge \beta \ge u_{min}$ with u_{max} and u_{min} being determined by the system's physical properties. The feasible combinations of α and β form the triangle T as displayed in Figure 8 (right). Therefore, the output of the Preisach model is determined by integrating the product of the weighting function $\mu(\alpha,\beta)$ and the operator $\hat{\gamma}_{\alpha\beta}$ over the triangle T.

The model output is dependent on the extremal values in the history of the input sequence u(t) as depicted in the example in **Figure 9**. The set of dominant maxima and minima determines the output of the system. Due to the wipe-out property of the Preisach model, input values larger than past dominant maxima or smaller the past minima wipe out the effects of the older extrema. The dominant extrema are marked in the input sequence depicted in Figure 9 (left). At any instant the Preisach plane can be divided into two regions, the one in which the relay operator outputs are +1, marked dark gray in Figure 9 (right), and the one in which the relays' outputs are -1. Both areas are separated by a descending staircase function, the corners are determined by past reversal points in the input sequence.



Figure 9: Input sequence with dominant, as well as wiped out extremal values (left) and Preisach plane with correspondingly activated elemental operators (right).

After applying the identification algorithm presented by Mayergoyz to determine the Preisach function from first order descending curves /11/, the Everett map E is defined /14/, which contains the change of the output value f(t) as a function of α and β :

$$\mathsf{E}(\mathsf{u}_{\alpha},\mathsf{u}_{\beta})=\mathsf{f}_{\alpha}-\mathsf{f}_{\alpha\beta}. \tag{3.2}$$

Since $\alpha \ge \beta$ during the measurement, only one half of the map can be constructed by measurements. The missing values are given by $f_{\alpha\beta} = -f_{\beta\alpha}$. Thus the value of $f_{\alpha\beta}$ can be calculated for any single combination of α and β .

With the sets of past dominant maxima H and dominant minima L, the Preisach model output can then be expressed for any given sequence of inputs u(t) by

$$f(t) = f_{min} + \sum_{k=1}^{n(t)-1} \left[f_{H_k, L_k} - f_{H_k, L_{k-1}} \right] + \begin{cases} \left[f_{H_n, u(t)} - f_{H_n, L_{n-1}} \right] & \text{if } \dot{u}(t) < 0, \\ \left[\left[f_{u(t), u(t)} - f_{u(t), L_{n-1}} \right] & \text{if } \dot{u}(t) > 0 \end{cases}$$
(3.3)

with f_{min} being the output corresponding to $u = u_{min}$ (all relays set to -1).

For a given Preisach model a computationally compact inverse can be derived from (3 .3), if the first-order curve data surfaces $f_{\alpha\beta}$ are strictly monotonically increasing with respect to the parameters α and β . This will result in the inverse of the Everett map G, given by

$$G(f_{\alpha}, f_{\alpha\beta}) = u_{\alpha} - u_{\beta}$$
(3.4)

With this mapping the unknown input u(f(t)) to achieve the desired output f(t) can be computed using

$$u(f(t)) = u_{\min} + \sum_{i=1}^{k-1} G(F_{d_{i+1}}, F_{d_i}) + G(f(t), F_{d_k})$$
(3.5)

with F_d being the set of past output extreme values.

3.2. Identification and feedforward compensation

The hysteretic behavior of the system was identified by producing a series of first order descending curves. An input signal was chosen to lead the output along an ascending branch of the major loop, at distinct values, chosen as suggested in /15/, the input reverses producing a descending curve in the input-output-diagram, terminating at negative saturation.

Due to the symmetric hysteresis loop, it is apparent, that the relation $\mu(\alpha,\beta) = \mu(-\beta,-\alpha)$ is valid. Therefore it is obvious, that for the identification of $\mu(\alpha,\beta)$ also the first-order increasing curves could have been used which are attached to the limiting descending branch.

After the derivation of the inverse Preisach model, the desired joint angle is fed into the inverse model whose output serves as the input to the feedforward structure in Figure 4. The resulting match between desired and measured angle is shown in **Figure 10**. It can been seen, that the inverse model allows a significant reduction of the width of the resulting hysteresis between actual and desired angle and will, in combination with an appropriate feedback controller, allow a very precise control of the manipulator segment.



Figure 10: Open-loop hysteresis compensation using inverse Preisach model measured with a single manipulator stage.

4. Controller design

To ensure precise tracking in the presence of disturbances, creep, and model uncertainties, it is imperative to complement the feedforward compensator with a feedback controller.

The idea of the control scheme, depicted in **Figure 11**, is to combine the feedforward hysteresis compensator and a model-following controller (MFC) based on the nominal dynamic model to implement an effective tracking controller.

The feedforward compensator is responsible to provide the adequate value to compensate the static hysteresis as described in Section 3.2. The fundamental idea behind the modelfollowing controller structure is to separate the tracking control from the disturbance rejection problem in the controller design, by including a plant model in the model control loop which is controlled by the tracking controller. As the model control loop is disturbance free, the track-



Figure 11: Control structure with feedforward hysteresis compensator and a model-following controller (MFC) consisting of model and disturbance rejection loop.

ing controller can thus be designed to provide good tracking performance. The output of the plant model serves as reference value to the disturbance rejection loop containing the actual plant, providing a filtered reference. The main advantage of the setup is that the inverse plant model, which is usually needed for feedforward control, does not need to be calculated, as all the signals in the control loop can be calculated with the direct model. The controller output

 u_{mod} in the model loop, which is necessary to produce an output of φ_{mod} is known. The output of the tracking controller provides a feedforward control signal which compensates the dynamic behavior modeled in the previous loop and is added the output of the disturbance rejection controller. If the plant model reflects the exact behavior of the actual plant, the plant will be driven to the desired values by the feedforward signal alone. As there are always modeling errors and disturbances acting on the actual plant, the disturbance rejection controller has to compensate those effects. Since the controller in the model loop provides for the tracking performance, the controller of the second loop with the actual plant can be laid out solely for good disturbance rejection. Due to the fact that there is only a feedforward connection between the loops, the stability of the control system is not compromised, as long as the stability of the individual control loops is ensured. For more information regarding MFC see Osypiuk et al. in /16/.

Due to the hysteretic behavior of the plant, its gain is dependent upon the current amplitude and direction, while it shows a similar dynamic behavior over the range of possible joint angles. A typical step response along with an approximation of the dynamic behavior as a second order system with two real poles at s = 23 rad / s is shown in **Figure 12**.

The gain of the nominal plant model is derived from the in-/output characteristic as shown in **Figure 14**. With this model a PI controller is designed with whose zero one of the poles is cancelled, while the gain is set to provide for a damping of $D = 1/\sqrt{2}$, as shown in **Figure 13**. Due to the nonlinearity induced by the modeled hysteresis, the response of the full model lags behind the response simulated with the same controller and the linear approximation. The hysteresis nonlinearity induces an uncertainty in the gain parameter which has to be taken into account in the controller design for the disturbance rejection loop. As shown in Figure 14, although it induces a parametric uncertainty, the extremal values of the gain can be derived from the in-/ouput characteristic, which defines a bounding sector. Along with the







Figure 13: Step response of the controlled model with simulated hysteretic behavior

parameter uncertainty, an unstructured uncertainty bounded by the function in **Figure 15** is taken into account in the controller design process, to account for higher frequency influences and modeling errors. To ensure a good disturbance rejection, especially for stationary and low frequency disturbances acting at the plant output, the sensitivity function is weighted accordingly in the H_∞-controller design. The disturbance rejection controller is then derived as a robust controller for the uncertain open-loop plant model via the μ -synthesis, as in /17/.





Figure 15: Selected function bounding the considered unstructured uncertainties.

Figure 16 shows a comparison of the step responses of the controlled joint angle. It can be seen, that the system's tracking dynamics clearly benefits from the model-following control design. While showing comparable overshoot, the output's rise time is significantly reduced by the combination of inverse Preisach feedforward compensation in combination with the reference model following control loop. The disturbance rejection controller, which can be designed specifically for this purpose, allows a significant reduction of the influence of high frequency noise and load fluctuations resulting from stick effects in the manipulator joints.



Figure 16: Step response experiment performed with a single manipulator stage controlled by a single loop PID controller (green) and by model-following controller (red).

5. Summary

In this paper the control architecture for a manipulator actuated by pneumatic artificial muscles is presented. After a brief description of the used muscle type and their pressure-forcelength-relations, these characteristic are used to form a feedforward structure for the control of a single pair of antagonistic muscles in the manipulator structure.

Due to the symmetric setup of the muscles in the used manipulator, the feedforward structure, the nonlinear mean relation of the muscles compensate each other in the unloaded case resulting in a symmetric hysteresis of the open loop plant between desired and measured joint angle. It is shown, that this symmetric hysteresis nonlinearity fulfills all necessary conditions to describe it by a Preisach model approach. A Preisach model is identified, its inverse is used for an approximate feedforward compensation of the hysteresis nonlinearity.

The actuation by pneumatic antagonistic muscles limits the accessible angles in each joint. The used manipulator is designed to construct highly dexterous versatile robots with kinematic redundancy. To allow precise path tracking of the kinematically redundant manipulator in spite of the limitations of the realizable joint angles, these limitations have be taken into account already in the trajectory planning and redundancy resolution. It is shown, that a simple joint angle minimization is not sufficient to prevent the violation of the possible joint angles. Therefore, a redundancy resolution scheme is presented that ensures the joint limit avoidance through optimization with a weighting function. The joint trajectories derived from the redundancy resolution are the used as reference values for the individual joint controllers.

The joint controllers are realized as a model-following controller, the direct and inverse Hysteresis model is used to control the model-control loop, its controller output is fed into the disturbance rejection loop as a feedforward term. The controller of the model loop is designed for good tracking performance, while the disturbance rejection controller is optimized for good disturbance rejection in the presence of disturbances and parametric uncertainties. Measurements are presented to demonstrate, that the resulting controller outperforms comparable single loop controllers in experimental investigation.

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7. Nomenclature

φ	Joint angle
L _A , L _B	Muscle lengths
r _u , r _o , I _u , I _o	Elemental segment link lengths
x , q	Cartesian space and joint space coordinates
λ	Lagrange multipliers for the optimization problem
X , X ⁰ ,, X ^p , X ^{p+1}	Vector of zeros of the optimization problem
u	Desired angle input sequence
f	Actual angle output sequence
α, β	local extremal values of the joint angles for hysteresis model
$\hat{\gamma}_{\alpha\beta}$, $\mu(\alpha,\beta)$	Hysteresis operator and weighting function of hysteresis model