Improving the Dynamic Behavior of a Servodriven Electro-hydraulic Robotic Manipulator

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Abstract

The authors detail two servo-control strategies which improve the performance of servodriven electro-hydraulic robotic manipulators. The first servo-controller is pragmatic approach based on both empirical controller design and fuzzy logic and results presented demonstrate that its performance clearly surpasses that of the conventional P-controller. The second servo-controller is a robust state-space controller designed by applying the Ackermann parameter space method. This controller uses both the measured angular position and acceleration as state-variables to directly control the angular position of the revolute joints. In order to determine the angular acceleration, a contact-free acceleration sensor based on the Ferraris principle has been developed and described in detail. Results are presented which clearly demonstrate the improvement of the servo-control quality through use of the acceleration sensor.

1 Introduction

Recently, new applications using hydraulic manipulators have necessitated a more ambitious specification with respect to positioning accuracy, speed and user-friendliness. These new applications include semi-automatic excavation on building sites [1], loading and unloading of ships with semi-automatic crane systems [2], fully automated washing of commercial airplanes with large manipulators [3] and automated masonry construction on the building site utilizing a mobile robot [4].

In order to meet the demands of these applications, the following problems, which represent challenges for future development, must be met:

- insufficient availability of high level control concepts which utilize path control, coordinate transformation and jerk limitation,
- strong, non-linear coupling forces due to the movements of other axes in the kinematic chain make servo-control of axes low down in the kinematic chain difficult,
- limited bandwidth and positioning accuracy of servo-control strategies based on conventional methods and
- lack of suitably economic, reliable and accurate sensors for measurement of angular acceleration.

Using the example of a mobile masonry construction robot, "BRONCO" (Bricklaying Robot for Use on the Construction Site) [4, 5], this paper takes some steps towards addressing the last three challenges in the list above.

Firstly, two different approaches to improving the performance of conventional servo-control methods are presented. The first method employs an algorithm based on fuzzy logic which utilizes empirically determined P-

Controller parameters in a rulebase structure to control the position of the hydraulic cylinder. This fuzzy method utilizes an existing absolute position sensor integrated in the hydraulic cylinder for servo-control thus offering cost-effective, robust servo-control where no extra sensors are required. The second servo control paradigm is based on robust state-space control and utilizes the measured angular position and acceleration of an axis to control its angular position. In contrast to the fuzzy approach, the state-space concept offers greater controller accuracy but at an higher cost due to the necessity of position and acceleration sensors.

In order to generate the acceleration signal required by the state-space controller, several options are possible: reconstruction from the position signal using differentiation and filtering, the use of observers and direct measurement. This paper presents a new type of acceleration sensor which is non-contacting, accurate and robust. This sensor is based on the Ferraris principle and can be used for measurement of acceleration of both revolute and translational axes. Moreover, the use of the measured acceleration signal in the state-space controller allows greater compensation of disturbance forces (Newton's second law of motion) compared to conventional PID controllers.

The first section of this paper discusses some general aspects of fuzzy control as applied to drive technology, describes the design methodology of the fuzzy controller and presents a comparison between a standard P-controller and the fuzzy controller. Following on from this, the second section of the paper discusses the issues involved in the design and implementation of a robust state-space controller and presents a comparison between a P-controller and the state-space method. A detailed description of the acceleration sensor is presented in the third section and a summary of future research activities rounds off the paper.

2 Design and Implementation of a Fuzzy-Servo Controller

Within the field of robotics, where fast sampling frequencies, strict positioning accuracies and under-damped mechanical structures are common, the idea of parameter adaptive controller has not been readily adopted due to stability considerations and computing requirements. As an alternative the gain scheduling paradigm for conventional controllers has been used to adapt the controller response to a given operation point. An alternative algorithm to conventional gain schedulers is the fuzzy controller, which consists mainly of a rulebase with a set of "*if... then...* " rules. Because a fuzzy algorithm actually interpolates between the rules in its rulebase, if the consequents (the „then" part of the rule) of a fuzzy algorithm are conventional controller algorithms, then a gain scheduling controller results. This type of fuzzy algorithm is known as the Takagi-Sugeno algorithm [6]. In contrast to the conventional gain scheduled controller, the fuzzy controller can also utilize linguistic information combined with conventional controller algorithms in its rulebase.

In order to use fuzzy logic in robotic applications some practical aspects have to be considered. Fuzzy algorithms possess a large number of parameters which must be determined by the user or by means of an optimization strategy. The large number of parameters is one of the main disadvantages of fuzzy algorithms and can lead to implementation problems. The memory requirements of fuzzy algorithms are mainly dependent of the number rules in the rulebase and in the case of fuzzy control certainly exceeds that of conventional PID-controllers. The computation time for fuzzy controllers depends largely on the number of input and output variables and on the number of rules that are fired in the rulebase. Simple fuzzy algorithms can be programmed so that their computation times are kept low. Thus only in special cases is dedicated "fuzzy hardware" such as ASIC solutions used. In general fuzzy controllers should be kept simple in order to keep the number of parameters, memory requirements and computation times to a minimum.

The design procedure for the fuzzy controller for the first axis of the masonry robot is described in this section and was based on the usual empirical procedure used for the determination of the proportional constant k_V for a P-Controller - using small signal step responses of the closed loop controlled first axis, the proportional constant k_V is set so that a fast rise time without overshoot is achieved. The conventional P-controller for the first axis of the masonry robot was configured for an operating point corresponding to a cylinder position of 135 mm. The rule consequents of the fuzzy controller (which correspond to P-controllers) were determined for different operating points, whereby the direction of the velocity of the cylinder was also considered. Thus the fuzzy controller used is equivalent to a gain scheduled P-controller (interpolating between a set of P-controllers), whereby the conventional P-controller optimized for an operating point of 135 mm was also included. Figure 2-1 shows the characteristic of the empirically identified fuzzy controller.

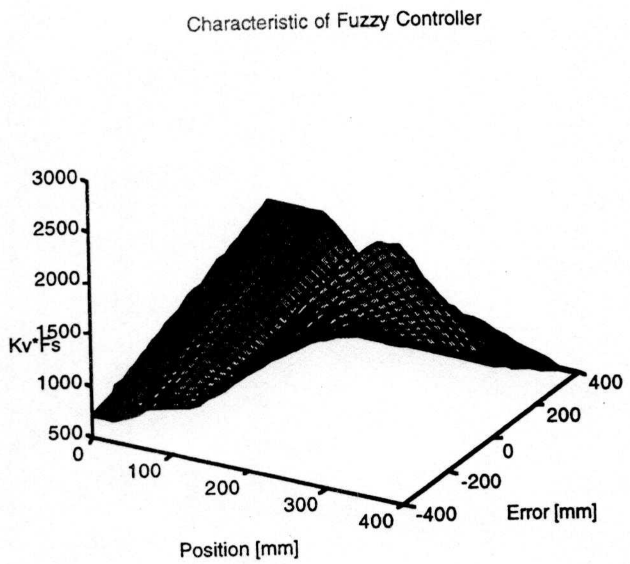

Figure 2-1 : Proportional gain characteristic of the fuzzy controller (sampling frequency Fs = 100 Hz).

Figure 2-2 shows a comparison between the control performance of the fuzzy controller and the conventional P-controller over a path of 10 - 380 mm. Clearly the fuzzy controller offers improved control performance in comparison with the P-controller as is seen by the reduced following error.

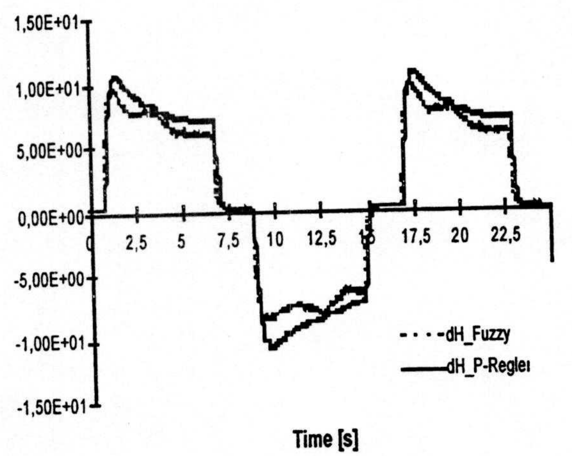

Figure 2-2 : Following error of fuzzy controller and P-controller.

Overall the fuzzy controller described in this section represents a robust and cost-effective servo-controller where no extra sensors are required. The controller offered an improvement of approximately 20% in the following error compared with the standard P-controller. More time is however required in order to determine the fuzzy controller parameters. Table 2-1 presents an overview of the rule consequents that were used in the fuzzy controller.

Operating Point [mm] / Position Error	35	75	135	200	275	370
Negative	700	900	1000	1500	2250	3000
Zero	1100	1200	1000	1200	1500	1750
Positive	1500	1500	1000	900	750	500

Table 2-1 : Table of rule consequent values for the fuzzy controller - each element is Kv * Fs.

3 Robust State-Space Servo Control

The fuzzy control paradigm presented in the last section is a so-called indirect method, where the position of the hydraulic cylinder is measured and used as the controlled variable (the direct method uses the measured angular position φ of the axis as the controlled variable). Other controller designs for this indirect control paradigm have been described in detail in [5]. The main advantage offered by the indirect control strategy is the fact that the absolute measurement system which is integrated into the hydraulic cylinder is exploited, thus offering a robust and cost effective solution suitable for use in the harsh building site environment as well as relatively simple commissioning. This approach does suffer from the following disadvantages:

- in the case of robot control the angular position φ setpoints must be converted to cylinder position setpoints which leads to inaccuracy mainly attributable to the inevitable geometric errors in the robots construction. These errors are cumulative for multi-axis manipulators and thus lead to a considerable reduction in the overall achievable positioning accuracy of the manipulators TCP,
- without integral terms in the controller structure or high pass filtering of the load pressure, steady state errors result due to disturbance forces on the arms mechanical system,
- the current measurement resolution of the typical translational position sensors is 0.01 mm and is not high enough to allow the accurate reconstruction of further state-variables by means of differentiation (due to quantization noise) and
- the overall disturbance rejection of the controller is characterized by slow dynamics due to the fact that disturbances occur outside of the closed loop controller.

In order to address some of these difficulties the direct control of the angular position with a state-space controller using feedback of several state-variables has been investigated. By means of angular acceleration feedback, disturbance forces can be directly detected and compensated for (Newton's second law of motion).

Before considering the design of the state-space controller, the behavior of a P-controller for angular position φ will be examined. Figure 3-1 shows the response of the P-controller for the main axis of the masonry robot with maximum moment of inertia (the arm is fully extended with a stone weighing 50 kg) for a proportional gain of $k_V = 3.5$ 1/s.

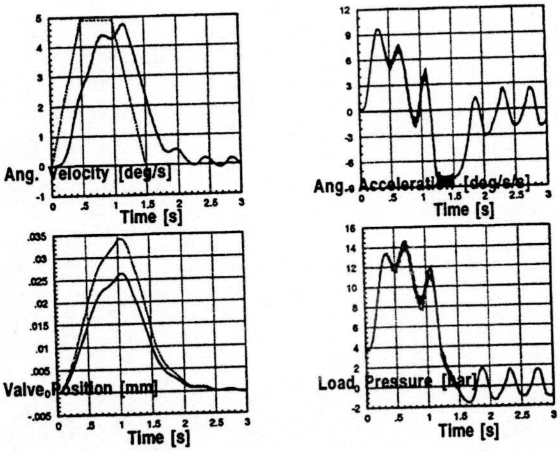

Figure 3-1 : P-controller response for the main robot axis with maximum load ($k_V = 3.5$ 1/s)

It is evident from Figure 3-1 that the closed loop response is very near the stability limit despite the low proportional gain. In order to improve the overall system damping and thus increase the dynamics of the controller, the feedback of further state-variables was found to be necessary.

The effective moment of inertia of the main axis of the masonry robot depends on the position of the other robot axes and varies between 296 and 2700 kgm^2. Because an on-line, axis-position dependent adaptation of the controller parameters is not realistic (due to the large computational overhead) [7], the design of a robust state-space controller based on the parameter space design methods from Ackermann was decided upon. Due to their robust nature such controllers are tolerant of both structural and parameter inaccuracies in the dynamic models used for the controller design. Moreover, the damping ratio of the closed loop controller can be specified to lie within specific boundaries by selecting pole areas within the state-space.

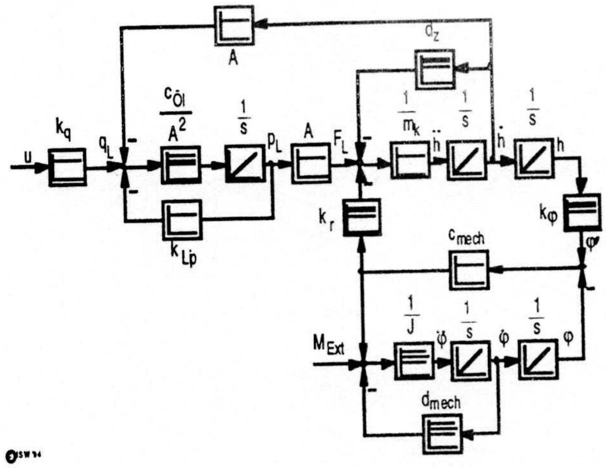

Figure 3-2 : Linear model of the main axis of the masonry robot.

In order to utilize the parameter space design methodology from Ackermann, a linear state-space model is necessary. The linear model illustrated in Figure 3-2 has been derived from a detailed non-linear model by means of non-linear decoupling algorithms. The parameters $c_{\ddot{O}l}$, k_φ and k_r are proportional to the piston stroke of the hydraulic cylinder, the moment of inertia J is directly proportional to the angular positions of all arm axes and the damping ratios d_Z and d_{mech} depend primarily on the cylinder velocity or angular velocity of the axis.

The following state-space vector has been chosen for the model shown in Figure 3-2:

$$\underline{x}^T = \begin{bmatrix} \varphi & \dot{\varphi} & \ddot{\varphi} & \dot{h} & p_L \end{bmatrix}^T \tag{1}$$

The systems continuous time state-space equation is:

$$\begin{bmatrix} \dot{\varphi} \\ \ddot{\varphi} \\ \dddot{\varphi} \\ \ddot{h} \\ \dot{p}_L \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ -\frac{c_{mech}}{J} & -\frac{d_{mech}}{J} & \frac{k_\varphi c_{mech}}{J} & 0 & 0 \\ 0 & -\frac{c_{mech}}{J} & -\frac{d_{mech}}{J} & -\frac{c_{mech} K_p}{J} & 0 \\ \frac{c_{mech} k_r}{m_K} & 0 & -\frac{k_\varphi k_r c_{mech}}{m_K} & -\frac{d_Z}{m_K} & \frac{A}{m_K} \\ 0 & 0 & 0 & -\frac{c_{\ddot{O}l}}{} & -\frac{c_{\ddot{O}l} k_{Lip}}{A^2} \end{bmatrix} \begin{bmatrix} \varphi \\ \dot{\varphi} \\ \ddot{\varphi} \\ \dot{h} \\ p_L \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \frac{k_q c_{\ddot{O}l}}{A^2} \end{bmatrix} \cdot u \tag{2}$$

This state-space equation is to be sampled with a sampling period of Ts = 10 ms and serves as a basis for the design of a digital state-space controller with the following control law:

$$u(k) = -\underline{k}^T \underline{x}(k) \tag{3}$$

with $\underline{x}(k)$ from (1) and

$$\underline{k}^T = [k_1 \quad k_2 \quad k_3 \quad 0 \quad 0]^T \tag{4}$$

Figure 3-3 shows the structure of the resulting state-space controller. At this point in the design it is assumed : all state-variables can be directly measured.

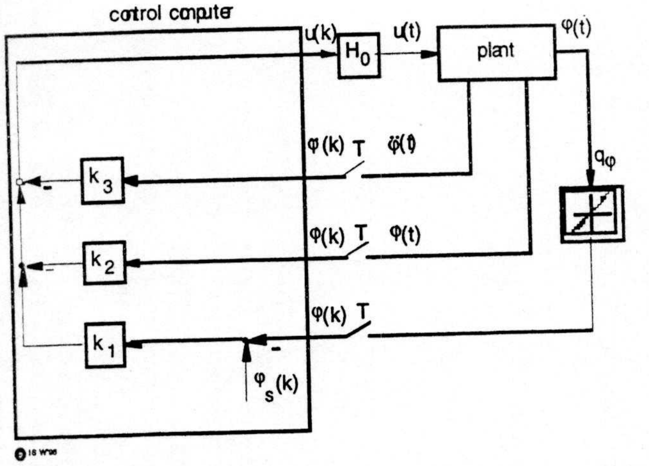

Figure 3-3 : Third order state-space controller with ideally measured state-variables.

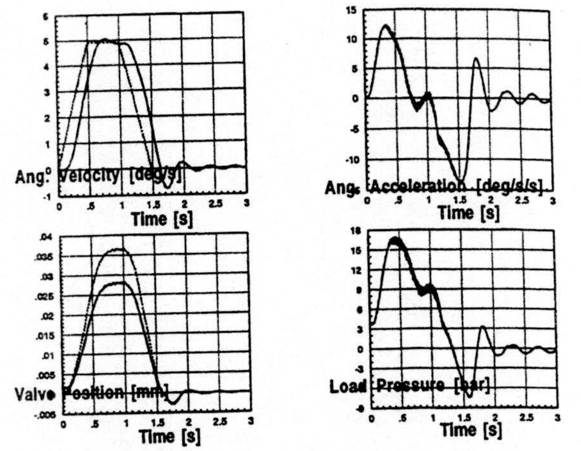

Figure 3-4 : Positioning operation with maximum load using a state-space controller with direct measurement of the angular acceleration ($k_1 = 7$ 1/s, $k_2 = 0$, $k_3 = 0.0565$ s).

For the design of a robust state-space controller using the parameter space methodology, two extreme parameter sets which represent maximum and minimum load were selected. For each parameter set a solution for the controller gain matrix was found where the specified damping ratio of the closed loop system is fulfilled. The intersection of these two areas represents the allowable area for the gain matrix, which fulfills the specified dynamic behavior for system operating points at both load extremes and thus for the complete range of load dependent operating points.

A graphical interpretation of the results of the parameter space methodology is only useful for a one or two dimensional controller. As this controller is three dimensional, no illustration has been included in this paper. Based on extensive simulation, the gain coefficient for the angular velocity of the axis was found to have little effect on the overall controller performance and thus:

$$k_2 = 0 \tag{5}$$

Due to the extreme parameter variation, it was not possible to obtain a robust controller for all load operating points that met the required relative minimum damping ratio of $D_{min} = 0.7$. In order to achieve a robust controller for all load dependent operating points and to avoid the necessity of adaptation, the minimum achievable relative damping ratio was set to $D_{min} = 0.28$. To rule out extremely slow decay, the absolute minimum damping ratio was set $d_{min} = 2$ 1/s.

Figure 3-4 shows the results of the robust state-space controller using an acceleration signal from the sensor described in the next section.

From Figure 3-4 it is clear that the maximum value for the gain coefficient k_1 is now 7 1/s, which is twice that of the proportional gain coefficient k_V of the P-controller discussed earlier, thus clearly offering faster response times. In order to achieve this value, the feedback of the angular acceleration through the gain coefficient k_3 is necessary. The following sections details a sensor suitable for the direct measurement of the angular acceleration of an axis.

4 Contact-free Measurement of Angular Acceleration

In order to use the state-space controller presented in the last section, some method for the determination of the angular acceleration is necessary. Three approaches have been considered for use with BRONCO:

- *Differentiation and filtering of the angular position sensor* - the main disadvantage of this approach is the quantization noise that results from the differentiation which is proportional to both the sampling time and the quantization of incremental optical encoder used for the measurement of the angular position. Moreover, non-linearities in the position sensor cause harmonic distortion of the position signal.
- *The use of observers based on state-space control theory* - these algorithms are used to predict the acceleration based on both measured signals and linear time invariant (LTI) models of the process. Due to the type of models used, these algorithms do not provide enough accuracy.
- *Direct measurement of angular acceleration* - only possible if the extra cost of the sensor is acceptable.

This section discusses the direct measurement of the angular acceleration and presents a new type of acceleration sensor. Further discussion of the first two options can be found in [8].

As an alternative to classical concepts for acceleration measurement where two translational acceleration sensors are mounted perpendicularly, a sensor based on the Ferraris principle can offer excellent resolution and noise rejection [9]. This sensor consists of an Arago's disc attached to the robot arm which moves with respect to a fixed coil and magnet system. This simple configuration, shown in Figure 4-1, facilitates the contact-free measurement of the relative angular acceleration between the Arago's disc and the fixed magnet and coil system. The Arago's disc is attached directly to the robot arm without coupling or extra bearings. If the rotation of the axis is limited then the Arago's disc can be constructed as a segment. This principle is also applicable to translational systems, where an eddy current plate would replace the Arago's disc [10].

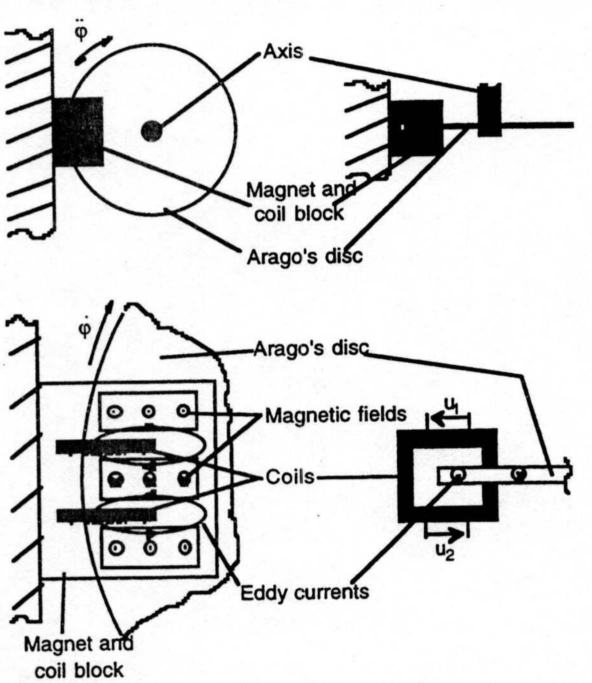

Figure 4-1 : Design of the angular acceleration sensor based on the Ferraris principle.

The sensors principle of operation can also be derived from Figure 4-1. By means of rotation of the Arago's disc, which is constructed from conductive non-magnetic material e.g. aluminum, eddy currents are generated within those parts of the disc that are within the magnetic field of the fixed magnet system. These eddy currents cause a secondary magnetic field whose strength is proportional to the angular velocity of the Arago's disc. Any *changes* in this secondary magnetic field generates an e.m.f. in the coils (which have highly permeable cores e.g. ferrite). The e.m.f. in the coils is directly proportional to the angular acceleration of the robot arm.

An integrated instrumentation amplifier is used to amplify and add the two induced voltages. This voltage is then read by an A/D converter and can be used as the acceleration state-variable. To ensure maximum sensitivity for small angular accelerations, the following design characteristics must be adhered to:

- A strong magnetic field for excitation is achieved by the use of NeFeB permanent magnets.
- A high number of turns was used for the sensor coils.
- High gain, low noise instrumentation amplifiers are used for the voltage amplification in the Ferraris sensor.
- The largest possible diameter is used for the Arago's disc.
- Noise rejection is maximized by means of stringent electrical and magnetic screening.

The current sensitivity of the prototype sensor is approximately 20 mV/deg s^{-2} and the bandwidth of the sensor is greater than 5 kHz.

5 Conclusions and Further Research

Using the main axis of the masonry robot BRONCO two contrasting control strategies have been described. A fuzzy controller using only the built-in position sensor of the hydraulic cylinder was shown to offer better performance than a conventional P-controller. By adding two extra sensors, the design of robust state-space controllers using the parameter space methodology from Ackermann was described. These controllers allow the direct control of angular position with great accuracy. Using this design strategy robust controllers can be designed which fulfill dynamic criteria for all load dependent operating points. Investigations have shown that the dynamic response of the position controller is increased by a factor of two through feedback of the state-variable angular acceleration.

A comparison of strategies for the determination of the angular acceleration of the robots arms was carried out. Direct measurement of the angular acceleration is clearly the superior method and results in greatly improved disturbance rejection whilst offering improved controller performance.

The concept of a contact-free acceleration sensor based on the Ferraris principle was described. This sensor is capable of accurate, contact-free measurement of both angular and translational acceleration and is characterized by its simple, cost effective and robust construction.

The investigation of strategies for servo-control of electro-hydraulic drives and the development of suitable sensor systems play key roles in the future research activities at the Institute for Control Technology (ISW). The following points detail future activities:

- feedforward compensation strategies in order to reduce the following errors of the individual robot axes,
- compensation of non-linearities by means of empirical data-based, non-linear mapping functions such as artificial neural networks and fuzzy logic methods,
- investigation into adaptive control techniques for the load-dependent, on-line adjustment of the controller parameters [11],
- investigation into linear and non-linear observer strategies for the determination of the angular acceleration and
- research into decoupling methods for compensation of known disturbance forces from axes further along the kinematic chain.

Further investigation and implementation on the BRONCO robot of the acceleration sensor together with the new non-linear interpolation unit for the incremental optical encoder round off the planned future activities in this area.

6 References

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