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A NEW APPROACH TO SENSORLESS AND VOLTAGE CONTROLLED AMBs BASED ON NETWORK THEORY CONCEPTS

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Abstract

Active magnetic bearings (AMBs) as actuators operate not only in the direction from the amplifier to the bearing magnet and then to the rotor, but also in the **opposite direction,** from the rotor back to the amplifier. In this paper, such effects are not dismissed as deviation from the ideal, but are used to **improve** the design of the sensing system. The AMB is interpreted as a **two-port** converting electrical (current & voltage) into mechanical values (force & velocity) and vice versa. This is the basis for assessing some unconventional control schemes including **voltage control** and the **"sensorless" bearing**. By this term, we would like to designate a rotor-bearing model with bearing voltage as input and bearing current as output, using no specific sensing hardware. It can be shown that such a system is observable and controllable. The paper presents a short discussion of the fundamental AMB equations in the new context. An **example** of a sensorless bearing realized at our laboratory illustrates the **practical feasibility** of this new approach to AMB modelling and control.

1. Introduction

The "classical" modelling of control plants is often based on idealized unidirectional signal-flow representations. Looking at the energy transmissions inside a system, however, it can be seen that some elements such as actuators and amplifiers are actually of a **bidirectional** nature.

Methods based on measuring the airgap dependent inductance e.g. by means of some high frequency modulation or pulsing are known and have been patented since many years (/Sit 67/, /Schef 75/ and others), but they do not seem to have evolved beyond experimental setups.

In this paper we would like to take the entirely different approach of using the **controllability and observability** of the AMB-plant with **voltage input and current output**. First feasibility tests have been made in 1987 /Vi 88/ and a current project at our Institute aims at improving the practical performance.

We concentrate here on AMBs with a pair of two opposite electromagnets as shown in fig. 1 since this is the most common setup for rotor bearings. The main results of this paper are nevertheless also applicable to the one-sided case of magnetically levitated vehicles or special rotor designs using gravity or combinations with passive magnetic bearings.

Flux-sensing also fits nicely into the framework of this work. Flux control shares many advantages with voltage control. Practical results have been obtained at our Institute. They are described in the contribution "Cost-Effective Implementation of AMB" by Zlatnik and Traxler /Zl 90/, at this same symposium. Here we therefore concentrate on voltage-controlled and sensorless bearings and we will not discuss flux sensing.

2. The Basic AMB-Equations

The basic AMB equations are obtained from Maxwell's laws. This derivation is not shown here. Secondary effects such as stray fields and saturation are neglected. Furthermore, it is assumed, that the complete energy of the magnetic field is concentrated in the active airgap, the flux in the iron core is neglected. Fig. 1 shows the actuator considered:

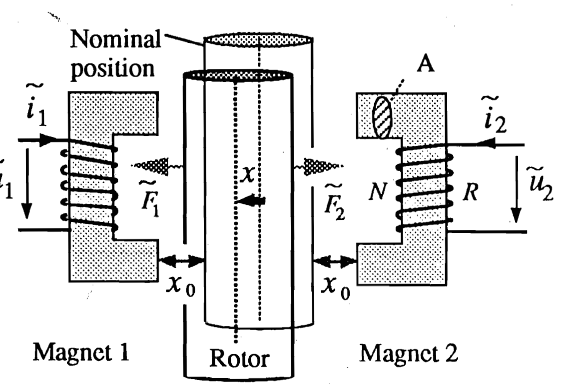

Fig.1 Notations for a two-sided actuator with one mechanical degree of freedom, the rotor displacement x . A displacement to the left is defined positive, for x=0 the air gaps are x_o. More symbols are listed in table 1 on the next page.

The equations relevant for control layout are obtained from a linearization for the operating point, by defining constant operating-point (or nominal) values (subscript zero) and variable components (subscript one or two, indicating the left or right magnet of fig.1).

Operating point

x_0 : Nominal airgap
i_0 : Nominal (or premagnetisation) current

Variables

$\tilde{i}_1 = i_0 + i_1$ $\tilde{i}_2 = i_0 + i_2$ Currents in coil 1 and 2
(Corresponding relations for forces & voltages)

Basic bearing constants:

N : Number of Windings
A : Iron Cross Section
R : Copper Resistance

Secondary bearing constants:

$L = NA\,\mu_0/2x_0$: inductance at x = const.= 0
$k_i = L\,i_0/x_0$: Force-current factor
$k_s = k_i\,i_0/x_0$: Force-displacement factor

Table 1: Notations ($\mu_0 = 1.257 \cdot 10^{-6}$ Vs/Am)

With the assumptions stated before, the linearized relation of force F_1 and voltage u_1 can be found as

$$\frac{dF_1}{dt} = \frac{i_0}{x_0}(u_1 - Ri_1) \qquad (1)$$

A second basic equation relates current change to voltage in the coil and displacement velocity:

$$\frac{di_1}{dt} = \frac{1}{L}u_1 - \frac{R}{L}i_1 - \frac{i_0}{x_0}\dot{x} \qquad (2)$$

The more familiar relation (3) can be obtained by substituting the integral of (1) into the integral of (2)

$$F_1 = k_i\, i_1 + k_s\, x \qquad (3)$$

These equations are valid only for the linearized components of force, voltage and current as defined in table 1.

Equation (2) describing the coil voltage is of minor importance when the classical current control scheme is used. In the present paper however, it provides the basis for voltage controlled AMBs and the sensorless bearing through the voltage induced by rotor motion in the magnetic field. The constant k_i not only relates the force to the current but also appears with the contribution of the rotor velocity $\dot{x}$ to the voltage u_1. Its dimension is [N/A] = [Vs/m].

3. The AMB as a Two-Port

The AMB can be interpreted as a ***two-port*** converting electrical variables (current i_1 & voltage u_1) into mechanical ones (force F_1 & velocity $\dot{x}$) **and vice versa**. Equations (1) and (2) can be summarized in a transfer matrix. At the same time, we transform to the Laplace domain where differentiation is replaced by the Laplace variable s. For simplicity, variable names are kept the same as in the time domain.

$$\begin{bmatrix} F_1 \\ \dot{x} \end{bmatrix} = \begin{bmatrix} \frac{i_o}{x_o}\frac{1}{s} & -\frac{i_o}{x_o}\frac{R}{s} \\ \frac{1}{k_i} & -\frac{x_o}{i_o}s - \frac{R}{k_i} \end{bmatrix} \begin{bmatrix} u_1 \\ i_1 \end{bmatrix} . \qquad (4)$$

Fig. 2 gives an *equivalent circuit* for the AMB two-port. It consists of a resistance R, an inductance L and an idealized "basic AMB two port".

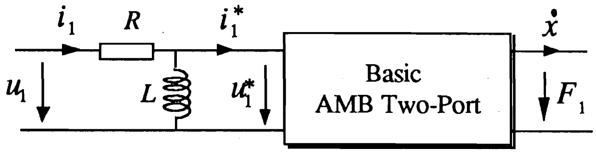

Fig. 2 The AMB as two-port: Equivalent circuit. The mechanical variables can be interpreted as electrical ones according to the classical analogy force-voltage and current-velocity.

If the mechanical variables force and velocity are interpreted as electrical ones according to the classical (i.e. force-voltage and velocity-current analogy), this AMB-two-port becomes equivalent to an ideal transformer with an s-dependent constant. Its transfer matrix is

$$\begin{bmatrix} F_1 \\ \dot{x} \end{bmatrix} = \begin{bmatrix} \frac{i_o}{x_o}\frac{1}{s} & 0 \\ 0 & -\frac{x_o}{i_o}s \end{bmatrix} \begin{bmatrix} u_1^* \\ i_1^* \end{bmatrix} \qquad (5)$$

The sign follows from the definition of the positive directions at the output of the two-port. The basic AMB is *lossless*, it has the property of converting the entire electrical power into mechanical power *and vice versa*:

$$i_1^* \cdot u_1^* = -F_1 \cdot \dot{x} \qquad (6)$$

As opposed to other two-ports such as dc-motors and transformers, the basic AMB transfer matrix is a function of the Laplace variable s.

Two-ports are often operated as actuator and sensor. A dc-motor, for instance, is basically controlled by means of the current and can then be interpreted as a "torque-source". Sometimes it is used as a "velocity-source" employing voltage control. According to the two-port concept, the dc-motor may also serve as velocity or torque-sensor, as actually realized in some applications

The AMB also can be operated as actuator, sensor or both, actuator and sensor, at the same time. It can not only serve as velocity sensor like the dc-motor, but it has the additional possibility of operating as a position sensor. From equation (5) it can be seen, that the rotor deflection x_1 is proportional to the current i_1^* of the basic AMB 2-port.

$$x = -\frac{x_0}{i_0}\, i_1^* \qquad (7)$$

Therefore current i_1 must contain somehow the information on the displacement x. Current is easily measured and this is actually implemented for almost any practical AMB system, be it only to protect the amplifier from overcurrent. From this fact, the idea of the feasibility of a "sensorless" bearing was derived.

4. State-Space Model

The complete state-space model for the actuator-bearing-rotor system includes at least two mechanical states (velocity and displacement). In addition, each electro magnet contributes one state variable to the model. In the case of two-sided actuators (fig. 1), two state variables, e.g. the currents in the coils, are necessary for each mechanical degree of freedom to completely describe the behavior of the open loop system.

Fig. 3 shows the state-space model for such a system, including Newton's law

$$m\,\ddot{x} = F_1 - F_2 = \tilde{F}_1 - \tilde{F}_2 \qquad (8)$$

where m is the equivalent rotor mass effective at the actuator.

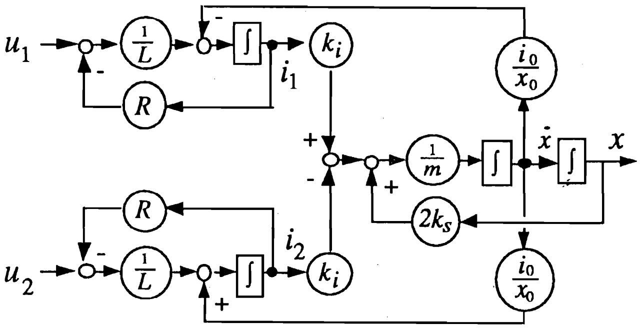

Fig. 3 ***Linearized state-space model for one mechanical degree of freedom and two coils*** *according to fig. 1. The two currents (i_1, i_2,) in each coil of the bearing, rotor velocity $\dot{x}$ and deflection x are used as state variables. This model's observability from the current measurements alone is the basis for a practical sensorless bearing system. Currents are measured in the amplifiers and can be used as controller inputs, voltages as plant inputs.*

The MIMO-system (**M**ultiple **I**nput **M**ultiple **O**utput) shown in fig.3 is observable from the current measurements (i_1, i_2) alone. Using the voltage inputs (u_1, u_2), it is also controllable. This means that **measuring the rotor displacement x is not needed** for control.

This has been demonstrated in practical setups by Vischer and in a student project of our Institute /JV 90/. A patent /VTB 88/ has been applied. Some possibilities for control layout making use of the results above are now elaborated.

5. Transformations of the State-Space Model and Transfer Functions

The state space model shown in fig. 3 is used to design a bearing control with voltage instead of current as input variable. This will be called "voltage control". Voltage control has been investigated thoroughly by many authors /Ul 84/, often in the context of maglev vehicles (e.g. /Jay 81/, /Br 80/)

The system of fig. 3 is observable if at least two of the three outputs (i_1, i_2, x) are available to the controller. The following two cases, both of which have some advantages for AMB applications, will be examined further:

- voltage control combined with three measurements (i_1, i_2 and x)
- voltage control combined with the current measurements only (sensorless bearing)

One way to control the above systems is to implement a Luenberger observer and a state feedback controller. The full state-feedback matrix has 8 coefficients (2 inputs, 4 states). Some additional control parameters are used for the Luenberger observer. Such controllers were built and tested at our institute. A voltage controlled AMB with and without sensor was realized as described above (see also section 8 on experiments).

As we deal only with a single mechanical degree of freedom, we seek to simplify this controller. It is possible to describe the plant (fig. 3) as a set of two SISO-systems (Single Input Single Output), as shown in fig. 4. If the four values (i_1+i_2), x, $\dot{x}$ and $\ddot{x}$ (or force, see e.g. /GC 77/ or /GMM 77/) are used as state variables instead of i_1, i_2, x and $\dot{x}$, the MIMO-system can be replaced by a 3rd order and a first order SISO-system.

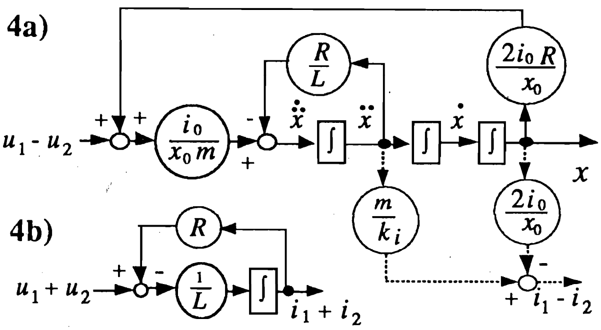

Fig. 4 Transformed state-space model for the system of fig. 3. This choice of state variables produces two decoupled subsystems, fig. 4a (with states x, $\dot{x}$ and $\ddot{x}$) and fig. 4b with the single state variable (i_1+i_2,)

Fig. 4a shows that the rotor movement only depends on the difference between the two input voltages u_1 and u_2, whereas the sum of the currents i_1+i_2 is only a function of the sum u_1+u_2.

The transfer function of the first subsystem (fig. 4a) is

$$x = \frac{\frac{i_0}{m\,x_0}}{s^3 + \frac{R}{L}s^2 - \frac{2\,R\,i_0^2}{m\,x_0^2}}\,(u_1 - u_2) \tag{9}$$

This subsystem is a triple integrator for R=0 (R is the copper resistance). The parameter R destabilizes this open-loop system.

The transfer function of the 2nd subsystem (fig. 4b) is

$$(i_1 + i_2) = \frac{1/L}{s + R/L}\,(u_1 + u_2) \tag{10}$$

which is a stable first order system independent of the rotor movement.

In fig. 4, the current difference (i_1-i_2) it is shown to be a difference of state variables. Acceleration as state variable can be replaced by (i_1-i_2). The transfer function (11) from input (u_1+u_2) to output (i_1-i_2) nicely shows the operation principle of the sensorless bearing.

$$(i_1 - i_2) = \frac{\frac{1}{L}s^2 - \frac{2\,i_0^2}{m\,x_0^2}}{s^3 + \frac{R}{L}s^2 - \frac{2\,R\,i_0^2}{m\,x_0^2}}\,(u_1 - u_2) \tag{11}$$

Fig. 5 shows the corresponding simple state-space model.

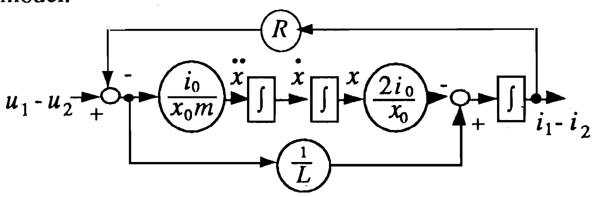

Fig. 5 ***Transformed state-space model of the SISO-plant of fig.4b for sensorless operation.*** *(State variables: (i_1-i_2), x and $\dot{x}$) This system together with the subsystem of fig.4b leads to a simple linear controller.*

The transfer functions (9) & (11) are of full order, therefore it can be deduced that the voltage controlled AMB-plant is observable and controllable from the measurements (i_1+i_2) and x ***or*** (i_1-i_2).

Since the subsystem (fig. 4b) is stable, it is sufficient to control the SISO-system (fig. 4a) characterized by equation (11). Again, this has been experimentally verified. However, a simple controller (proportional feedback, see section 7.1) for the subsystem (fig 4b) enhances the performance of the entire system.

6. Multiple Mechanical Degrees of Freedom

The extension to a full order system with multiple mechanical degrees of freedom is straightforward. As before, each pair of opposing electro magnets is separated into two subsystems. The subsystems (fig 4b) are independent of the mechanical system.

The influence from one mechanical degree of freedom to another acts just like an **additional force input** at the corresponding summation points in figures 3 4 or 5. Decentralization, i.e. the implementation of local feedback based on a complete model, is feasible in most practical cases /Bl 84/, with the obvious implications on the model order used for analysis. With such a layout approach, the online computing power requirements grow only proportional to the number of control channels.

In many cases, it is even possible to simplify one step further and to base control layout itself on a decentralized model, which brings us back to the simple models described in sections 4 and 5.

7. Control

Given a state-space model of the sensorless AMB as shown in fig 1 and knowing that the system is observable and controllable, an appropriate control can be found in a straightforward manner. There is a large number of publications on AMB control. A representative choice can be found in this symposium and in /Sch 88/. Results often can be combined with concepts presented here. Some specific control features relevant in the context of this paper are now shortly treated.

7.1 Operational Point Controller

It is again assumed that two opposite magnets with separate coils, as shown in fig.1 are used for each degree of freedom. The current and voltage sums and differences used as state variables in fig. 4 are

$$\tilde{i}_1 + \tilde{i}_2 = 2\,i_0 + i_1 + i_2 \quad\text{and}\quad \tilde{i}_1 - \tilde{i}_2 = i_1 - i_2$$

$$\tilde{u}_1 + \tilde{u}_2 = 2\,u_0 + u_1 + u_2 \quad\text{and}\quad \tilde{u}_1 - \tilde{u}_2 = u_1 - u_2 \tag{12}$$

Using (12), a control law for the subsystem of fig. 4b can be found as

$$\frac{\tilde{u}_1 + \tilde{u}_2}{2} = P\left(i_{0_{des}} - \frac{\tilde{i}_1 + \tilde{i}_2}{2}\right) \tag{13}$$

where i_{odes} is the desired premagnetisation or nominal current and P a proportional feedback. Since this servo has the property of controlling the premagnetisation current to a desired value, we refer to it as "operational point controller ".

It has been stated before that the two SISO-systems fig.4a & fig.4b are independent of each other, which allows for a separate control design for each of those subsystems. The analysis was based on the *linearized* AMB model. However, only a *high* proportional feedback of the working point controller can guarantee the linearization to be accurate since equation (3) is only valid close to the working point.

Fig.6 shows how to connect the amplifiers to the controller taking advantage of the state-space representation of section 5 (fig. 4).

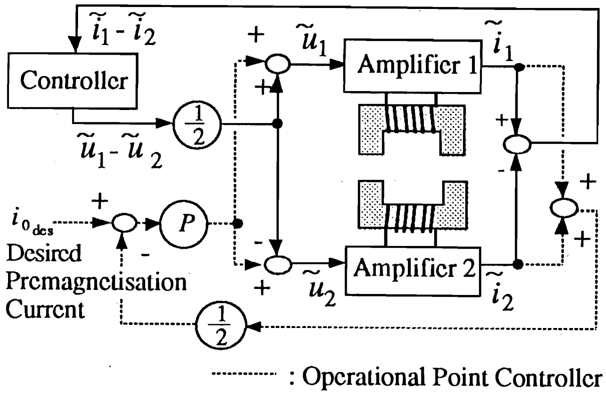

Fig.6 Working point controller connections for the voltage controlled bearing

The purpose of the working point controller can be summarized as follows:

- It improves the accuracy of linearization.
- It simplifies control by reducing plant order and the number of inputs. Single degree of freedom mechanical models become SISO.

7.2 Voltage-Controlled Bearings

A variety of measurement combinations is possible.

From a measurement of displacement x and (i_1-i_2), the acceleration (or force) can be obtained with a simple summation. A similar result can be obtained with flux measurement (/Vi 88/, /VTB 88/, /ZT 90/).

Measuring just x, a PD^2 is the most simple control necessary for the third order system.

The sensorless bearing is of course the most spectacular output variable combination. The simplest possible linear controller for the sensorless bearing is

$$i_1 - i_2 = \frac{b_2 s^2 + b_1 s + b_0}{a_1 s + a_0} u_1 - u_2 \tag{14}$$

In practice, we did not try this simple controller, but we used a state feedback with observer as described in sections 5 and 8.

7.3 The Voltage-Controlled AMB Compared to the Classical Current-Control

Strictly speaking the term "current-controlled bearing" designates a special voltage-controlled bearing consisting of two current controllers as inner loops and a position control as outer loop. As magnet current in reality is a state variable (eq. (2)), the dynamics of the inner control loop is usually neglected for treatment of the outer loop with current as plant-input. The transfer function of the plant of this outer loop, a simple current controlled AMB, is

$$x = \frac{k_i}{m} \frac{1}{s^2 - p^2} i_1 - i_2 \tag{15}$$

where $p = \sqrt{\frac{m}{2k_s}}$

The current controlled AMB has the *advantage* of being independent from copper resistance. Furthermore its transfer function is of 2nd order whereas the voltage controlled bearing is a 3rd order system .

The open-loop plant with current input has however the *disadvantage* of being "strongly unstable" (pole at $+p$). The plant with voltage input is also unstable, but to a lesser degree. The root-locus plot (fig. 7) shows the poles of the open-loop 3rd order plant (fig. 4a or eq.(9) and (11)) as a function of the copper resistance R.

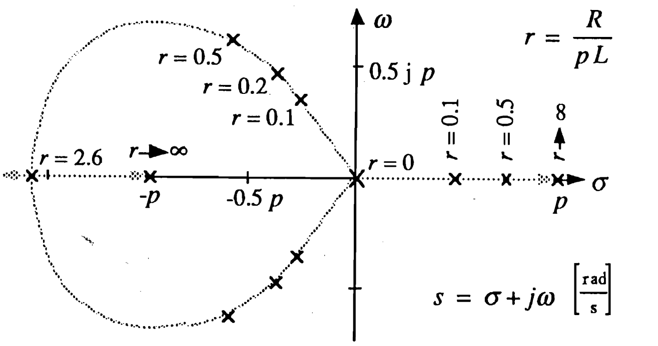

Fig. 7 Poles of the 3rd-order plant as function of copper resistance R. *The normalized copper resistance r is typically in the range of 0.5% to 5%. This leads to 3 open-loop poles closer to the origin than for the 2nd-order plant of eq. (15).*

It can thus be expected that a voltage-controlled AMB is at least theoretically easier to stabilize and less sensitive to noise and time lag than a current controlled one. A quantitative analysis of this statement and a more detailed comparison of voltage and current controlled bearings is given in /Vi 88/.

8. Experiments

In practice, the sensorless bearing is difficult to realize and sensitive to parameter uncertainties. We did not yet achieve a high stiffness. One way to operate it, is to build a Luenberger observer (with i_1 and i_2 as inputs) for the system of 4th order according to fig. 3 and to check it against a position measurement. A state feedback can then be implemented and sensorless operation is achieved by switching position feedback from the measured signal to the estimated one.

For an experimental rotor with linear (not switched) power amplifiers, this was implemented in /JV 90/ on a signal processor with a sampling time of 120 µsecs. With a robust but not very stiff state feedback, it could then successfully be switched from the measured displacement to the estimated one. Measured step responses in both operation modes are shown below:

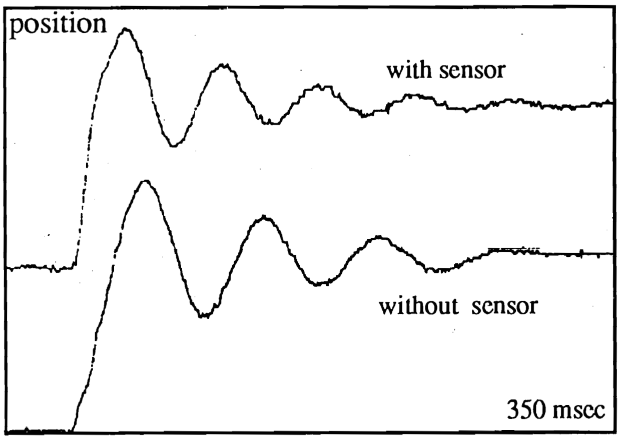

Fig. 8: Measured step responses (peak amplitude about 0.2 mm) of an AMB system with state feedback and position measurement on the top curve, with sensorless operation from a Luenberger observer and current measurements only on the bottom curve. The state feedback is the same in both cases. However, the observer is very sensitive to the copper resistance of the coil.

9. Conclusions

The AMB actuator is regarded as a two port in the framework of network theory. This leads us to reconsider the choices for state, input and output variables of the AMB system. Results including voltage control, flux control (in /ZT 90/) and a sensorless bearing are presented.

Voltage control might be promising for many applications, as advantages are clearly indicated by theory. The sensorless control scheme using the observability of the AMB-actuator with voltage input and current output has been implemented experimentally. Although this particular type of bearing does not yet have very good performance, it could eventually be improved and used in some low-cost applications.

The general trend is towards an increase in control software sophistication (higher order, observer) with the advantage of making better use of the hardware.

Further research is needed in all domains in the scope of this contribution.

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