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A Robot-Arm with Compensation for Bending

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Bearing elements in mechanical systems like robot- and manipulatorarms have the property of a limited stiffness, statically as well as dynamically. The stiffness of these elements may be increased by the application of heavier constructions, but this leads to bigger masses, which is in general not desirable.
In the present research the phenomenon of (position-)feedback is applied to increase and control the stiffness of a robot-arm. The deviation of the desired manipulator position can be measured and this deviation signal is fed back to the control/drive unit, which performs a correction towards the desired position.
A description is given of the construction and behaviour of a horizontal - at one end fixed - robot-arm. Due to the finite stiffness, the arm will bend if a force is applied at the free end. A reduction of this bending (increase in stiffness) may be achieved by measuring this deflection and using this control signal to activate the actuators to return the free end to its original position. The actuators lift the robot-arm as an angler his stick.
The robot-arm is an aluminium square beam with a length of 1 m and is mounted by four actuators to the fixed world. The behaviour of the actuators is based on the effect of piëzo-electricity, while the measuring system is formed by a semiconductorlaser and a resistive gate sensor.
For quasi static changes the behaviour of the actuator is very good; it takes 0.2 sec. by the resistive gate sensor to detect the position of the free end of the robot-arm. This means that a correction for a position-stepchange is performed in 0.3 sec.

1. INTRODUCTION.

The bearing elements in mechanical systems like robot- and manipulator-arms, have the property of finite stiffness, statically as well as dynamically. Necessary joints in such systems make the construction even worse and may add backlash and hysteresis to the system.

The application of heavier constructions is one of the methods to increase the stiffness but this leads to bigger masses and bigger moving masses are in general not desirable. Also materials with a higher stiffness may be used. Another method is the application of the phenomenon of feedback to increase and control the stiffness of a robotarm. If the manipulator has more degrees of freedom, the deviation from the desired position can be corrected by the control unit. The deviation of the desired manipulator position is measured by an independent sensor. This deviation signal is fed back to the control/drive unit which performs a correction action towards the desired position.

Also man applies this principle in using his relative supple arm and wrist in maintaining a certain position with his hand independent of a carrying load. One type of insufficient stiffness is the bending of a manipulator arm by applying a force at the free end (Fig. 1).

A possible reduction of this bending (increase in stiffness) may be achieved by measuring the deflection and using this deviation as a control signal to activate the actuators to return the free end to its original position. In this paper a description is given of the design, the construction and the behaviour of a horizontal- at one end fixed - robotarm, as shown in Fig. 1.

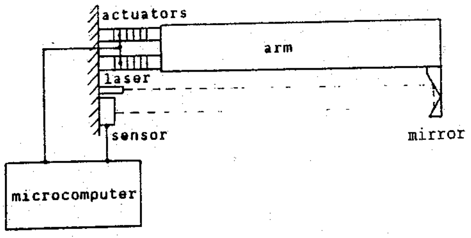

Fig. 1. Schematic diagram of the robotarm.

The different components of the robotarm are the aluminium arm, the actuators, the measuring system and the control unit with a microcomputer.

- The basic form of the robotarm is an aluminium square beam with a side of 100 mm, a wallthickness of 3 mm and a length of 1 m.
- The actuators are based on the principle of piëzoelectricity. Applying an electrical tension on a thin layer of piëzoelectric material results in a change of thickness of this layer. The actuator is created by putting 60 flat rings of this material on a stack formed by a bar. This bar is mounted under prestress. Four of these bars are put in a square and this actuator set forms the connection of the robotarm to the fixed world.
- The measuring system consists of a source and a sensor. The source is a semiconductorlaser. The laserbeam is reflected at the end of the arm by a special mirror - a retroreflector - and detected in a resistive gate sensor of 200 x 300 pixels. In this way the position of the free end can be determined.
- The control unit creates a control signal from the difference of the actual and the desired position and via a digital P.I.D.-controller in the microcomputer and a high voltage unit, the actuators are activated. In Sec. 2 a more extended description of these components is made.

An analysis of the dynamic model of the robotarm is presented in Sec. 3. In Sec. 4 the elements of the controller and the controlling process with (simulation) results are given. Loads for robot- or manipulatorarms have to be small because of the resulting deformation. By building an actuator in such an arm, the load may be bigger before inconvenient deformation occurs either the construction can stay light. The application of piëzo-electrical crystals in actuators is very well possible. They have a very small time constant but there are also some negative points such as the small strain and the application of high voltages.

2. DESCRIPTION OF THE SYSTEM.

2.1. The robotarm.

The basicform of the robotarm is an aluminium square beam with a side of 100 mm, a wallthickness of 3 mm and a length of 1000 mm. The weight of the arm is 35 N. Fig. 2. shows the construction and the dynamic model.

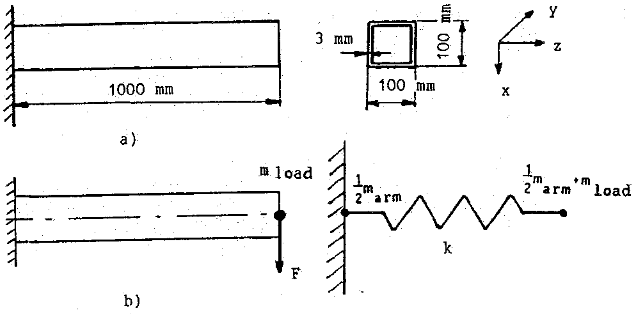

Fig. 2. The robotarm: construction (a) and dynamic model (b).

Typical data of this arm are:

m_{arm} = 3.5 kg : mass of the arm
k = 3.6 10^5 N/m : spring constant of the arm
$I_{xx} = I_{yy} = 174$ cm^4 : surface moment of inertia
$I_{xy} = I_{yx} = 0$ cm^4 : surface moment of inertia
a_{max} = 5 m/s^2 : maximum acceleration at the free end
m_{load} = 5kg : load at the free end (dynamic case)

It is assumed that the mass of the arm is equally distributed over the whole length. Starting from these data two situations are considered.

The static case in which a load force of 50 N is applied at the free end in a direction perpendicular to the axis of the arm. The dynamic case in which a mass of 5 kg - having a maximum acceleration of 5 m/s^2 - is applied at the free end of the arm. Assuming that the acceleration is linear over the length of the arm and also that a superposition can be made of the displacements, the following results are obtained. [Table 1.]

Concerning the vibrations of the arm an estimation for the lowest eigenfrequency can be made according to the model in Fig. 2 with:

$$\omega = \sqrt{\frac{k}{m}} \tag{1}$$

$$k = \frac{3EI}{l} \tag{2}$$

		x	y
Displacement at the free end [mm]	- statically - dynamically - totally	0.17 0.08 0.25	0.14 0.08 0.25
Torsion at the free end [10^{-3}radian]	- statically - dynamically - totally	0.25 0.12 0.37	0.20 0.12 0.32

Table 1. Displacement and torsion at the free end.

The springconstant of the arm is: $k = 3.6\ 10^5$ N/m and depending upon the presence of the extra mass of 5 kg the lowest eigenfrequency changes from 37 Hz to 73 Hz.

2.2. The actuator.

Several physical phenomena have been investigated for the choice of the actuators. In the described construction is chosen for actuators based on the effect of piëzo-electricity. In a piëzo-electrical crystal there is an interaction between the electrical and mechanical state of the crystal.

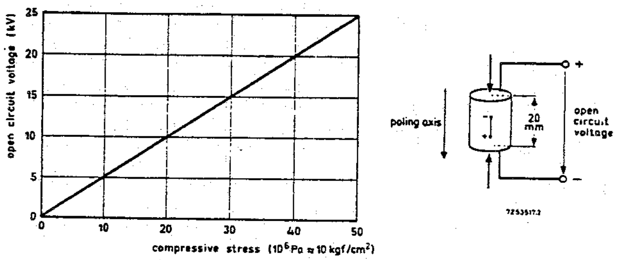

Fig. 3. Relation between mechanical stress and electrical tension in a piëzo-electrical crystal.

An electrical tension applied on a thin layer of piëzo-electrical material results in a change of thickness of this layer and on the other hand a change in the length by compressive stress in an electrical voltage between both ends. The relation between the electrical and mechanical quantities may be described by the following formula:

$$\begin{pmatrix} \varepsilon \\ D \end{pmatrix} = \begin{pmatrix} s^E & d \\ d & \varepsilon^T \end{pmatrix} \begin{pmatrix} \sigma \\ E \end{pmatrix} \qquad (4)$$

with E = strenght of the electrical field [V/m]
σ = mechanical stress [N/m^2]
ε = strain [-]
D = dielectrical displacement [$\frac{N}{Vm}$]
s^E, d, ε^T: material constants

In the next example the achievable strain ε is calculated for the material PXE-5 under the following conditions:
Mechanical stress : $\sigma = 0$ [N/m^2]
Material constant : $d = 384\ 10^{-12}$ [m/V]
Electrical field strength: $E = 10^6$ [V/m]
(maximum in air)

Substituted in (4) follows:

$$\varepsilon = \frac{\Delta l}{l} = s^E\,\sigma + dE = dE = 3.8\ 10^{-4}\ [-] \qquad (5)$$

A large strain may be obtained by a high electrical field strength so the parole is high voltages and thin layers. This means that thin layers can be used either in the form of flat rings or in the form of thin cylinders. Thin cylinders have the disadvantage that they become too supple for the quotient length/thickness > 20. This resulted in the choice for thin layers. Piëzo-electrical crystals have a high stiffness, a high eigenfrequency and a good stability. They can be used in a wide temperature-range and there is a good linearity between the electrical and mechanical quantities.

It may be mentioned that also actuators based on the effect of magnetostriction - strain by applying a magnetic field - have been investigated. Moreover in comparison with piëzo-electric crystals, they show less good properties mainly due to temperature sensitivity and magnetic saturation.

So, an actuator in this robot-arm is created by putting 60 flat rings of piëzo-electrical material - thickness 1mm,, outerdiameter 1" and innerdiameter 6 mm - on a stack formed by a bar. The bar is mounted under prestress.

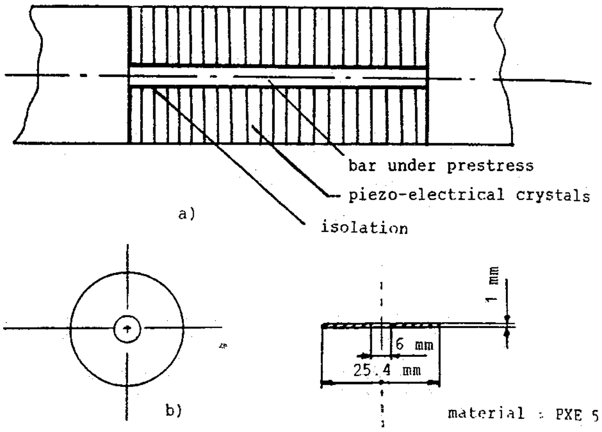

Fig. 4. The construction of an actuator (a) and piëzo-electrical crystal (b).

The piëzo-electrical crystals are electrically connected in parallel by silver contacts. Because of the fact that by the prestress only a slight decrease or increase of the thickness is used the electrical tension varies around the average of 350 Volt so from 0 to 700 Volt. Four of these bars are put in a square and this actuator set forms the connection of the robot-arm to the fixed world. By activating the bars (more or less positive) in the right combination a bending of the robot-arm in the desired direction can be achieved.

Compensation of the deviation at the free end of the robot-arm can be carried out by two methods. These possibilities have both been considered with respect to the positioning of the actuators.

1. By applying forces at the free end of the arm, this means actuators inside the arm (see Fig. 5).
2. By reversed bending of the arm at the fixed end, this means that the actuators form the connection between the arm and the fixed world (see Fig. 6).

Only the second method - already mentioned above - has been constructed. The Figs. 5 and 6 show the basic construction for these methods. Also a simulation with a finite element program MARC has been performed.

If the manipulator-arm has a distributed mass of q[kg/m], a length l and if an external force F and moment M is applied at the free end, for the deviation f(l) and the tilt angle $\phi(l)$ at the free end follows:

$$f(l) = \frac{ql^4}{8EI} + \frac{Fl^3}{3EI} + \frac{Ml^2}{2EI} + l\phi(0) \qquad (6)$$

$$\phi(l) = \frac{ql^3}{8EI} + \frac{Fl^2}{3EI} + \frac{Ml}{2EI} + \phi(0) \qquad (7)$$

Method 1:
With one end fixed $\phi(0) = 0$, the necessary moment to have a deviation $f(l) = 0$ may be derived from Eq. (6).

$$M = -2\left(\frac{ql^2}{8} + \frac{Fl}{3}\right) \qquad (8)$$

Also calculations from the finite element program according to Fig. 5 show that the deflection at the end may be corrected by applying moments with the actuators inside the robot-arm, although a deviation-angle will result. An external force of 50 N needs - with respect to the position of the actuators - two correction forces of 222 N each by the actuators. The result is:

		f[mm]	ϕ[mradian]
Deviation by F = 50 N	without correction with correction	0.17 0.0	0.25 -0.09

Table 2. Deviation by activating actuators inside the arm.

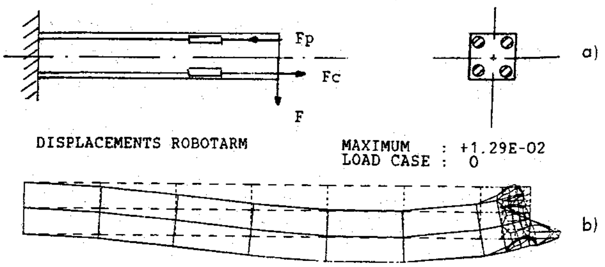

Fig. 5. Actuators in the robotarm (a) and displacement (b).

Method 2:
With the actuators between the fixed world and the robot-arm, the necessary angle $\phi(0)$ to have a zero deviation $f(l) = 0$ can easily be derived from (6):

$$\phi(0) = -\left(\frac{ql^3}{8EI} + \frac{Fl^2}{3EI} + \frac{Ml}{2EI}\right) \qquad (9)$$

The result of the rebending by the actuators if an external force of 50 N at the free end is applied is shown in Table 3.

		f[mm]	ϕ[mradian]
Deviation by F = 50 N	without correction with correction	0.17 0.0	0.25 0.075

Table 3. Deviation by activating actuators at one side of the arm.

In the description mentioned above, only the deviation in one dimension has been regarded, but it is clear that this may be extended to two. More complicated corrections e.g. for torsion may be achieved by activating the four actuators separately.

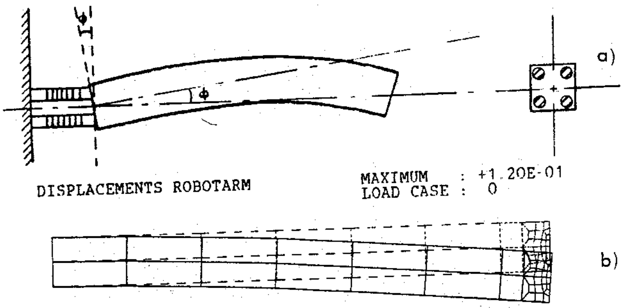

Fig. 6. Actuators at the end of the robotarm (a) and displacement. (b)

2.3. The measuring system.

The position of the free end of the robot-arm - the deviation in x- and y-direction - is measured by using a lasersystem. These deviations have to be measured in spite of the bending of the end of the arm.

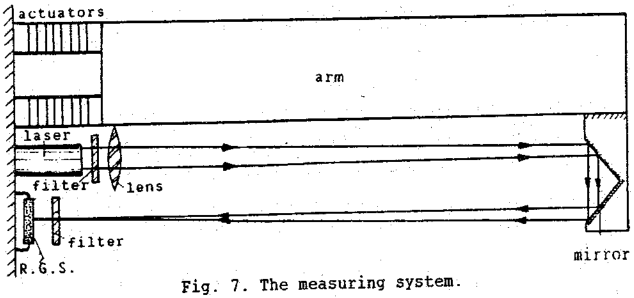

Fig. 7. The measuring system.

The source of this lasersystem is a collimatorpen - a semiconductorlaser with $\lambda = 820$ µm and an output of 2 mW- and it is mounted at the fixed end of the robot-arm. The detector is a resistive gate sentor - mounted right below - with 300 x 200 pixels of 14 x 28 μm^2 each so a surface of 4.2 x 5.6 mm^2.

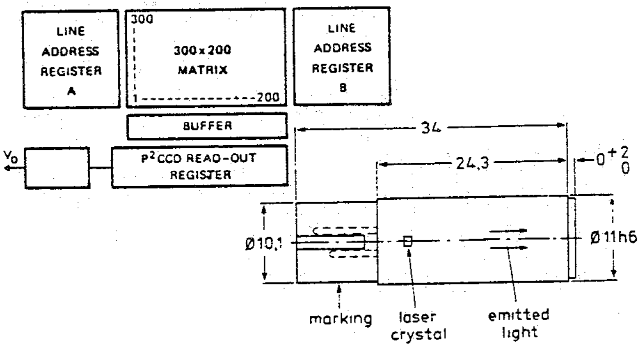

Fig. 8. The collimatorpen (lasersource) and resistive gate sensor.

The transmitted laserbeam is conducted through lenses for collimating and converging and reflected by a retroreflector (triple mirror) - mounted at the free end of the robot-arm - before it touches the resistive gate sensor. The retroreflector has the special property that only the translation (in x- or y-direction) and not the rotation (by the tilt-angle) of this mirror effects the reflected laserbeam.
A filter reduces the energy of the laserbeam for the resistive gate sensor to the allowable amount of 19 µW/cm². For the choice of the mirror at the free end, the possibility of a flat mirror has been rejected, because of the fact that also a tilt of the mirror effects the direction of the refelected beam and succeedingly the target position on the sensor. The retroreflector (triple mirror) is based on the idea of the prism. In Fig. 9 is shown how a prism reflects the laserbeam in the case of translation and rotation.

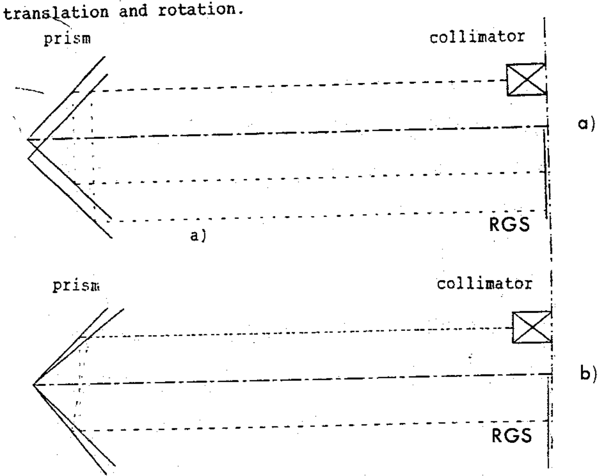

Fig. 9. Effect of translation (a) and rotation (b) of the prism on the laserbeam.

In this one-dimensional case, the only the translation (in x-direction) and not the rotation influences the direction and so the position on the sensor (in x-direction). The reflected beam is always parallel to the orginal beam. For a two-dimensional meaurement of the deviation (in x- and y-direction) a simple prism is unsuitable and a triple mirror (Fig. 10) is necessary.

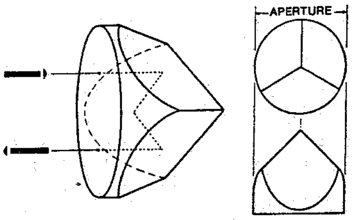

Fig. 10. The retro-reflector or triple mirror.

The retro-reflector consists of three surfaces, which are perpendicular to each other (see Fig. 10). The triple mirror reflects a laserbeam always in the same direction where it comes from. Only the translation of the mirror determines the target position of the beam on the sensor. A rotation of the mirror has no effect. So, this retroreflector is a necessary device in the measuring part of the construction.

2.4. The dynamic model.

A two dimensional model of the robotarm has been made with a finite element program. The arm has been divided into the following elements with local mass- and stiffness matrices:
- the foundation,
- the actuators and
- the arm into five parts.

All these elements are finally composed to a discrete mechanical system with viscous damping.

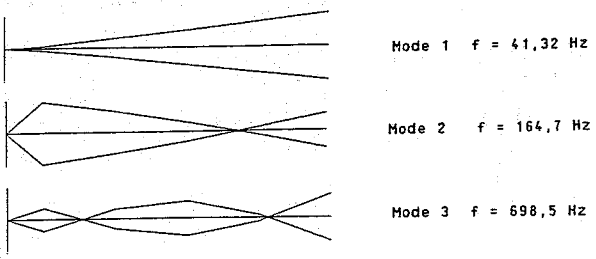

Fig. 11. Vibrations of the robot-arm by modal analysis.

With the program TRANSF. the transferfunctions of the system can be calculated and compared with the results of a modal analysis. This comparison is carried out in order to fit the data for the dampingsmatrix. As shown in Fig. 11 there are three vibration-modes: 41.3 Hz, 164.7 Hz and 698.5 Hz. The first two measured and calculated modes are within 1%.

2.5. The controlling system.

The reflected laserbeam does not hit the resistive gate sensor in the centre. From this fact deviation signals in x- and y-direction are derived and sent tot the control unit to activate the actuators, which perform corrections for the right positioning.

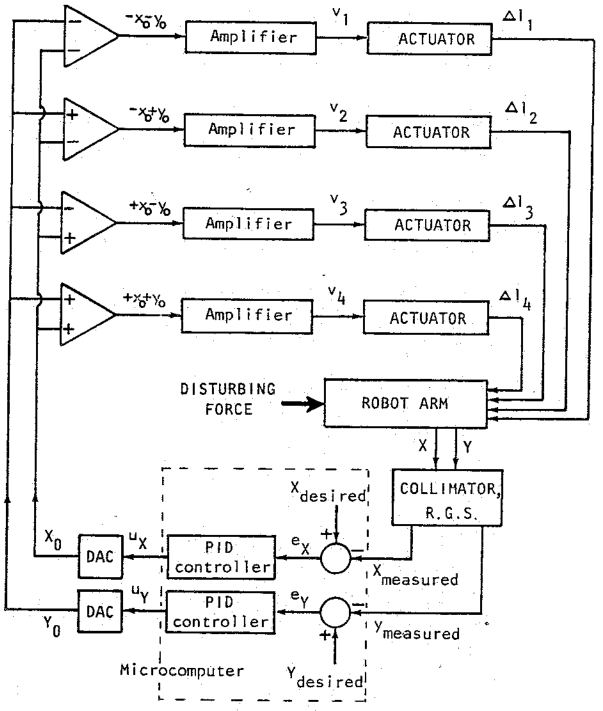

Fig. 12. The controlling system of the robot-arm.

The bending of the arm should be corrected in the directions x and y, they may be considered to be uncoupled. This means that the controller can be split into two separate controllers as shown in Fig. 12. Before starting the controller a calibration procedure should be carried out to obtain the desired position (x,y). Due to a disturbing force deviations are measured and fed to the PID-controller in the microcomputer. This is a digital controller - implemented in an INTEL 8085 micro processor - whose algorithm is according to the following discretized formula:

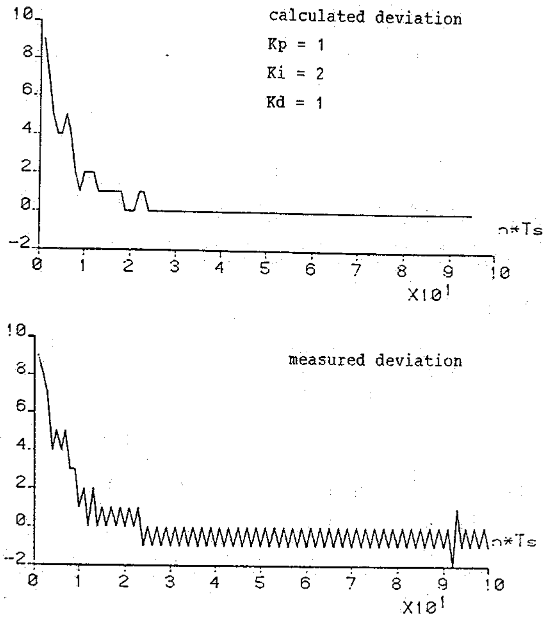

Fig. 13. Measured and calculated stepresponse with a P.I.D.-controller (K_p=1, K_i=2, K_d=1).

$$u(nT) = k_p e(nT) + k_i \sum_{k=1}^{n} e(kT) + k_d\{e(nT) - e(nT-T)\} \qquad (10)$$

The resulting control signal u(nT) is sent via a DAC to a differential amplifier and succeedingly to the high tension units to activate the actuators. The deviation in x- and y-direction is derived from the resistive gate sensor and transferred into 8 bit numbers by an ADC. Detecting the laserbeam in the matrix of pixels is timeconsuming. The sampletime T_s of the sensor is 20 ms (50Hz) and a disavantage for the system in controlling sense.

To estimate the settings of the P.I.D.-controller a simulation-program has been made of the complete system and controller. A realized and calculated respons is shown in Fig. 13. The deviation is given in bits (1 bit = 7 μm). The controller parameters can not be made too large because of the danger for instability. This is caused by the large sampletime 20 ms of the sensor. With regard to the main time constant of the system ($\tau = \frac{1}{42}$ = 24 ms) the favourable sampletime should be about 2 ms.

CONCLUSIONS.

Methods to increase the stiffness of a robot-arm are a better design or the use of other materials or active elements. The first two methods are based on the fact that the bending of a robot-arm is inversely proportional to EI. The use of active elements is based on the phenomenon of feedback, which also man applies with his supple limbs.

Piëzo-electrical crystals are very well applicable as actuator materials. They have a small time constant, good stiffness and are good controllable. Disadvantages are the small strain, high electrical tensions (isolation) and their behaviour as capacitors with a remaining electrical charge. The measuring system in the complete construction has a too large time constant (20 ms) and should be diminished to about 2 ms. In the present construction it limits the controller properties because of instability danger. The flexible microcomputer is a good controller and has the possibility of adapting the controller parameters during the performance.

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