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Mulders, P.C.; Kreffer, G.J.; Bax, W.H.M.; van der Wolf, A.C.H.

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Design and Modelling of a Modular Robot System

P. C. Mulders (2), G. J. Kreffer, W. H. M. Bax, A. C. H. van der Wolf (1),
Eindhoven University of Technology/Netherlands
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A modular robot system - consisting of a linear and a rotary actuator and for loads up to 50 kg - has been developed. The linear robot arm is driven by a DC motor, has a length of 1 m, a maximum velocity of 1 m/s, an acceleration of 5 m/s² and an accuracy of 0.01 mm. The rotational module is also driven by a DC motor with an angular velocity of ±2 rad/s, an acceleration of ±2 rad/s² and an accuracy of ±0.1 rad. With a 3D-force sensor touch - and replay of trajectories will be performed. The updating of the parameters in the algorithm for adaptive control depends on the number of the state-space dimensions of the model. The optimal algorithm of the controller is based on a good knowledge of the system, so from this modular robot an extended dynamic model has been made, which is verified by modal analysis techniques.

Next a model reduction has been done - to obtain a simulation model or a control model - and this is necessary to test adaptive path control algorithms with respect to the phenomena of parameter variations during trajectory performance.

KEYWORDS: Mechatronics, simulation, computer adaptive control.

1. INTRODUCTION

In order to obtain experience in robot design and to test advanced control systems as well, a modular robot system for loads up to 50 kg has been developed, which will consist of linear and rotary actuators. One of each type has been constructed and built together in the mean time, as shown in Fig.1. The linear robot arm is driven by a DC motor of 1 kW, has a length of 1 m, a maximum velocity of ±1 m/s, an acceleration of 5 m/s² and an accuracy of ±0.01 mm. The rotational module is also driven by a DC motor of 1 kW, has an angular velocity of ±2 rad/s, and angular acceleration of ±2 rad/s² and an angular accuracy of ±0.1 rad. So the tangential accuracy is of the same order as the radial accuracy.

The aim of this work is also to study optimal (adaptive) control algorithms on systems with place- and time dependent parameters during trajectory performance and to try this out on practical systems of industrial scale. Experiments on this item already have been done with the linear robot arm [1] and with the modular robot [2].

The optimal algorithm of the controller is based on the minimization of a performance criterion-function and so the control signals are obtained.

The performance integral may contain e.g. contributions of the deviations in trajectory positions and velocities but also the control efforts like the motor control signals. Even the boundaries for the control signals may be taken into account.

The updating of the parameters in the algorithm for adaptive control depends on the time to solve the matrix-riccati equation and this is strongly dependent on the number of the state-space dimensions of the model.

Fig. 1. Photograph of the modular robot system.

So optimal trajectory control algorithms are based on a good knowledge of the system, but on the other hand these models should not be too complex, because they may increase the computation time of the optimal control law so that on-line control becomes impossible.

Besides the optimal control law method a number of other optimal trajectory control strategies can be mentioned e.g.
- the PI control
- the computed torque method [2]
- the model reference adaptive control (MRAC) method. [2]

All these algorithms are based on a good knowledge of the system. So from this modular RT robot system an extended model - simulation model - has been made, which is verified by modal analysis techniques. Next this extended model has been reduced - to a control model - to enable on-line computation of the optimal trajectory control law. See Fig. 5.

2. DESIGN OF THE MODULAR ROBOT.

A view of this modular robot system is given in Fig. 2.

![Fig. 2 View of the modular robot system](image)

The major specifications of the linear actuator are shown in Table 1.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum velocity</td>
<td>1 m/s</td>
</tr>
<tr>
<td>Maximum acceleration</td>
<td>±5 m/s²</td>
</tr>
<tr>
<td>Maximum load</td>
<td>50 kg</td>
</tr>
<tr>
<td>Stroke</td>
<td>1 m</td>
</tr>
<tr>
<td>Position accuracy</td>
<td>0.01 mm</td>
</tr>
<tr>
<td>System</td>
<td>Heidenhain LS 513</td>
</tr>
<tr>
<td>Power source</td>
<td>DC-motor: Axem MC 19 PR 26</td>
</tr>
<tr>
<td>Control system</td>
<td>µC PID</td>
</tr>
</tbody>
</table>

Table 1. Design specifications of the linear actuator.

The mechanical construction is fairly stiff due to the hollow frame construction, while at the same time the masses are kept minimal. The arm has been constructed with slide guide-ways, which enables the preloading of the spindle and the application of roller bearings for the main bearing system.

The rotation of the motor into a translation of the actuator is converted by a spindle with a ball screw nut. An advantage of this combination is that the backlash can be eliminated by preloading the nut. A disadvantage is that the rotary speed is limited because of the critical speed of the spindle.

The DC motor is of the disc-armature type with the following characteristics:
- a very small mechanical time constant. With a load of 50 kg this becomes 26 ms.
- a continuously adjustable speed
- the largest torque at low speed.

The disadvantage however is the poor resistance against overheating. This is important because the criterion for design was very determined by the 100% duty cycle. Coupled to the motorshaft is also a tachogenerator and a rotational encoder.

For direct position measurement along the arm an optical digital incremental encoder has been mounted, type Heidenhain LSS13 with a length of 1020 mm and an accuracy of ±0.01 mm. The necessary frequency range of the encoder is determined by the speed of the arm and the accuracy of the scale.

The free end of the linear robot arm is extended with a 3D-force sensor, based on the bending principle and measured by strain gauges. The force sensor is used in the TEACH mode.

Table 2. The major specifications are shown in Table 2.
maximum angular velocity: $\pi \times 2$ rad/s
maximum angular acceleration: $\pi \times 2$ rad/s$^2$
maximum angular range: $\pi \rightarrow 2\pi$ rad
position accuracy: $10^{-5}$ rad
position measuring system: Heidenhain LIDA 360
power source: DC-motor - BBC-MC 19P
controller system: µC, PID - or state controller

Table 2: Design specifications of the rotational module.

The transmitting module is based on a cylinder with side ribs - to minimize the deformation - and is fixed to a groundplate. The transmission from the motor to the turntable consists of a 4 stage toothed wheel combination with divided and preloaded wheels - realized with torsion springs - to eliminate backlash. The toothwheels 2, 3, 5 and 7 are divided and preloaded, so each conversion is backlash-free.

The transmission ratio - starting from the motorside - as the quotient of the number of teeth is respectively: 45/21; 83/21; 83/23 and 1369/23 and gives a total reduction of 181.

This transmission has been chosen after considering alternatives with toothed wheel combinations and a harmonic drive. The selection criteria were: the transmission ratio, the stiffness, the efficiency, the backlash, the moment of inertia and the height of the construction.

The range of the rotational module is - like the linear actuator - limited by Hall switches.

The DC motor BBC-AXEM MC 19P is of 1 kW and of the disc-armature type and driven by the recommended amplifier UO5V03 of BBC. Coupled to the motor shaft is a tachogenerator and a rotational encoder. For direct position measurement of the turntable an optical digital incremental encoder as a linear line is mounted along the circumference of the turntable Heidenhain LIDA 360 with 20300 lines/cm and a pulse shaper EXE-702, and an interpolation factor of 1; 5 and 25 and a divider of 1; 2 and 4. By this the accuracy may be multiplied by 25 x 4 = 100.

The various components as the moment of inertia, stiffness, damping etc. are given in the model description in Ch. 4

3. THE CONTROL SYSTEM OF THE MODULAR ROBOT.

3.1 The hierarchical control structure.

The on-line computer capacity of one controller is often too small or not fast enough to implement an advanced control algorithm in real time.

The controller system consists of 4 Intel single board computers - working in parallel - and 1 RAM board.

The boards can communicate directly - i.e. the interrupts - via the multibus system. Data however are transported to each other via the common RAM-board 028.

The rotation as well as the control is performed by its own board Intel SBC 1860/3, coupled to its own input (the measuring system) and its own output (the motors/actuators) by the Intel SXI-interfaces.

The task of each SBC 1860/3 is:
- to calculate - according to a control algorithm - the motor voltages
- to read the position of each module
- to store these data - motor voltages and positions - into the RAM board.

The task of the master SBC 1860/3 is:
- to synchronize the software in both the other SBCs
- to transfer data over the RS 232 bus

A PC 80386 is coupled to the Master SBC. In this PC software may be developed and tested. By a data switch it can be used as a terminal for each SBC.

The optimal control law and the nominal trajectory is calculated off-line by this computer and the results are transmitted to the SBCs. The PC also serves to diagram the measurement data.

3.2 Trajectory control strategies.

The statement that a good controller is based on the best estimate of the system structure is considered in a simplified way shown in Fig. 4:

- Feedforward
- Feedback

Fig. 4. Feedforward- and feedback control

If a system $S$ needs to perform a certain trajectory $y$ then the problem is to determine the necessary input signal $u$ from that response. The best feedforward controller $C$ would be the inverse of the best estimate of the system, so $C = S^{-1}$. However, as any physical system has a less or an equal number of zeros than poles this means that $C = S^{-1}$ should have the opposite and needs to have predictive properties and can not be realized. The desired controller $C = S^{-1}$ is easily obtained by the feedback loop and increasing the open loop gain $K = \text{over the frequency range}$ (4-b). $C$ is $1/S$.

At the transition to (4-c) the system $S$ itself is used as the model, so with $K = \text{over the frequency range}$ a feedback controlled system is created.

In the keynote paper at CIRP 1992 "Advanced controllers for feed drives" from Y. Koren and C.C. Lo more detailed controllers are discussed.

Optimal (adaptive) trajectory control algorithms are applied on systems with place - and time dependent parameters during trajectory performance. A number of strategies may be mentioned here e.g.

- P.I.D. method
- computed torque method
- the model reference adaptive control (MRAC) method
- the optimal control law with performance index

All these strategies are based on a good knowledge of the system. Only the optimal control law with performance index will be described more in detail (Fig. 5).

On the modular robot system a 3D-force sensor is mounted to perform teach-and replay trajectory operations. The desired trajectory is known or firstly carried out by the robot by movement of the end effector with the 3D-force sensor. The positions of the end-effector represent that desired trajectory and by identification (Control model - computed torque method) a related sequence of motor input signals is obtained. Then the desired trajectory is again performed eventually with varying parameters in which the already known motor control signals are updated - by state feedback - by the new control algorithm, as shown in Fig. 5.
The presented model of Fig. 6 has 11 degrees of freedom.

$$ \mathbf{q}^T = (q_0, q_1, q_2, q_3, \gamma, \phi_0, \phi_1, \phi_2, \phi_3, \phi_4) $$

The rotation and translation are coupled to each other, so also the eigenfrequencies. These are also dependent on the position \( x_0 \) of the linear actuator (varying from -0.270 to +0.365 m) and an eventual load \( m_L \) [kg].

### Table 3. Eigenfrequencies of the coupled system [Hz].

<table>
<thead>
<tr>
<th>( m_L ) [kg]</th>
<th>( x_0 ) [m]</th>
<th>( f_1 )</th>
<th>( f_2 )</th>
<th>( f_3 )</th>
<th>( f_4 )</th>
<th>( f_5 )</th>
<th>( f_6 )</th>
<th>( f_7 )</th>
<th>( f_8 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-0.270</td>
<td>18</td>
<td>110</td>
<td>182</td>
<td>284</td>
<td>366</td>
<td>435</td>
<td>445</td>
<td>488</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>20</td>
<td>122</td>
<td>182</td>
<td>284</td>
<td>371</td>
<td>435</td>
<td>445</td>
<td>506</td>
</tr>
<tr>
<td>-0.365</td>
<td>19</td>
<td>134</td>
<td>182</td>
<td>284</td>
<td>377</td>
<td>443</td>
<td>445</td>
<td>528</td>
<td>6590</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>17</td>
<td>109</td>
<td>182</td>
<td>284</td>
<td>371</td>
<td>435</td>
<td>445</td>
<td>505</td>
</tr>
<tr>
<td>0.365</td>
<td>15</td>
<td>120</td>
<td>182</td>
<td>284</td>
<td>376</td>
<td>443</td>
<td>445</td>
<td>524</td>
<td>6590</td>
</tr>
</tbody>
</table>

#### 4.1 Model of the linear actuator.

If the degrees of freedom are represented by the vector \( \mathbf{q} \), the external moments by \( \mathbf{Q} \) and with \( M \) the mass-matrix, \( D \) the damping-matrix and \( \mathbf{K} \) the stiffness-matrix in which:

$$ \mathbf{q}^T = (q_0, q_1, q_2, q_3, x) \text{ and } Q^T = (0, T_1^T, 0, 0, 0) $$

the linear actuator is described by the differential equation:

$$ M \ddot{\mathbf{q}} + D \dot{\mathbf{q}} + K \mathbf{q} = \mathbf{Q} $$

The motor torque \( T_1 \) acts on moment of inertia \( J_i \).

For the estimation of the lowest eigenfrequency a single D.O.F. system is considered. A moment of inertia \( J_i \) is transferred to a mass \( m_i = J_i (2\pi f_0)^2 \).

The masses can be transferred and summarized to the end of the chain of masses and the springs- applied in series- can be reduced to one spring constant.

$$ \frac{1}{k} \sum_{i=1}^{n} \frac{1}{k_i} \mathbf{m}_{T,i} \frac{1}{k} \frac{1}{k_i} $$

With the respectively data the lowest eigenfrequency \( f_0 \) becomes:

$$ f_0 = 125 \text{ kg} \times \frac{1}{1.3 \times 10^5 \text{ N/m}} = 110 - 134 \text{ [Hz]} $$

The dynamic model of the linear robotarm has been measured with a Fourier analyzer (HP 5423) and calculated with a special programme. The value of \( f_0 \) depends on the position \( x_0 \) of the linear actuator.

<table>
<thead>
<tr>
<th>( x_0 ) [m]</th>
<th>( f_0 ) [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.270</td>
<td>110</td>
</tr>
<tr>
<td>0</td>
<td>122</td>
</tr>
<tr>
<td>0.365</td>
<td>371</td>
</tr>
<tr>
<td>-0.365</td>
<td>439</td>
</tr>
<tr>
<td>0</td>
<td>506</td>
</tr>
</tbody>
</table>

If the linear actuator is considered as the extended model then the other eigenfrequencies [Hz] are:

$$ f_2 = 506 $$

#### 4.2 Model of the rotational module.

The rotational module may also be described by:

$$ \dot{\mathbf{q}}^T = (q_0, q_1, q_2, q_3, \gamma) \text{ and } Q^T = (0, T_1^T, 0, 0, 0) $$

The motor torque \( T_2 \) acts on moment of inertia \( J_2 \).

The lowest eigenfrequency is \( f_0 = 18 - 20 \text{ [Hz]} \).

The value of \( f_0 \) depends on the position \( x_0 \) of the linear actuator.

<table>
<thead>
<tr>
<th>( x_0 ) [m]</th>
<th>( f_0 ) [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.270</td>
<td>18</td>
</tr>
<tr>
<td>0</td>
<td>19.5</td>
</tr>
<tr>
<td>0.365</td>
<td>18.9</td>
</tr>
</tbody>
</table>

If the rotation-module is considered as the extended model then the other eigenfrequencies [Hz] are:

<table>
<thead>
<tr>
<th>( f_1 )</th>
<th>( f_3 )</th>
<th>( f_4 )</th>
<th>( f_7 )</th>
<th>( f_9 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.5</td>
<td>18</td>
<td>182</td>
<td>284</td>
<td>445</td>
</tr>
</tbody>
</table>
4.3 Model reduction.

The necessity to make an extended model (Fig. 6) with 11 degrees of freedom (D.O.F. rotation 6 and translation 5) is based on the idea to describe the reality as good as possible. The behaviour of the robot may so be predicted over the complete frequency - or time domain.

Nevertheless there will always be a discrepancy between reality and the simulation model due to unmodelled dynamics. A disadvantage will also be the duration of a simulation result, especially if a small time step is applied.

By reducing the complexity (less D.O.F.) of the model a compromise is made between the accuracy and the duration. But there is another reason for model reduction, i.e. the realization of a controller via a control model.

As elucidated in Ch. 3.2 "Trajectory control strategies" a controller (like the optimal or adaptive control law) is based on the system knowledge (model). The controller is even frequently updated by solving the matrix Riccati equation - if the parameters change during trajectory performance.

By this reason the on-line controller is based on a simpler control model and so a balance is made between accuracy and time. In spite of the model reduction the derived controller should be robust enough with respect to control phenomena like stability.

Model reduction is arbitrary and some methods are known e.g. Guyan. In general the lowest eigenfrequency has most influence on the system dynamics and this one should be present in the reduced model. Considering the eigen

\[
\mathbf{Q} = \begin{bmatrix} \mathbf{r}_m & \mathbf{v} & \mathbf{x} \\ \mathbf{r}_m & \mathbf{v} & \mathbf{x} \end{bmatrix}
\]

\[
\mathbf{J}^R = \mathbf{F}(\mathbf{x})
\]

\[
\mathbf{Q} = \begin{bmatrix} \mathbf{r}_m & \mathbf{v} & \mathbf{x} \\ \mathbf{r}_m & \mathbf{v} & \mathbf{x} \end{bmatrix}
\]

\[
\mathbf{J}^R = \mathbf{F}(\mathbf{x})
\]

\[
\mathbf{Q} = \begin{bmatrix} \mathbf{r}_m & \mathbf{v} & \mathbf{x} \\ \mathbf{r}_m & \mathbf{v} & \mathbf{x} \end{bmatrix}
\]

\[
\mathbf{J}^R = \mathbf{F}(\mathbf{x})
\]

Fig. 7 Reduced models of the rotation-translation robot.

The combination of the translation- and rotational module however are a challenge to the adaptive control system during trajectory performance. [1] [2] The behaviour of the real system may be very well described by an extended model with 11 D.O.F.

For simulation experiments with a controller the robot can be described by a 5 D.O.F. reduced simulation model while the controller is based on the 3 D.O.F. reduced control model without affecting the robustness of the controller. [2]

LITERATURE


