Design and modelling of a modular robot system

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A modular robot system - consisting of a linear and a rotational 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 10⁻² rad. With a 3D-force sensor each - and replay of trajectories will be performed. The free end of the linear actuator is extended with a DC motor, has a maximum velocity of 1 m/s, an acceleration of 5 m/s² and a maximum load of 50 kg. 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 10⁻³ rad. So the tangential accuracy is of the same order as the radial accuracy.

Besides of the optimal control law method a number of other optimal trajectory control strategies can be mentioned e.g. - 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 signals. See Fig. 2.

2. DESIGN OF THE MODULAR ROBOT.

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>Position measuring</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 or state controller</td>
</tr>
</tbody>
</table>

Table 1. Design specifications of the linear actuator.

The construction of the linear actuator is shown in Table 2.

2.2. The construction of the rotational module.

The major specifications are shown in Table 2.
The on-line computer-capacity of the system. Data however are transported to each other via the common transmission bus RS 232. The optimal control law and the nominal trajectory is calculated off-line by this computer and the results are transmitted to the SBC's. The rotation as well as the translation is controlled by its own input (the measuring system) and its own output (the motor amplifier). The motor interface may conduct motor voltages and positions into the RAM board.

Table 2. Design specifications of the rotational module.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>M.J. (maximum moment of inertia)</td>
<td>2750 kgm^2</td>
</tr>
<tr>
<td>I (inertia of the construction)</td>
<td>1100 kgm^2</td>
</tr>
<tr>
<td>stiffness</td>
<td>200 MPa</td>
</tr>
<tr>
<td>damping</td>
<td>10000 Ns/m</td>
</tr>
<tr>
<td>wheel combinations</td>
<td>45/21; 83/21; 83/23; 136/23</td>
</tr>
<tr>
<td>total reduction of 181</td>
<td></td>
</tr>
<tr>
<td>number of teeth</td>
<td>45, 83, 83, 136</td>
</tr>
<tr>
<td>Hall-switches</td>
<td>420</td>
</tr>
</tbody>
</table>

3. THE CONTROL SYSTEM OF THE MODULAR ROBOT.

3.1 The hierarchical control structure.

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 translation is controlled by its own input (the measuring system) and its own output (the motors amplifiers) by the Intel SUX-interfaces.

The task of each SBC 186/03 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 186/03 is to:
- synchronize the software in both the other SBCs
- 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 SBC's. 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.

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 is:

\[ C = S^{-1} \] is easily obtained by the feedback loop and increasing the open loop gain \( K = \) over the frequency range (4-b) from \( C = \frac{1}{S} \) to \( S \).

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

In the keynote paper at CRISP 1992 "Advanced controllers for feed drives" from Y. Koren and C.C. Lo more detailed controllers are discussed. [12]

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 [2]
- the model reference adaptive control (MRAC) method [2]
- the optimal control law with performance index [1].

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-in 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.

\[ y(t) = A(t) \dot{y}(t) + B(t) u(t) \]  
\[ \dot{L}(t) = R^{-1}(t) B(t) \dot{y}(t) \]  

where \( R \) is the weighting matrix for the control signals in the performance index and the optimal \( \dot{P}(t) \) is found by solving the matrix-ricatti equation:  

\[ \dot{P}(t) = \ldots \]
The presented model of Fig. 6 has 11 degrees of freedom. 

\[
x^T q = (p_0, p_1, p_2, p_3, q_1, q_2, q_3, q_4, q_5, q_6, x)\]  

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

![Fig. 6. Extended model of the modular robot system.](image)

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

<table>
<thead>
<tr>
<th>(f_0) [Hz]</th>
<th>110</th>
<th>122</th>
<th>134</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f_1)</td>
<td>0.270</td>
<td>0</td>
<td>0.365</td>
</tr>
</tbody>
</table>

### 4.2 Model of the rotational module.

The rotational module may also be described by:

\[
M \dot{q} + D \dot{q} + K q = Q
\]

with 

\[
q^T = (p_0, p_1, p_2, p_3, q_1, q_2, q_3, q_4, q_5, q_6, x) \quad \text{and} \quad Q^T = (0, T_1, T_2, 0, 0, 0)
\]

The motor torque \(T_1\) acts on moment of inertia \(J_1\).

The lowest eigenfrequency is \(f_0\) a single D.O.F. system is considered, like in the model of the linear actuator.

The lowest eigenfrequency is \(f_0\) = 18.9 \(\pm\) 20 [Hz]

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

<table>
<thead>
<tr>
<th>(x(t)) [m]</th>
<th>-0.270</th>
<th>0</th>
<th>0.365</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f_0) [Hz]</td>
<td>18</td>
<td>19.5</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_2)</th>
<th>(f_3)</th>
<th>(f_4)</th>
<th>(f_5)</th>
<th>(f_7)</th>
<th>(f_8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>122</td>
<td>371</td>
<td>439</td>
<td>506</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.1 Model of the linear actuator.

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

\[
q^T = (p_0, p_1, q_1, q_2, q_3, q_4, q_5, q_6, x) \quad \text{and} \quad Q^T = (0, T_1, T_2, 0, 0, 0)
\]

the linear actuator is described by the differential equation:

\[
M \dot{q} + D \dot{q} + K q = Q
\]

The motor torque \(T_1\) acts on moment of inertia \(J_1\).

For the estimation of the lowest eigenfrequency a single D.O.F. system is considered. A moment of inertia \(J_1\) is transferred to a mass \(m_1\) = \(J_1 / (2\pi f_0^2)\).

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.

\[
f_0 = \frac{1}{2} \sqrt{\frac{m}{k}}
\]

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

\[
m = 125 \text{ kg} \quad k = 1.3 \times 10^7 \text{ N/m} \quad f_0 = \frac{1}{2\pi} \sqrt{\frac{m}{k}}
\]

\[
f_0 = 110 \pm 134 \text{ [Hz]}
\]

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 \(x(t)\) of the linear actuator.

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

<table>
<thead>
<tr>
<th>(f_1)</th>
<th>(f_2)</th>
<th>(f_3)</th>
<th>(f_4)</th>
<th>(f_7)</th>
<th>(f_8)</th>
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<tr>
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<td>19.5</td>
<td>18</td>
<td>18.9</td>
<td>18.9</td>
</tr>
</tbody>
</table>

4. MODELLING OF THE MODULAR ROBOT.

Although the modular robot has been constructed with many distinct components, each with its own properties like mass, stiffness etc, the combination leads to a system with divided parameters. In this chapter an attempt is made to realize a lumped mass model - with artificial components - which describes the behaviour of the robot as good as possible.

This approach is a.o. based on previous studies [3] about drives of motor-tacho-spindle-carriage combinations.

For the linear actuator this means e.g. that to the moment of inertia of the motor is added the half of the spindle-part between motor and ballscrew nut plus coupling and so this parameter varies also with the radial position of the linear actuator.

At the rotational module each spindle has at each side a toothed wheel, so this parameter varies also with its own properties like mass, stiffness etc.

An extended model of both modules is given in Fig. 6.

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.

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 might increase the computation time of the optimal control law - according to (2) and (3) - so that on line control becomes impossible.

The presented model of Fig. 6 has 11 degrees of freedom. 

\[
x^T q = (p_0, p_1, p_2, p_3, q_1, q_2, q_3, q_4, q_5, q_6, x)\]  

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

\[
f_0 = \frac{1}{2\pi} \sqrt{\frac{m}{k}}
\]

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

\[
m = 125 \text{ kg} \quad k = 1.3 \times 10^7 \text{ N/m} \quad f_0 = \frac{1}{2\pi} \sqrt{\frac{m}{k}}
\]

\[
f_0 = 110 \pm 134 \text{ [Hz]}
\]

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 \(x(t)\) of the linear actuator.

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

<table>
<thead>
<tr>
<th>(f_1)</th>
<th>(f_2)</th>
<th>(f_3)</th>
<th>(f_4)</th>
<th>(f_7)</th>
<th>(f_8)</th>
</tr>
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<td>19.5</td>
<td>18</td>
<td>19.5</td>
<td>18</td>
<td>18.9</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_2)</th>
<th>(f_3)</th>
<th>(f_4)</th>
<th>(f_7)</th>
<th>(f_8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.5</td>
<td>18</td>
<td>19.5</td>
<td>18</td>
<td>18.9</td>
<td>18.9</td>
</tr>
</tbody>
</table>

If the rotation-module is considered as the extended model then the other eigenfrequencies [Hz] are:
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, specially if a small time step is applied. By reducing the complexity (less D.O.F.) of the simulation 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

![Fig. 7 Reduced models of the rotation-translation robot.](image)

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