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Adaptive Control of a Modular Robot System

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1. INTRODUCTION

The aim of this work is a study of optimally adaptive control algorithms on systems with place- and time-dependent parameters varying during trajectory performance - and to implement this on mechanical manipulators of industrial scale. Experiments on this item already have been done with a linear robot arm. [1]

To test these advanced control systems, a modular robot system - for loads up to 50 kg consisting of a linear and a rotary actuator, as shown in Fig. 1 - has been constructed.

Industrial robots are used today for various purposes and until now robust control has been studied mostly under the assumption that actuators are stiff and that the links can be modelled as rigid bodies. Therefore most robots have a very stiff construction in order to avoid deformations and vibrations. For higher operating speeds industrial robots should be lightweight and fast. Hence, more accurate dynamic models should be taken into account to pursue better dynamic performance.

With respect to these developments a number of (optimal) adaptive trajectory control strategies may be mentioned here e.g.:

- the PID method
- the computed torque method
- the model reference adaptive control (MRAC) method.

All these methods should be considered with regard to convergence, stability and robustness. With the P.I.D.-controller the deviation from the nominal trajectory is used in proportional, integral and differential form to correct the P.I.D. gain factors which are chosen with respect to the system dynamics. For coupled systems with interaction this controller type leads often to instability. Hence, more accurate dynamic models should be taken into account to pursue better dynamic performance.

2. DESIGN AND MODELLING OF THE MODULAR ROBOT

2.1 The construction of the linear robot arm.

The linear robot model is based on the minimization of a performance criterion function, which may contain e.g. contributions of the deviations in trajectory positions and velocities, but also the control efforts like the motor control signals. [1] Even the boundaries for the control signals may be taken into account. The feedback control signals are formed by an optimal linear combination of the state variables of the system, which means optimal pole-placement.

The updating of parameters in the algorithm for adaptive control depends on the time to solve the matrix-ricatti equation - derived from the performance criterion function - and this is strongly dependent on the number of state-space dimensions of the model. So the optimal trajectory control algorithm is based on a good knowledge of the system, but on the other hand the model should not be too complex, because it might increase the computation time of the optimal control law, so that on-line control becomes impossible. The two concepts mentioned above are not well applicable to flexible robots with elastic deformations and time varying parameters.

Adaptive control is a process of modifying one or more parameters of the control system to force the response of the closed-loop system towards a desired trajectory. Among the various types of adaptive robot control systems the model reference adaptive control (MRAC) systems are important since they lead to relatively easy to implement systems, with a high speed of adaptation and may be used in a variety of applications. However it is still difficult to derive convergence, stability and robustness conditions. The applied MRAC system is described more detailed in Ch.3.

Study of the various control methods have been performed both in reality and computer simulations. So from this modular RT robot system an extended model - simulation model - has been made, which is verified by modal analysis techniques. Next the extended model has been reduced to a control model on which the various mentioned control methods are based.

Table 1. Design specifications of the linear robot arm.

<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>2 m/s^2</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>Power source</td>
<td>DC-Motor: Aemc MC 19 PW 26</td>
</tr>
<tr>
<td>Control system</td>
<td>μC PID - or state controller</td>
</tr>
</tbody>
</table>

The mechanical construction is fairly stiff due to the hollow frame construction. The rotation of the motor into a translation of the actuator is conveyed by a screw with a screwdriver nut. An advantage of this combination is that the backlash can be eliminated by preloading the motor. The DC motor is of the disc-armature type. Coupled to the motor shaft is a tacho-generator and a rotational encoder.

For direct position measurement along the arm an optical linear digital incremental encoder has been mounted. 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.

2.2. The construction of the rotational module.

The mechanical construction 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 arm consists of a 4 stage toothed wheel combination with divided and preloaded wheels - realized with torsion springs - to eliminate backlash.
The task of the master SBC 18603 is to:

This model has 11 degrees of freedom:

**Table 2. Design specifications of the rotational module.**

Coupled to the motor shaft is also a tachogenerator and a subdivider of 1:2 and 4. By this the accuracy may be multiplied by 25 x 4 x 100.

### 3.3 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.

**Fig. 2. The hierarchical controller system.**

The controller system (Fig. 2) consists of 4 Intel single board computer working in parallel - and 1 RAM board.

The rotation as well as the translation is controlled by its own board Intel SBC 18603, coupled to its own input/feedback system and its own output (motor amplifier by the Intel SBC-interfaces).

**Fig. 3 Reduced models of the rotation-translation robot.**

**3.1 The non-adaptive controller.**

The computed torque controller computes by a control model the nominal control voltages for the motors.

So the control signal consists of a PD controller and varying parameters. The PD controller is based on a simpler control model and varies the control signal as the desired one in the reduced model.

**Fig. 4 The non adaptive controller.**

The control model has 3 degrees of freedom:

Then the non-linear differential equations of motion are obtained.

### 3.2 Model reduction.

Motors.

So the control signal becomes too big. From the RT-configuration the 3 non-linear differential equations of motion are obtained. In the non-adaptive case the adaptation algorithm is out of operation, so these two cases may be well compared.

Motors.

For the RT-robot a non-adaptive and an adaptive control have been designed. In the non-adaptive case the adaptation algorithm is out of operation, so these two cases may be well compared.

For direct position measurement of the turntable an optical digital incremental encoder as a linear encoder is used. This encoder is coupled to the motor shaft and delivers the nominal control voltages for the motors.

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For direct position measurement of the turntable an optical digital incremental encoder as a linear encoder is used. This encoder is coupled to the motor shaft and delivers the nominal control voltages for the motors.
\[ u_{\text{model}} = \begin{bmatrix} M(q) \dot{q} + \dot{q} + C(q, \dot{q}) \ddot{q} + F \end{bmatrix} \]

The real trajectory is compared with the desired trajectory and the deviation and PD control effort is obtained:

\[ \dot{e} = \dot{q} - \ddot{q} \]
\[ u_{\text{PD}} = -K_p \dot{e} - K_d \dot{e} \]

The assumption is made that deviations in the rotation or translation only lead to a control effort in that degree of freedom. This means that \( K_p \) and \( K_d \) are of the following structure:

\[ K_p = \begin{bmatrix} K_{p1} & 0 & 0 \\ 0 & K_{p2} & 0 \\ 0 & 0 & K_{p3} \end{bmatrix} \]

\[ K_d = \begin{bmatrix} K_{d1} & 0 & 0 \\ 0 & K_{d2} & 0 \\ 0 & 0 & K_{d3} \end{bmatrix} \]

The feedback gains are determined such that the control strategy is stable with polies in the left half of the s-plane.

3.2 The adaptive controller.

Adaptive control is a special kind of feedback, in which the states of a process are divided into two categories, characterized by the difference in speed. The sign of the deviations of the degrees of freedom are quickly changing, while the modelparameters are slowly changing.

The fast control loop is the PD-controller with the modeldependent feedforward compensated torque part. The systemparameters are adaptively determined such that the robot is forced to behave as the reference model. The adaptation algorithm is described in (18).

Like in the previous case the control effort is divided in a computed torque (control model) part and a PD-part:

\[ u_{\text{controller}} = \begin{bmatrix} \dot{q} \end{bmatrix} - K_p \begin{bmatrix} \dot{q} \end{bmatrix} - K_d \begin{bmatrix} \dot{q} \end{bmatrix} \]

\[ u_{\text{PD}} = \begin{bmatrix} P \end{bmatrix} \begin{bmatrix} \dot{q} \end{bmatrix} - \begin{bmatrix} \ddot{q} \end{bmatrix} \]

Now the model reference adaptive control concept is described. It is defined as a second order differential equation.

\[ \ddot{\xi}(t) + 2 \zeta \omega \dot{\xi}(t) + \omega^2 \xi(t) = \ddot{\eta}(t) \]

With \( \zeta \) and \( \omega \) the dampingfactor and the undamped eigenfrequency.

This results into:

\[ \ddot{\xi}(t) + \omega \zeta \dot{\xi}(t) + \omega^2 \xi(t) = \ddot{\eta}(t) \]

So summarizing the main properties of the adaptive control concept are:

1. Two control loops. a fast loop for the degrees of freedom and a slow loop to adapt the control parameters.
2. Feedback takes place from the performance of the fast loop.
3. The feedback gains \( K_p \) and \( K_d \) are also adaptively determined such that the robot is forced to behave as the reference model.

3.3 The adaptation algorithm.

Like in the previous case the control effort is divided in a computed torque (control model) part and a PD-part.

The modeldependent part can be written as:

\[ M(q) = A^T(\dot{q}) + B^T \dot{q} + c(\dot{q}) + F \]

And so the control effort is:

\[ u_{\text{controller}} = A(\dot{q}(t)) + B(\dot{q}(t)) + (C(q)) + F(t) \]

With:

\[ A(t) = \begin{bmatrix} [A_1(t)]^T & [A_2(t)]^T & [A_3(t)]^T \end{bmatrix} \]

\[ B(t) = \begin{bmatrix} [B_1(t)]^T & [B_2(t)]^T & [B_3(t)]^T \end{bmatrix} \]

\[ C(t) = \begin{bmatrix} [C_1(t)] & [C_2(t)] & [C_3(t)] \end{bmatrix} \]

The PD-part of the control effort is time dependent and may be written as:

\[ u_{\text{PD}} = -K_p \dot{e} - K_d \dot{e} \]

With:

\[ K_p = \begin{bmatrix} K_{p1} & 0 & 0 \\ 0 & K_{p2} & 0 \\ 0 & 0 & K_{p3} \end{bmatrix} \]

\[ K_d = \begin{bmatrix} K_{d1} & 0 & 0 \\ 0 & K_{d2} & 0 \\ 0 & 0 & K_{d3} \end{bmatrix} \]

Referring to (13) and (15) there are 17 controlparameters:

- The control model:
  \[ A^T_1 \dot{q} + B_1 \dot{q} + F_1 \]
- The feedback gains:
  \[ K_{p1} \]
- The computed torque part of the input signal:
  \[ A^T_2 \dot{q} + B_2 \dot{q} + F_2 \]

A description of the real behaviour of the robot is done by a model. This is a non-linear robot equation with unknown parameters:

\[ \ddot{\xi}(t) + 2 \zeta \omega \dot{\xi}(t) + \omega^2 \xi(t) = \ddot{\eta}(t) + F(t) \]

Here \( A^T, B^T, C^T \) and \( F^T \) are matrices, in which the elements are non-linear and unknown functions of the degrees of freedom.

The control effort is formed by the computed torque (model part) and the PD-feedback:

\[ \ddot{\xi}(t) = -K_p \dot{\xi}(t) - K_d \dot{\xi}(t) + (A^T_2 \ddot{\xi}(t) + B_2 \dot{\xi}(t) + F_2) \]

In which the deviation \( \ddot{\xi} \) is defined in (6).
The gains are not chosen properly, unsensible.

-2
controller performs better than the non-adaptive controller.

The performance of the adaptive controller on different loads is shown in Fig. 10. The minimal sample-time is 7 ms, derived from the implementation and also applied in the simulations. In Fig. 7 the results of the non-adaptive controller are shown with and without the computed torque part (feed forward control of the desired trajectory).

If an extra load is applied to the robot an additional uncertainty is introduced to the control law. In Fig. 8 the position-errors are shown with a load of 50 kg and a load of 0 kg for the non-adaptive controller.

If the control parameters are updated only every 20 samples a difference in the realised errors could hardly be noticed.

4.3 Implementation on the RT robot.

With the real RT robot the same experiments have been performed as described in the simulations. It may be concluded that the use of the computed torque part improves the performance considerably.

CONCLUSIONS

The application of feedforward (computed torque) control derived via a control model calculated from the desired trajectory as a nominal control effort improves the control performance considerably. The non-adaptive controller is sensitive to load variations, so a load of 50 kg makes the control performance worse.

The adaptive controller is preferable if the robot dynamics are poorly known. In that case a non-adaptive controller will give a bad control performance and possibly lead to instability. The adaptation mechanism estimates the best control parameters and is an improvement compared to the non-adaptive controller. The adaptive controller is also rather robust: An initial deviation of the parameters values of the control model with 30% causes the adaptation mechanism to update the control parameters quickly and results again in a good control performance.

LITERATURE


