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Adaptive Control of a Modular Robot System

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Adaptive control is a process of modifying one or more parameters of the controller and these adaptive control algorithms are specially important for flexible manipulators with place- and time-dependent parameters, varying during trajectory performance. Here an adaptive controller is described as a combination of the computed torque method and an adaptive PD controller based on the Model Reference Adaptive Control (MRAC) method. It has been applied to a modular robot for loads up to 50 kg consisting of a linear and a rotary actuator showing these parameter variations. Necessary models - extended and reduced - of this modular robot have been made and the proposed controller has been tested in simulations and in the real configuration also with respect to stability, convergence and robustness.

KEYWORDS: Robots, adaptive control.

1. INTRODUCTION

The aim of this work is a study of optimal and adaptive control algorithms on systems with place- and time-dependent parameters varying during trajectory performance and to implement these 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.

On the robot system a 3D-force sensor is mounted to perform teach- and replay trajectory operations. After the teach-operation the desired trajectory is again performed eventually with varying parameters, in which the already known motor control signals are updated by the adaptive control algorithms.

Industrial robots are used today for various purposes and until now robotcontrol 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 light weight constructions to reduce the driving torque/force requirements and to enable the robotarm to respond faster. Hence, more accurate dynamic models should be taken into account to pursue better dynamic performance.

With respect to these developments a number of optimal and 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 and the P.I.D. gain factors are chosen with respect to the systemdynamics. For coupled systems with interaction this controller type leads often to instability.

By the robust and simple structure, the PID controller is often used as a standard to compare with other controllers.

The linear optimal controller 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-vector 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.

So another approach to improve the behaviour of robots is the computed torque control method, sometimes called the inverse dynamics control. The necessary torques are calculated from the prescribed trajectory and here the control law is designed explicitly on the basis of a model in order to compensate for robot non-linearities. If flexibilities play an important role, it often results in an unstable system behaviour.

So the aim is to search for a control law achieving both reasonable trajectory tracking and a certain stabilization of acceptable vibrations.

Adaptive control is a process of modifying one or more parameters of the structure of the control system to force the response of the closed-loop system towards a desired trajectory. Among the various types of adaptive 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 tested.

2. DESIGN AND MODELLING OF THE MODULAR ROBOT

2.1 The construction of the linear robotarm

Table 1. Design specifications of the linear robotarm.

<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/s²</td>
</tr>
<tr>
<td>maximum load</td>
<td>30 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 system</td>
<td>Heidenhain LS 513</td>
</tr>
<tr>
<td>power source</td>
<td>DC-motor: Axem MC 19 PK 26, 1 kW</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 converted by a spindly with a ball screw nut. An advantage of this combination is that the backlash can be eliminated by preloading the load.

The DC motor is of the disc-armature type. Coupled to the motor shaft is also a tachogenerator and a rotational encoder.

For direct position measurement along the arm an optical linear digital incremental encoder has been mounted. Type Heidenhain L813 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 linear. The free end of the linear robotarm 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 grounded plate. 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 task of the master SBC 186103 is to:

This model has 11 degrees of freedom: components, each one with its own properties like mass, stiffness etc. the computer and the results are transmitted to the SBC's.

Although the modular robot has been constructed with many distinct behaviour previous studies

The rotation as well as the traiislation is controlled by its own board htel SBC 404.

An accuracy may be multiplied by an interpolation factor of 1:

encoder as a linear has enough to implement an advanced control Jlgorithm in reai time.

2.3 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.

Table 2. Design specifications of the rotational module.

Coupled to the motor shaft is also a tachogenerator and... couples to the motor shaft is also a tachogenerator and

In this chapter an adaptive controller is proposed, which is a combination of the computed torque method for the main control input and an adaptive PD controller. In this chapter an adaptive controller is proposed, which is a combination of the computed torque method for the main control input and an adaptive PD controller. In

The control model has 3 degrees of freedom:

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

Rotation:

Translation:

Substituting the desired trajectory in equation (2) to (4) delivers the nominal control torques, from which the nominal control voltages for the motors may be derived:
The real trajectory is compared with the desired trajectory and the deviation and PD control effort is obtained:

\[ \varepsilon = \ddot{q} - \ddot{\theta} \]

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:

\[ K_p = \begin{bmatrix} K_{p1} & 0 \end{bmatrix}, \quad K_d = \begin{bmatrix} K_{d1} & 0 \end{bmatrix} \]

The feedback gains are determined such that the total system is stable with poles 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 signals related to the degrees of freedom are quickly changing states, while the modelparameters are slowly changing. The fast control loop is the PD-controller with the modeldependent feedback gains and feedback gains of the slow control loop there is a reference model, which describes the desired trajectory in terms of the deviation. The controlparameters are determined such that the robot is forced to behave as the reference model. The adaptation of the control parameters is done by using the deviation and the reference model.

Adaptive Control (MRAC) approach, given by Seraji [3],

\[ \text{Fig. 6 The desired trajectory.} \]

\[ \text{Combining (16) and (17) results in a differential equation for the deviation.} \]

\[ A^T \ddot{\hat{\theta}} + (B + K_p \hat{\theta} + (C + K_d \hat{\theta}) = (P - \hat{P}) + (A - \hat{A}) \dot{\hat{\theta}} + (B - B) \dot{\theta} + (C - C) \theta \]

\[ \text{The desired trajectory } \ddot{q} \text{ and } \dot{\theta} \text{ are at the right hand side of the equation (17). If the control parameters are constant, then the deviation will asymptotically become zero, but depend on } q_d \text{ and } F. \text{ Therefore } A, B, C, \text{ and } F \text{ have to be adapted such that the right hand side of (18) becomes zero.} \]

\[ \text{The feedback gains } K_p \text{ and } K_d \text{ are also adapted to get stability of the closed loop at the desired performance.} \]

\[ \text{If the position - velocity error is defined as } \xi(t) = (x(t) - \dot{x}(t))^T \]

This transforms (18) into the adaptive system:

\[ \ddot{\xi}(t) + 2 \xi(t) = 0 \]

With \( \xi \) and \( \dot{\xi} \) the relative dampingfactor and the undamped eigenfrequency.

This results in:

\[ \ddot{x}(t) + 2 \xi \dot{x}(t) + \xi^2 x(t) = 0 \]

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 disturbances.

2. The controlparameters are adapted on-line.

3. Feedback takes place from the performance of the fast loop.

4. MEASUREMENT RESULTS

4.1 Simulations.

The simulations have been performed with the package PC.Mathlab. It has a number of standard routines o.s. the Runge-Kutta difference routine to calculate the response of the robot via a simulation model. For this the model with 3 DOF (R3T21) has been chosen. With the control model 3 DOF (RZT21) the computed torque part of the input signal on the desired trajectory is calculated. The desired trajectory is a skew sine wave in both directions shown in Fig.6.
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).

\[
\begin{array}{c|c|c}
\text{Rotation} & \text{Translation} \\
\hline
0.1 & 0.3 & 0.5 \\
0.2 & 0.4 & 0.6 \\
0.3 & 0.5 & 0.7 \\
0.4 & 0.6 & 0.8 \\
0.5 & 0.7 & 0.9 \\
\hline
\end{array}
\]

Fig. 7 Position errors with the non-adaptive controller (--- with feedforward.)

It is clear that the use of the feedforward control improves the control performance considerably. 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 30 kg and a load of 0 kg for the non-adaptive controller.

\[
\begin{array}{c|c|c}
\text{Rotation} & \text{Translation} \\
\hline
-0.1 & -0.3 & -0.5 \\
-0.2 & -0.4 & -0.6 \\
-0.3 & -0.5 & -0.7 \\
-0.4 & -0.6 & -0.8 \\
-0.5 & -0.7 & -0.9 \\
\hline
\end{array}
\]

Fig. 8 Positions errors - non adaptive controller - different loads.

The control performance (Fig. 8) becomes less but no instabilities occur. So the controller is rather robust.

A comparison between the performances of the adaptive and the non-adaptive controllers (with a load of 0 kg) is shown in Fig. 9.

\[
\begin{array}{c|c|c}
\text{Rotation} & \text{Translation} \\
\hline
0.1 & 0.3 & 0.5 \\
0.2 & 0.4 & 0.6 \\
0.3 & 0.5 & 0.7 \\
0.4 & 0.6 & 0.8 \\
0.5 & 0.7 & 0.9 \\
\hline
\end{array}
\]

Fig. 9 Performance adaptive controller - vs. non adaptive controller (- - - - non-adaptive )

The initial conditions of the control parameters are at the start of the trajectory the same for both the adaptive as the non-adaptive controller. The adaptation mechanism adapts the control parameters during the trajectory. The adaptive controller performs better than the non-adaptive controller. The performance of the adaptive controller on different loads is shown in Fig. 10.

\[
\begin{array}{c|c|c}
\text{Rotation} & \text{Translation} \\
\hline
-0.1 & -0.3 & -0.5 \\
-0.2 & -0.4 & -0.6 \\
-0.3 & -0.5 & -0.7 \\
-0.4 & -0.6 & -0.8 \\
-0.5 & -0.7 & -0.9 \\
\hline
\end{array}
\]

Fig. 10 Position errors - adaptive controller - different loads.

The position - errors (see fig. 10 and 8) are reduced by a factor 2 for rotation and by a factor 6 for translation compared with the non-adaptive controller.

4.2 Robustness and Adaptation speed.

If the controlmodel does not fit well to the robot behaviour or if the feedback gains are not chosen properly, then the response of the real robot may become unstable.

The adaptive controller however will try to stabilize this effect. This is called the robustness of the adaptive controller, where the adaptation mechanism is able to stabilize an initial unstable controller. Also the adaptation mechanism restricts the feedback gain to become negative. In the case that the controlparameters is 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 R-T 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.

In Fig. 11 a comparison is made between the adaptive and the non-adaptive controller. The adaptive controller needs a sufficient long trajectory to estimate the controlparameters well. So the nominal trajectory here consists of four skew sine waves. The RT-robot is rather stiff, so small variations in the load are easily compensated by the PD-controller. With a load of 20 kg the adaptive controller tends to perform better.

The experiments described above have been done with maximum adaptation speed. If this speed is reduced by a factor twelve, there is nearly no difference in the position error.

CONCLUSIONS

The application of feedforward (computed torque) control derived via a control model, calculated from the desired trajectory and nominal control effort improves the control performance considerably.

The non-adaptive controller is sensitive to load variations. If 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 parametersvalues of the control model with 30% causes the adaptation mechanism to update the controlparameters quickly and results again in a good control performance.

LITERATURE


