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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 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.

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 algorithm.

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 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) 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.D.-controller the deviation from the nominal trajectory is used in proportional, integral and differential form to correct and the P.D. gain factors are chosen with respect to the system dynamics. 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.

Fig 1 Photograph of the modular robot system.

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-recursive 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 controller 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 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.

2. DESIGN AND MODELLING OF THE MODULAR ROBOT

2.1 The construction of the linear robotarm:

maximum velocity 1 m/s
maximum acceleration 2 m/s²
maximum load 30 kg
stroke 1 m
position accuracy 0.01 mm
power source DC-motor: Axem MC 19 PK 26, 1 kW
control system μC - PID - or state controller

Table 1. Design specifications of the linear robotarm.

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 ball-screw with a ball-screw nut. An advantage of this combination is that the backlash can be eliminated by preloading the screw.

The DC motor is of the disc-armature type. Coupled to the motorshaft is a reduction and a rotational encoder.

For direct position measurement along the arm an optical linear digital incremental encoder has been mounted 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 lineal. 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 T Eddie 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 turntable consists of a4 stage toothed wheel combination with divided and preloaded wheels - realized with torsion springs - to eliminate backlash.

Fig 2 Construction of the linear robotarm.

Fig 3 Construction of the rotational module.

Fig 4 Photograph of the modular robot system.
The task of the master SBC 186103 is to:

- The model has 11 degrees of freedom:

  - 2.4

  - DC-motor: BBC-MC 19P, 1 kW

  - Power source: Heidenhain LIDA 360

  - Control system: PID or state controller.

Table 2. Design specifications of the rotational module.

Coupled to the motor shaft is also a tachogenerator and a rotational encoder. For direct position measurement of the turntable an optical digital incremental encoder as a linear has been mounted along the circumference of the turntable type Heidenhain LIDA 360 with 20200 lines and a pulse shaper EPE-702 and an interpolation factor of 1:3 and 25 and a subdivider of 1:2 and 4. By this the accuracy may be multiplied by 25 x 4 x 100.

2.3 The hierarchical control structure.

The on-line computer capability of one controller is often too small or not fast enough to implement an advanced control algorithm in real time. As a consequence of this fact the controller is split into three parts: an on-line controller, an achieved controller and an off-line controller. A connection is made to realize the on-line controller based on a simplified control model and to balance the accuracy with respect to higher order control phenomena like stability.

The rotation as well as the translation is controlled by its own board called SBC.

3. MODEL REFERENCE ADAPTIVE CONTROL OF THE ROBOT.

For the R-T 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.

Non-adaptive controllers require exact knowledge of the system parameters and explicit use of the complex system dynamics. Uncertainties lead to a bad performance of the controller. In practice one has to deal with uncertainty in the system dynamics. A number of parameters as moments of inertia, loads and armaments may vary, so non-linearity in the actuators may be unknown. By applying feedback one may reduce the sensitivity for parameter variations. This leads to higher gain factors, bigger control efforts and increases the possibility of instability.

In adaptive control the model parameters of the system are estimated on-line. Based on this estimation the control effort is determined. As adaptive control is very suitable for manipulators, with a complex system description with unknown and varying parameters.

In this chapter an adaptive controller is proposed, which is a combination of the computed torque method for main control input and an adaptive PD controller acting on the deviation of the desired trajectory. The computed torque signal is derived directly from the equations of a control model. An adaptation algorithm based on the Model Reference Adaptive Control (MRAC) method adapts the PD gain-factors on-line for the additional linear part. The complete controller is applied to a simulation model as well as the real RT-robor.

3.1 The non-adaptive controller.

As stated before this controller consists of two parts, a model dependent feedforward controller and a PD controller.

The computed torque controller compiles by a control model the nominal control efforts, the torques to perform a desired trajectory. Next the PD-controller acts on and compensates for the occurring trajectory error. The control model has to be a representative reduced model of the complete system. It may not be too complex, because otherwise, the computation time of this part of the control signal becomes too big. From the RT-configuration the 3 D.O.F. model (R2 T1) has been applied here.

So the control signal consists of $\hat{u} = \hat{u}_{\text{model}} + \hat{u}_{\text{PD}}$.

The control model has three degrees of freedom:

- Rotation of the rotation module motor: $\hat{\theta}_m$
- Rotation of the turntable: $\hat{\phi}_m$
- Translation of the linear arm: $\hat{x}$

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

\[ M = J_2 R + \left[ \begin{array}{c} \frac{d^2 \hat{\phi}_m}{dt^2} + \frac{d \hat{\phi}_m}{dt} \hat{R} + \frac{\hat{R}}{\hat{x}} \frac{d \hat{R}}{dt} + \frac{\hat{R}}{\hat{x}} \frac{d \hat{R}}{dt} \end{array} \right] \]

\[ \hat{R} = J_1 R_2 + \left[ \begin{array}{c} \frac{d^2 \hat{x}}{dt^2} + \frac{d \hat{x}}{dt} \hat{R} + \frac{\hat{R}}{\hat{x}} \frac{d \hat{R}}{dt} + \frac{\hat{R}}{\hat{x}} \frac{d \hat{R}}{dt} \end{array} \right] \]

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:

$$\dot{e} = \dot{q} - \dot{\hat{q}}$$  \[(6)\]

$$u_{PD} = -K_P e - K_D \dot{e}$$  \[(7)\]

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:

$$K_P = \begin{bmatrix} K_{P1} & 0 & 0 \\ 0 & K_{P2} & 0 \\ 0 & 0 & K_{P3} \end{bmatrix}$$  \[(8)\]

$$K_D = \begin{bmatrix} K_{D1} & 0 & 0 \\ 0 & K_{D2} & 0 \\ 0 & 0 & K_{D3} \end{bmatrix}$$

The feedback gains are determined such that the real 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 states contained 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 feedforward (computed torque) part. The systemparameters and subsequently the control parameters (modelparameters and feedback gains) are not constant, but they are updated in a slower control loop as an answer to the change in the dynamics of the process and its disturbances.

$$\zeta(t) = \begin{bmatrix} \begin{vmatrix} (A_i)^{-1} [C_i + K_i] \end{vmatrix} & \begin{vmatrix} (A_i)^{-1} [B_i - K_i] \end{vmatrix} \end{vmatrix} \frac{\dot{q}(t)}{\dot{\hat{q}}(t)}$$  \[(19)\]

This transforms (18) into the adaptive system:

$$\dot{\hat{q}}(t) + 2\zeta \omega_n \hat{q}(t) + \omega_n^2 \hat{q}(t) = \ddot{\xi}(t)$$  \[(20)\]

With $\omega_n$ and $\zeta$ the relative dampingfactor and the undamped eigenfrequency. This results into:

$$\dot{\hat{q}}(t) + 2\omega_n \xi(t) + \omega_n^2 \hat{q}(t) = \ddot{\xi}(t)$$  \[(21)\]

With $\hat{q}(t) = [\hat{q}_1(t), \hat{q}_2(t), \hat{q}_3(t)]^T$, the vector of desired model position - velocity errors (21) may be written as:

$$(\epsilon(t) = 0)$$  \[(22)\]

The reference model is stable, so there exist a symmetric positive definite $6 \times 6$ matrix $P$, which obeys the Lyapunov equation

$$P = P_1 + P_2 + P_3$$  \[(23)\]

in which $D$ is the $6 \times 6$ system- and $Q$ is a symmetric constant $6 \times 6$ matrix. From this the adaptation algorithms are derived so that for a trajectory the state of the adaptive system converges to the reference model. The unknown robotparameters $A$, $B$, $C$ and $F$ are slowly time dependent compared with the adaptation.

For $\dot{R}(t) = P_1 \ddot{c}(t) + P_2 \dot{c}(t)$ and with the matrices $A$, $B$, $C$, $F$ representing the positive adaptationgains - defined by the designer - the controlparameters may be calculated from:

$$\ddot{R}(t) = P_1 \ddot{c}(t) + P_2 \dot{c}(t)$$  \[(24)\]

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. 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-Matlab. It has a number of standard routines so that the Runge-Kutta difference routine can calculate the response of the robot via a simulation model. For this the model with 3 DOF $(R_1, R_2, R_3)$ has been chosen. With the control model 3 DOF (RT21) 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 gains are not chosen properly.

4.2 Robustness and Adaptation Speed.

If the control model does not fit well to the robot behaviour or if the feedback controller performs better than the non-adaptive controller.

The performance of the adaptive controller on different loads is shown in Fig. 10.

If 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.

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).

The performance of the adaptive controller on different loads is shown in Fig. 10.

A comparison between the performances of the adaptive and the non-adaptive controllers is shown in Fig. 9.

The control performance (Fig. 9) becomes less but no instabilities occur. So the controller is rather robust.

The minimal sample-time is 7 ms, derived from the implementation and also applied in the simulations.

The results of the non-adaptive controller are shown with and without the computed torque part (feed forward control of the desired trajectory).

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 controller parameters are updated only every 20 samples a difference in the realized 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 closed loop 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 parameter values of the control model with 20% does not prevent the adaptation mechanism to update the control parameters quickly and results again in a good control performance.

LITERATURE


